TRANSIT COOPERATIVE RESEARCH PROGRAM

TCRP REPORT 71

Track-Related Research

Volume 6:

Direct-Fixation Track Design Specifications, Research, and Related Material

Part A

Direct-Fixation Track Design and Example Specifications

TRANSPORTATION RESEARCH BOARD

May 2005

CONTENTS

PART A

SECTION 1

Direct Fixation Track Design

For

TCRP Project D-07/Task 11

Development of Direct-Fixation Fastener Specifications and Related Material

by

Laurence E. Daniels
Railroad Consulting Engineer

William Moorhead
TRAMMCO

May 2005

SECTION 1

Direct Fixation Track Design

Table of Contents

SECTION 1

Direct Fixation Track Design

List of Figures

SECTION 1

Direct Fixation Track Design

List of Tables

Direct Fixation Track Design

I. INTRODUCTION

A. Purpose

The purpose of this section is to present track design principles and material evaluation methods for Direct Fixation fasteners and track.

B. Background

The primary purpose of Direct Fixation track is to minimize the track envelope in tunnels and to reduce the dead weight on aerial structures, compared to other forms of track. Direct Fixation track is also chosen for a number of other reasons and applications. Examples are:

- Train washes and areas prone to spills (fueling platforms, platforms for loading and unloading hazardous material)
- Locations where track to station platform relationships are important
- Locations where at-grade slab track has lower life cycle cost than ballasted track:
    - Transitions to structures
    - Adverse soil conditions
- Locations requiring high track reliability
    - Locations with poor maintenance access
    - High density routes
- Some configurations of embedded track (street track)

Direct Fixation track can produce exceptionally reliable long-term performance if designed and installed properly.

In addition to its basic function of holding the rail to line and gage, the Direct Fixation track fastener can provide favorable dynamic response and electrical isolation.

This section approaches Direct Fixation track design from the view of a new track design. The information is intended to also be useful for conducting

investigations of, and identifying beneficial improvements in, existing Direct Fixation installations.

The information in this section uses data from research[1] and American Railway Engineering and Maintenance of Way Association (AREMA) publications[2], along with references specifically cited.

C. Scope

The scope of this section is Direct Fixation track. Direct Fixation track is a subcategory of ballastless track. The term "Direct Fixation track" refers to a track using a plate-type assembly (Figure 1) to hold the rail in place on a support (usually a concrete support, but possibly steel or other superstructure material). Other categories of ballastless track are embedded rail track and embedded block track. Substantial portions of this section also apply to embedded block track, with exceptions or special considerations identified.

Within Direct Fixation plate-type fasteners, there are currently three general designs:

1. Bonded Fasteners, where elastomer is vulcanized (bonded) to a top steel plate and, in some designs, to a bottom steel plate. The edges of bonded fasteners also have bonded elastomeric material. A common practice is to bond elastomer to the underside surface of the bottom plate where there is a bottom plate.

2. Non-bonded Fasteners, where an elastomer pad is placed under a single top plate (usually without a bottom plate) without the pad bonded to the plate(s).

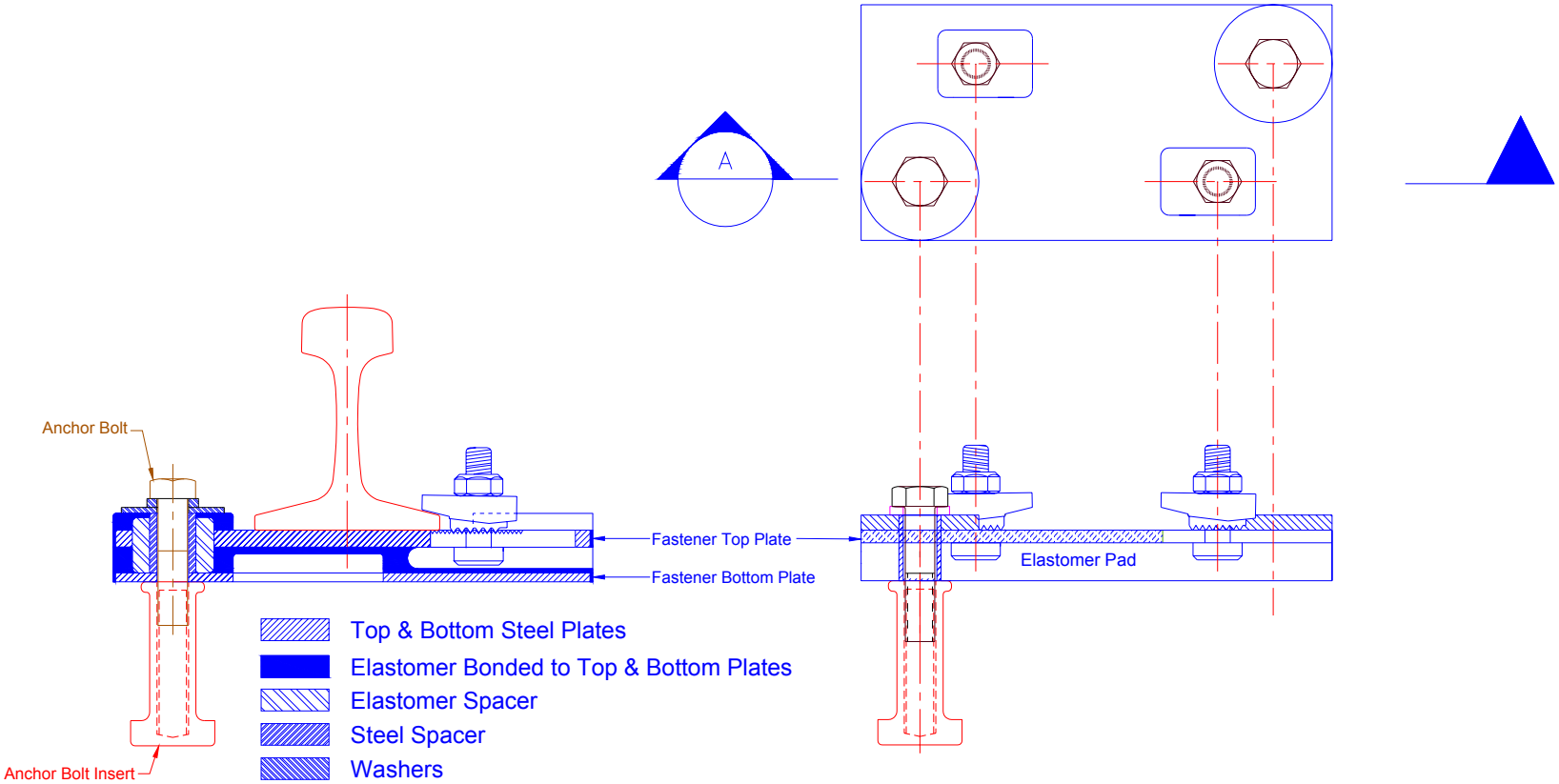
3. Contained fasteners, where the elastomer is encased in a frame. These fasteners may be bonded or non-bonded.

Illustrations of the various fastener types are in Figure 2 through Figure 6.

---

[1] Part B of this report. Part B summarizes Direct Fixation laboratory and field studies by J.M. Tuten and J.A. Hadden of Battelle, in collaboration with L.E. Daniels, for SEPTA, Kowloon-Canton Railway, and TCRP Project D-5 between 1995 and 1999.

[2] L.E. Daniels, Committee 5 Presentation on Elastic Fasteners, American Railway Engineering Association, Bulletin No. 752, October 1995, Proceedings Volume 96 (1995), pp. 277 to 293.



BONDED FASTENER EXAMPLE

SECTION A-A
NON-BONDED FASTENER EXAMPLE

Figure 1. Examples of Bonded and Non-Bonded Plate-Type Direct Fixation Fasteners. Rigid Rail Clip illustrated.

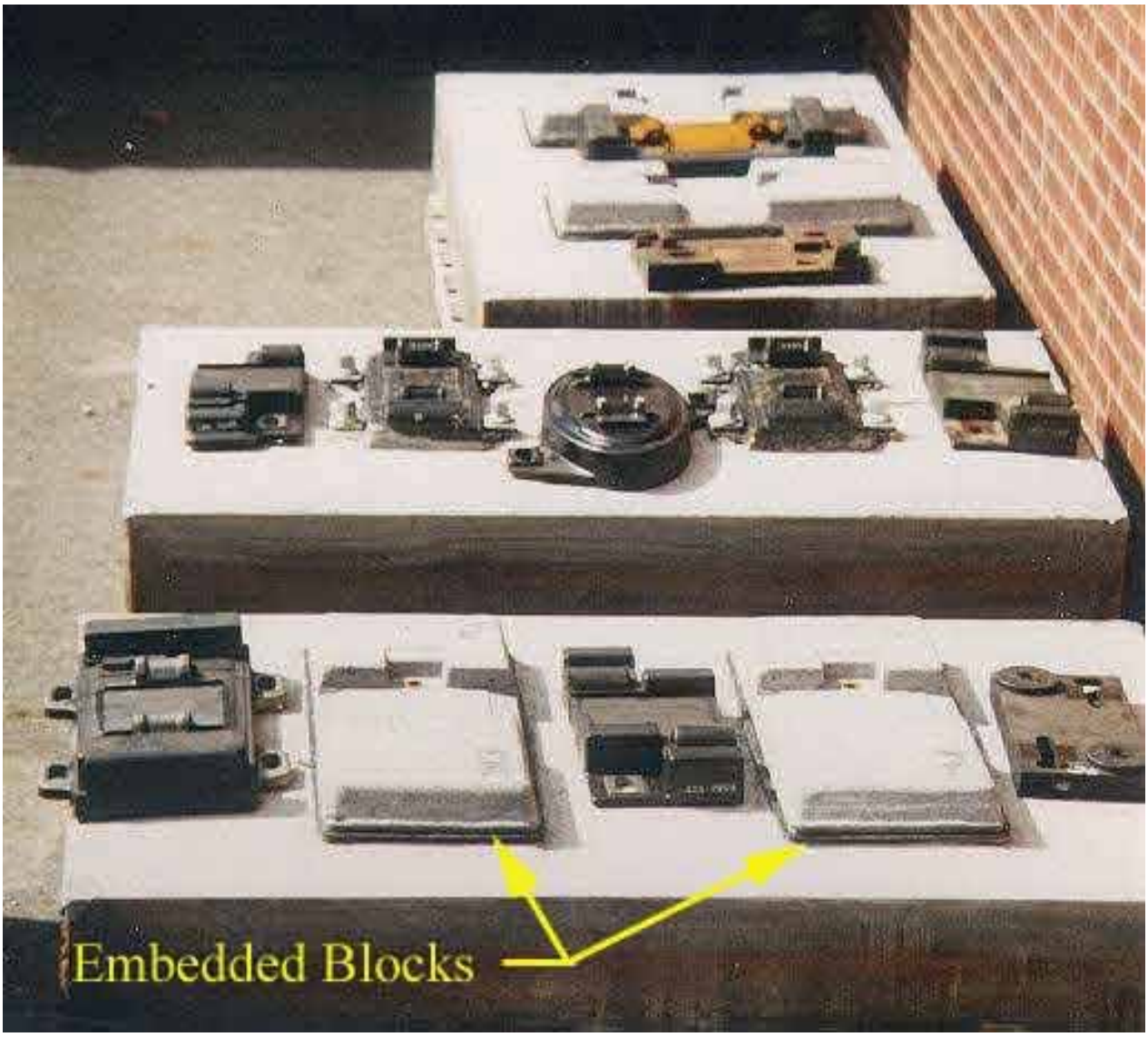


Figure 2. Example of Different Direct Fixation Fastener Designs.

All fasteners in this view are “plate-type” fasteners except the noted embedded block design. Not shown are rail clips, anchor bolts, and, for the embedded blocks, rail pads.

Figure 3. Examples of Bonded Plate-Type Direct Fixation Fasteners.

Figure 4. Examples of Bonded Plate-Type Direct Fixation Fasteners.

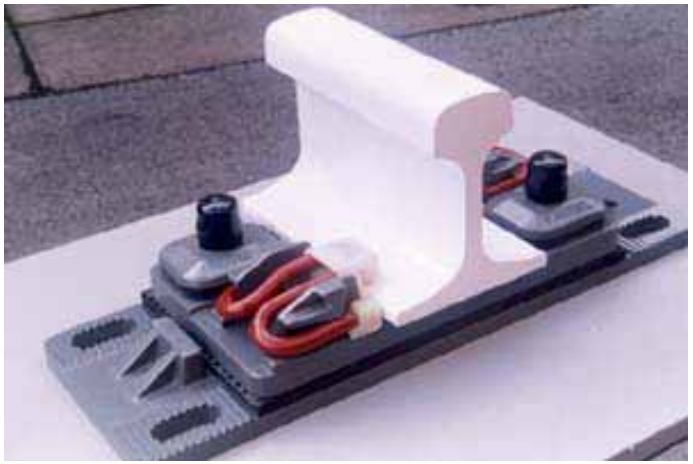


Figure 5. Examples of Non-Bonded Direct Fixation Fasteners.

Figure 6. Non-Bonded Fastener (left); Embedded Block Track (right).

The section's order is:

- II. Discussion on Basics
- III. Direct Fixation Track Design Steps
- IV. Determining Loads
- V. Direct Fixation Materials (elastomers, concrete and metals)
- VI. Fastener Design
- VII. Fastener Spacing
- VIII. Track Transitions
- IX. Construction Tolerances and Specifications

II. DISCUSSION ON BASICS

This subparagraph presents a broad view of Direct Fixation technical parameters, specifications and performance expectations developed in more detail later in this Section.

At the most fundamental level, Direct Fixation track is implemented primarily to reduce the cost of aerial structures by minimizing the dead load on the structure or to reduce the track envelope in tunnels, allowing smaller tunnels. The fundamental criterion for Direct Fixation track is long-term competence in providing rail support and restraint, and impact load protection for the supporting superstructure.

Any other criterion for Direct Fixation track is secondary to the fundamental criterion.

A. General Configurations

The options and benefits of different Direct Fixation fastener configurations are presented in Section VI.A, Fastener Design, General Considerations.

B. Mechanics Affected by Direct Fixation Fasteners

Because Direct Fixation fasteners have the capability of an engineered stiffness and electrical insulation, they have been recommended to mitigate ground vibration concerns and potential structural and utility damage from stray current. However, those capabilities have limitations which should be recognized.

1. *Vibration Mechanics*

In order to understand the dynamic response of Direct Fixation fasteners, definition of the dynamic system is required. In transit operations, a fastener is a component of a mechanical system composed, approximately, of a portion of the rail, a wheel and half an axle (when present), and the fastener. In laboratory tests, the system is the fastener and a piece of test rail[3]. The fastener has stiffness and damping characteristics. The wheel, axle and rail are the masses in this system. The following references to the Direct Fixation "system" are to these components.

Direct Fixation fasteners are vibration filters for vibrations above a fastener system's resonant frequency. Direct Fixation fasteners provide no vibration attenuation below the fastener system's resonant frequency. A Direct Fixation fastener system may amplify vibrations that are near the fastener system's resonant frequency.

The engineering model for fastener testing and response is a spring-damper-mass model, a textbook two-degree of freedom model. This is one of three models that are encountered in Direct Fixation subject matter. The other two are the Beam-on-Elastic-Foundation (BOEF) theory, used for most track engineering, and a parallel impedance model, used by noise and vibration specialists to represent wheel and rail response. Each of these is very different, and each has its own limitations. This report and all its relationships use BOEF theory unless the context is stated as the spring-damper-mass model. The parallel impedance model is not used.

Based on the spring-damper-mass model, the vibration filtering capability varies with the effective mass on the fastener. When a wheel is over a fastener, the fastener-rail-wheel system resonant frequency is between 30 Hz and 100 Hz, depending on the fastener design. When a wheel is approaching a fastener and only the rail is resting on a fastener, the fastener-rail system resonant frequency is between 100 Hz to 160 Hz, again depending on the fastener design.

The resonant frequency is the frequency at which the fastener begins to attenuate vibrations[4]. The vibration attenuation improves for higher

[3] Additional portions of the laboratory test apparatus may be included as part of the "system" if the apparatus is between the test rail and the load measurement cell.

[4] The resonant frequency also can be a point that amplifies, rather than attenuates, incipient vibrations. If the damping coefficient is low relative a parameter called the "critical damping coefficient", the incipient vibrations will be magnified. Whether amplification occurs at the resonant frequency or not, higher frequency vibrations will be attenuated.

frequencies. For this reason, the literature states[5] that vibration isolators must have a resonant frequency that is lower by a factor of 3 of the exciting or operating frequency.

A fastener system (fastener, wheel, rail) with a 50 Hz resonant frequency should not be expected to have full vibration attenuation for vibration frequencies less than 150 Hz and should have no attenuation effect on vibration frequencies less than 50 Hz, as an example.

The primary track mechanism creating ground vibration energy is the passing of a wheel, which appears as waves with frequencies between 5 and 20 Hz depending on vehicle speed[6]. In addition, all rail vehicles have fundamental motions inherent in their suspension systems to sway ("roll mode"), bounce ("pitch mode") and turn ("yaw mode"). These kinematic mechanisms occur between 0.75 Hz and 7 Hz for most rail transit vehicles. Direct Fixation fasteners can not filter these vibration sources from the support.

All Direct Fixation fasteners will filter impacts, which occur at frequencies of about 150 Hz and higher, and vibrations from short-wave corrugations (200 Hz and higher) but not long-wave rail corrugations (30 to 90 Hz)[7].

Please see paragraph VI.B.2, Fastener Dynamic Characteristics, for a detailed discussion of fastener characteristics and vibration attenuation.

2. *Electrical Isolation and Stray Current*

Direct Fixation fastener specifications require electrical isolation from traction power ground return current in the rail. Current leakage through fasteners may cause corrosion in a transit's facilities and nearby metal objects such as structural steel, rebar, utilities and pipelines.

Fasteners also provide insulation between the running rails, necessary for track circuit operation.

Fastener insulation may be defeated by moisture and debris accumulation around a fastener creating a leakage path for current. The fastener

[5] *Engineering with Rubber*, Editor Alan Gent, Hanser Publications, 1992, pg. 84.

[6] Passing wheels deflect the rail in wave form (referred to as the "precession wave") that travels with the wheel. A point in track sees this passing wave as an oscillation having a frequency defined by the wave's length and the duration from the beginning to end of the wave's passing.

[7] Transit rail corrugations produce both long-wave and short-wave rail corrugations superimposed over the other. The long-wave corrugations have a much larger amplitude and therefore are considered the greater contributor to ground vibrations.

insulation specifications are very conservative to minimize possible current leakage under all conditions.

Direct Fixation track benefits from periodic track cleaning to remove dirt and debris and attention to drainage to minimize current leakage.

Please see paragraph VI.B.3, Fastener Electrical Properties, for a detailed discussion.

C. Perspectives on Fastener Stiffness and Materials

The stiffness values must be stated at a specific load value because elastomers produce a non-linear load-deflection curve, meaning the stiffness will increase with increasing load.

Direct Fixation fasteners have two important mechanical characteristics: Static stiffness and resonance frequency. The first is a simple, intuitive characteristic most often cited as the key fastener property; the second is the true dynamic response characteristic. Please see paragraph VI.B for information on fastener dynamic characteristics.

For nearly all Direct Fixation fastener designs, the lateral fastener stiffness is influenced by the vertical fastener stiffness. This means that the vertical fastener stiffness must be high enough in most designs to provide sufficient lateral stiffness against rail lateral and rotational motion, unless the design supplements the restraint for these motions in some manner.

Anecdotal evidence from at least one case study of rail corrugations suggests that rail corrugation occurrence and growth is impeded by a lower fastener stiffness, especially in the presence of other treatments (rail lubrication, etc.). The desirable upper limit for the dynamic fastener stiffness appears to be about 750,000 lb/in, well above the stiffness value for any commercial Direct Fixation fastener.

At the lower limits of vertical stiffness, elastomer strain may be an issue depending on design of the fastener geometry and the fastener's elastomeric material.

The selection of a fastener stiffness value involves consideration of several requirements. Suggested stiffness values to meet the requirements are shown in Table A.

Table A. Suggested Fastener Vertical Stiffness Values for Transit

Requirement	Suggested Fastener Vertical Stiffness
Mitigate impact loads	Preferably 300,000 lb/in or less at maximum static load. Not to exceed 1,000,000 lb/in dynamic stiffness at maximum design load[8].
Minimize rail lateral and rotational motion	About 75,000 lb/in or greater if elastic rail clips are used and the fastener design does not have a rail rotation compensating feature.
Minimize wheel/rail dynamic interaction such as rail corrugations	Preferably 250,000 lb/in or less at maximum static load. Not to exceed 750,000 lb/in at twice the maximum static load.
Minimize elastomer strain	About 30,000 lb/in minimum. The actual minimum depends on the elastomer material, and size and shape of the elastomer. Within current fastener design concepts and materials, the suggested minimum stiffness is likely at limits of allowable elastomer strain for transit loading.

These values may not be appropriate for the following fastener designs:

- Multiple stiffness design. A fastener with low stiffness at low loads and increased stiffness at higher loads may have high strain rates from the higher loads by design.

- Fasteners that develop stiffness through elastomer shear rather than compression. This unique approach may provide low stiffness without the drawbacks of excessive lateral rail roll.

Materials (elastomers, metals) for Direct Fixation fasteners historically have been limited to a narrow range of rubber and rubber-like compounds for elastomers and a narrow range of steel or cast iron categories for metal components. However, compound designers and fastener designers have substantial flexibility within the specifications to mix compounds and configure fasteners in advantageous ways.

[8] Maximum design and dynamic load estimates are described later in this report section.

Fastener elastomers are sensitive to temperature. Fastener characteristics such as the resonance frequency (i.e. vibration filtering frequency) will vary with daily and seasonal temperature changes. There is no research that documents the amount of change that can be reasonably expected, but temperature may explain unexpected track responses when there is no other obvious influence.

Please see paragraph V, Direct Fixation Materials, for detailed discussion of fastener materials.

D. Variability of Fastener Properties

Direct Fixation fastener properties, particularly fastener stiffness, are not precise values.

Fastener elastomers have non-linear load-deflection curves. Fasteners therefore exhibit different stiffness values at different loads. The fastener will present different stiffness values as the wheel approaches and departs the fastener.

Manufacturing processes can introduce large variations in stiffness between fasteners in the same manufacturing lot (Figure 7).

The consequences of these variations are uncertainty in actual properties of individual fasteners. A circumstance where stiffness values vary significantly between adjacent fasteners in track will create higher loads on the stiffer fastener, potentially degrading the fastener. Stiffness variations between adjacent fasteners create non-uniform support conditions, potentially leading to adverse dynamic wheel/rail interaction.

However, these consequences have not been documented, meaning that the industry has not witnessed conditions or phenomena that would lead to suspicion that fastener property variability produces adverse behavior. While further study may be warranted, the pragmatic observation is reasonable track performance (including dynamic wheel/rail interaction) can be expected even with manufacturing variations in fastener properties as large as those in Figure 7 for most transit speeds.

The Research Report, Part B, presents measured fastener properties, including static and dynamic fastener stiffness for different fastener designs and for multiple fasteners of the same design.

The broader view from these measured values is the fastener manufacturing variability may produce properties equal in range to the variability between fastener designs (within transit loads). That is, the expected difference in fastener response and performance between most Direct Fixation fasteners is smaller than some proponents argue, likely due to fastener property variability.

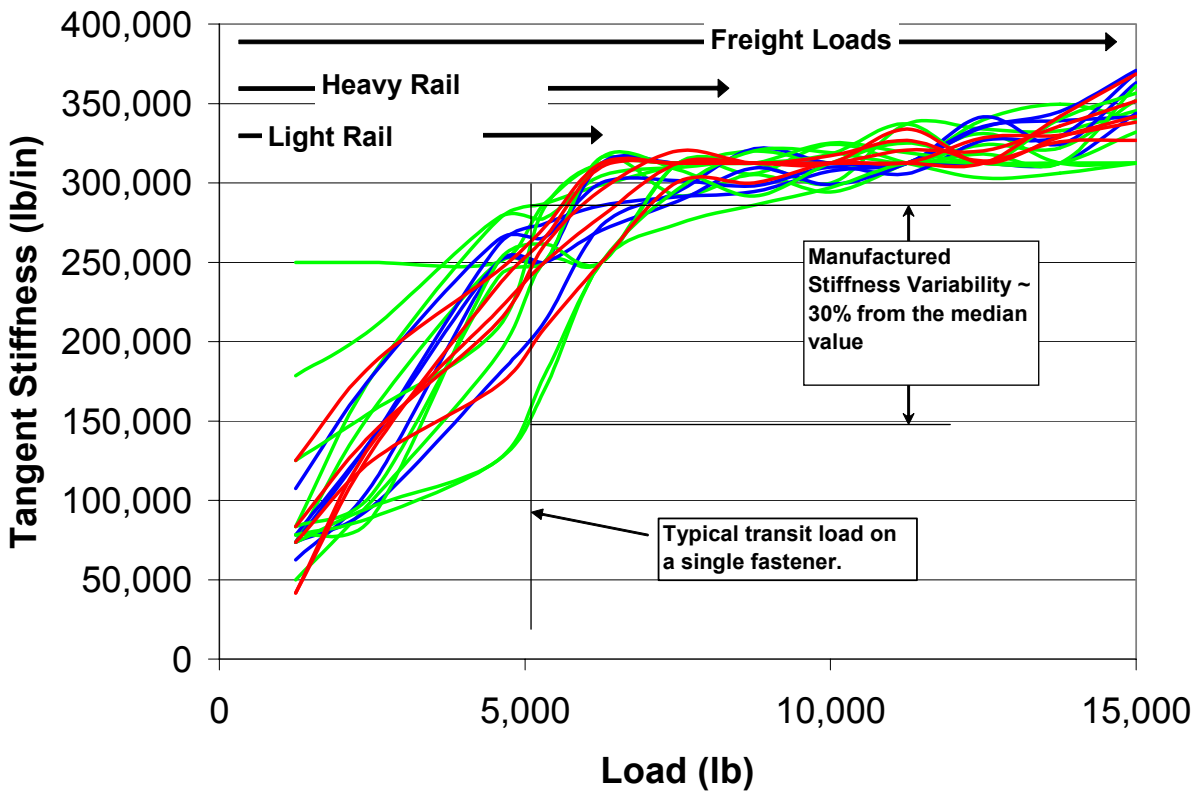


Figure 7. Manufacturing Fastener Stiffness Variability for 20 Fasteners of the Same Design within the Same Manufacturing Run.

A suggested specification stipulation is the measurement of static and dynamic stiffness on a more representative sample of fasteners (perhaps five fasteners) during qualification testing, allowing stiffness variation within 15% of the target stiffness at a stated load.

Further study of these issues is recommended.

III. DIRECT FIXATION TRACK DESIGN STEPS

This section briefly summarizes the sequence of developing Direct Fixation track designs.

Prior to a design, the basic choice to implement a Direct Fixation or similar ballastless track arrangement has already been made. That choice is usually based on cost. Direct Fixation track is chosen to allow smaller tunnel diameters or to reduce the cost of aerial structures by reducing track dead load. Resolving close clearances, concerns for track shifting (as at stations), and necessity for improved ground vibration control are among a number of additional reasons Direct Fixation track may be selected.

The design (or evaluation) sequence should proceed from the general to the specific:

1. The general conditions of an application are defined.

2. Design criteria are refined or, if not available, developed.

3. General track arrangements are identified; full understanding of the operating and environmental requirements for the application are developed.

4. Engineering estimates are developed for loads and other quantifiable factors in the track environment that may influence long-term performance.

5. Details of the design are developed to incorporate the fastener arrangement into the constraints and interfaces of each location.

6. The fastener(s) procurement specification and track construction specification are developed to reflect all the necessities of the project.

A transit system's general conditions should be available in its operating plan. Operating plans and design criteria should be reviewed at the outset and, if any stipulations or expected information is not in the documents, supplemented.

The frequency of fastener loading is developed from operating times, train frequency, maintenance windows, and train make-up for different service levels (usually stated in an operating plan). The design criteria should have details of the vehicles (axle loads, axle spacing, maximum brake rates and acceleration rates, and wheel diameter and profile), fastener spacing, maximum or minimum geometric parameters, maximum allowable rail break gap, requirements for restraining rail and guard rail if those are desired, and other basic information (rail size, rail cant, general technical references, etc.).

This general information review should include establishing familiarity with the local maintenance resources and practices, the most important aspect of judging the reliability level expected of the design. Too, the availability of local resources for minor and major maintenance may dictate features of the track design that allow more efficient maintenance under particular circumstances (where track access is highly restricted or there is limited working space, for example). At this stage, locations likely to require special configurations should be identified.

The track configurations are conceptually developed initially in parallel with alignment design and route investigations (identifying locations with noise, vibration, stray current, and public access sensitivities).

The track detailed design requires interdisciplinary activity to identify the approach to track support (plinth, grout pads, other), walkways, utility and system conduit locations, grade crossing configurations, accommodations for drainage, and ancillary facilities such as catenary locations, signal bungalow locations, etc.

The vertical, lateral and longitudinal loads are estimated at an early design stage based on the operating, vehicular, and alignment information. Load estimates are performed for different track configurations (open track, turnouts, track with restraining rail) in a project. Normally, the location with the worst load condition for each track configuration establishes the governing case for subsequent design, under the assumption that one fastener type will be procured for similar locations within the project.

These estimates are next used to evaluate whether any design criteria will be violated for different fastener configurations and technical capacities. Examples of evaluations that should be conducted at this step are:

- Rail deflections and bending stress from compound multiple axle vertical and lateral loads.
- Loads on each fastener.
- Rail break gap for the assumed fastener spacing and rail clip (requires information on aerial structure spans).
- Track loads transferred to aerial substructures for the assumed fastener spacing and rail clips.
- Adequate longitudinal rail restraint, generally necessary on grades of 3% or greater if elastic rail clips are intended for use.
- Adequate lateral fastener restraint.
- Fastener anchor bolt pull out capacity within the limits of minimum plinth depth requirements. Requires evaluation of the anchor bolt torque to restrain lateral loads and the anchor bolt insert capacity at the required bolt torque and minimum insert depth.
- Sensitivities of a design to tolerance accumulation that could affect performance. The following subparagraphs of this section discuss manufacturing and construction tolerances and their effects on performance.

These evaluations are typical. Other evaluations are performed as circumstances of the project warrant.

The result of these evaluations should confirm the general track design to meet the design criteria. The evaluation continues to test different arrangements until the design criteria are met within a reasonable cost, or a suitable compromise is identified. This process is iterative, adjusting track parameters in favorable directions. It also usually requires iterative evaluations between the track engineer and structural engineers and other disciplines to achieve full design criteria compliance for the least design and construction cost.

By the time the final design reaches 60% completion, the track configuration is required by interfacing engineering disciplines to be largely complete. Typical track details are complete, and special trackwork details are near completion.

The specifications for the fastener and for track construction are the final step.

Most large-scale designs do not proceed smoothly through these steps. The course is changed with revised alignments, revised structural designs, and additional information as the design matures. However, the design will move forward competently if at every stage the preceding steps are performed properly, or are re-visited to reestablish a proper basis for the changed design.

The balance of this section discusses Direct Fixation track design issues and engineering methods generally in the order of the design process described above. The following subsections assume a project has a designed alignment and all the background information has been gathered. The sequence of the following subsections commences with defining loads on the fastener.

IV. DETERMINING LOADS

Design loads for Direct Fixation track are vertical loads, lateral loads and longitudinal loads.

A. Vertical Wheel Loads

The design vertical loads are the maximum static wheel loads multiplied by a dynamic factor. In transit, the maximum wheel load is the “crush” load, usually stated as “AW3” or “AW4” in the agency’s design criteria. Where the vehicle loading diagram indicates the load varies by axle, the highest load is used as the basis for design.

Dynamic factors normally applied to the vertical load are either a stated factor in the design criteria (typically in the structural criteria) or the Association of American Railway (AAR) impact coefficient:

(1) $$\theta = \frac{33V}{100D}$$

Where:

θ	=	dynamic load coefficient
V	=	train speed (mph)
D	=	wheel diameter (inches)

1. Vertical Fastener Loads

The vertical design load on an individual fastener with a wheel directly over the fastener is estimated from BOEF theory.[9]

(2) $$V_{fstnr} = \frac{P}{2}\sqrt[4]{\frac{k_{fstnr}a^3}{4EI}}$$

Where (English units are followed by SI units in parenthesis):

V_{fstnr}	=	Vertical load, lb (N), on fastener with wheel centered over the fastener
P	=	Wheel load, lb (N)
a	=	Fastener spacing, in (mm)
E	=	Young's modulus for steel, psi (Pa)
I	=	Rail moment of inertia, in^4 (mm^4)
k_{fstnr}	=	Fastener stiffness at load P, lb/in (N/mm)

A useful rule of thumb for coarse estimates is the load on an individual fastener will be about 45% of the wheel load.

Note that the fastener stiffness, k_{fstnr}, is different from the track stiffness and the track modulus. Please see Attachment 1A for relationships among these parameters.

B. Lateral Wheel Loads

Lateral loads may be estimated with sufficient accuracy from the wheel and rail contact angle. The wheel profile is required for this estimate. The lateral load is generated as a vector component of the vertical load, produced by the angle of wheel/rail contact patch to horizontal. (Figure 8) For example, a conical wheel with a 1:20 tread on tangent track will produce about 500 pounds lateral load for every 10,000 pounds of vertical wheel load.

[9] S. Timoshenko, B.F. Langer, *Stresses in Railroad Track*, American Society of Mechanical Engineers Annual Meeting Proceedings, Nov 30 through Dec 4, 1931, Paper No. APM-54-26, pp. 277-302. The equation in this section is derived from the reference's equations 1, 4 and 9.

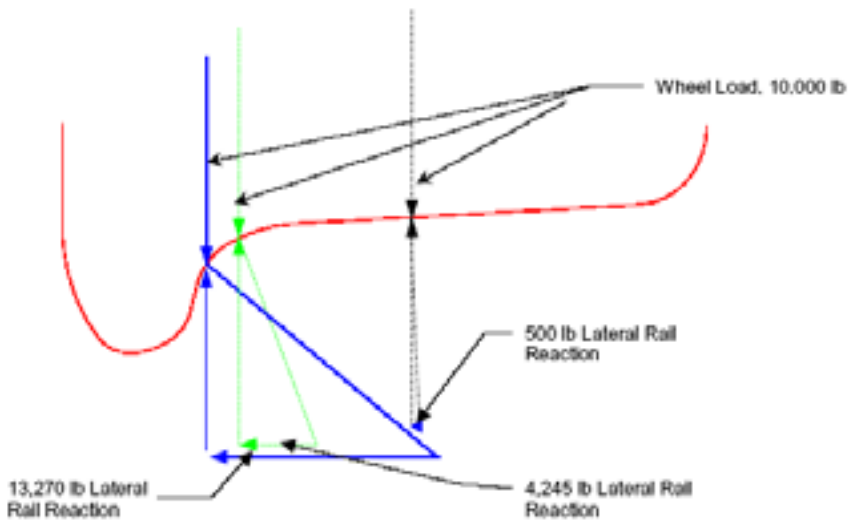


Figure 8. Illustration of Lateral Force Estimate.

The lateral force is determined by the angle of a line normal to the point of contact. The wheel lateral placement is that to produce the rolling radii difference between high and low rail wheels needed for the difference in travel distance between each wheel in curve negotiation.

In curves, the wheel is offset laterally such that the rolling radius differential between the inside and outside wheels compensates for the unequal curve radii of the inner and outer rails.

(3) $$x_w = \frac{r_0 a}{\lambda R}$$

(4) $$r_{outside} = r_0 + \lambda x_w$$

Where:

x_w	=	Lateral offset of an axle from centered position in track, in (mm) toward the outside of a curve
r_0	=	Nominal wheel radius, the wheel radius at the tape line. Use units of ft (m) in equation 3 and units of in (mm) in equation 4 for results in in (mm).
a	=	½ the track gauge. For track gage = 56 ½”, a = 28 ¼” (718 mm)
λ	=	Slope of the wheel profile stated as a ratio, i.e., 1/20 for 1:20 wheel profile taper
R	=	Curve radius, ft (m)
$r_{outside}$	=	Outside wheel rolling radius, in (mm)

The lateral wheel offset (Figure 9) produces the rolling radius difference needed for the difference in curve traveled distance between low and high rail wheels. The lateral wheel offset is valid only within the constant taper portion of a wheel profile. Once the wheelset lateral offset exceeds the flange clearance distance (about 3/8” or 9.5 mm), the wheelset will commence flanging.

The lateral wheel load can be determined using wheel and rail profiles in CAD software, displacing the wheel to obtain the rolling radius of the outside wheel (from equation 4) as the contact point for the rail similar to the illustration in Figure 8.

These estimates are legitimate for the purpose at hand, acknowledging a range of factors that are not considered These estimates will average near measured load data for all but the sharpest curves where the estimating method produces conservatively high values.

1. Lateral Loads on Individual Fasteners

a) Fastener Loads from Wheel Loads

Lateral fastener loads may be estimated using equation 2 but using the rail lateral moment of inertia, estimated lateral load, and fastener lateral stiffness.

b) Lateral Force from Thermal Rail Forces

Thermal rail forces generate a lateral load on fasteners in curves that is added to wheel and other rail forces. Figure 10 shows an example of lateral forces on a fastener for 30-in (762-mm) fastener spacing and for a range of temperature differences from rail neutral stress temperature. Detailed relationships for estimating lateral load from rail thermal forces are provided in Attachment 1C.

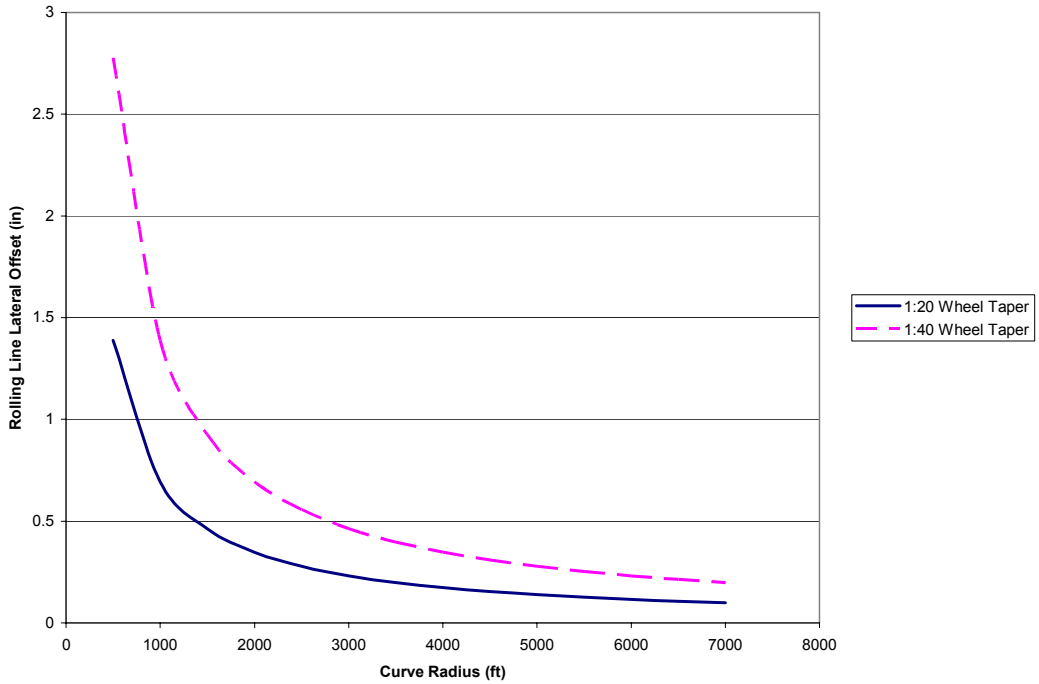


Figure 9. Wheel Lateral Offset in Curves.
Assumptions: Wheel Dia. = 28", Track Gauge = 56 ½".

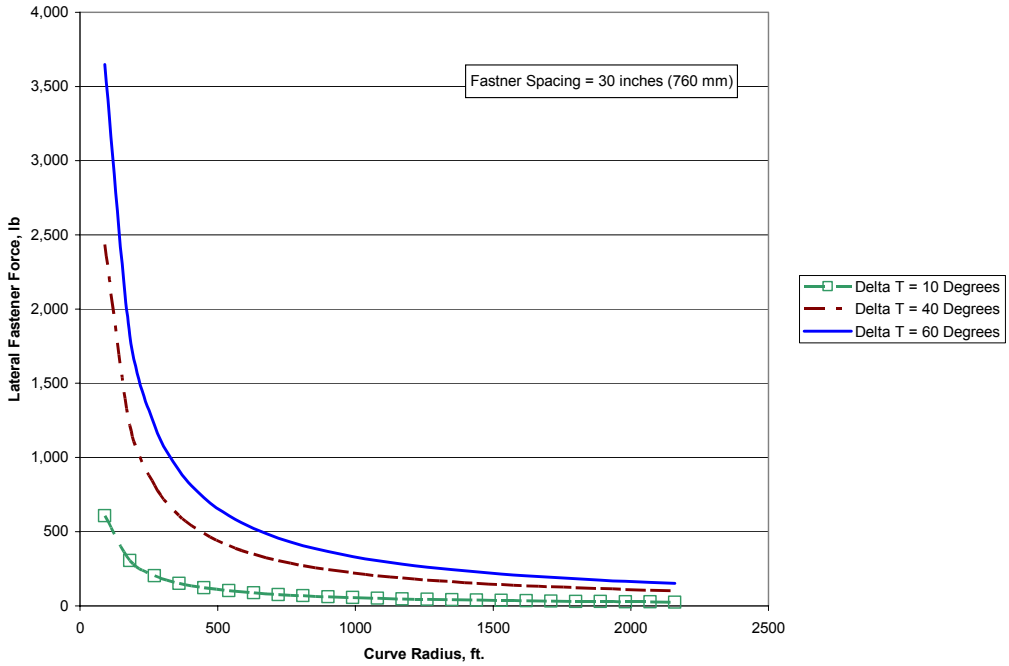


Figure 10. Lateral Fastener Force from Thermal Rail Force for 115 RE Rail for Different Temperatures above the Neutral Temperature (Temperatures are in °F).

C. Longitudinal Rail Loads

Longitudinal loads important to Direct Fixation fasteners are forces from (1) vehicle traction and (2) rail breaks. These forces produce a differential load across individual fasteners.

1. Vehicle Traction

Vehicle traction forces are estimated using AREMA Train Performance[10] calculations and using the maximum braking or acceleration characteristics for the vehicle.

Generally, vehicle traction forces become important on steeper grades where sufficient longitudinal force can be generated across individual fasteners to exceed elastic rail clip longitudinal restraint and move the rail through the fastener. Elastic fasteners with nominal toe loads of 2,500 to 2,750 pounds will restrain traction forces for most transit vehicles on grades up to about 3%, for example. The rail clip longitudinal restraint specification for steeper grades either requires increased longitudinal restraint or supplemental longitudinal restraint.

2. Rail Break

The force resulting from a rail break determines fastener spacing and required toe load.

Design for possible rail breaks intends to

- Minimize the gap resulting from a rail break
- For aerial structures, assess the force that may be imposed on piers

a) Rail Break Gap Estimates

Rail breaks are evaluated at the worst-case location, typically at a structure expansion joint where the full broken rail force will have the opportunity to develop in the adjacent pier (assuming it is the fixed end of the span).

The rail internal longitudinal force immediately before a rail break occurs is:

[10] *Manual for Railway Engineering*, American Railway Engineering and Maintenance of Way Association, Chapter 16, Part 2.

(5) $$P_{Longitude} = EA\alpha\Delta T$$

where

$P_{Longitude}$	=	Longitudinal rail force, lb (N)
E	=	Modulus of elasticity for steel, psi (Pa)
A	=	Rail cross-sectional area, in^2 (mm^2)
α	=	Coefficient of expansion for steel, 6.3 x 10^{-6}in/in/°F (12.1 x 10^{-6} mm/mm/°C)
ΔT	=	$T_{neutral} - T_{rail\ break}$, Rail temperature difference at the time of rail break from the rail neutral temperature, °F (°C).

The rail break temperature, $T_{rail\ break}$, is the lowest recorded ambient temperature for the site.

The longitudinal rail force, $P_{Longitude}$, is constrained from free contraction (after a rail break) by the longitudinal restraint of the fasteners. For elastic rail clips, the longitudinal restraint is

(6) $$R_{Fstnr} = N_{clips}\mu P_{TL}$$

where

R_{Fstnr}	=	Longitudinal resistance of one fastener, lb (N)
N_{clips}	=	Number of rail clips on the fastener (typically = 2)
μ	=	Coefficient of friction between the rail and rail clip (or insulator)
P_{TL}	=	Individual clip toe load, lb (N).

Coefficients of friction for various conditions of rail/clip (or insulator) mating surface are provided in Table B.

Table B. Rail-Clip Friction Values[11]

Rail and Seat Condition	Effective Friction Value for Longitudinal Restraint
Dry, Clean	0.50 to 0.59
Water, Light	0.48 to 0.57
Water, Heavy	0.47 to 0.57
Sand	0.45 to 0.58
Grease	0.35 to 0.53
Sand and Grease	0.37 to 0.51

[11] J.M. Tuten, *Performance of Direct Fixation Track Structure, Final Report*, Transit Cooperative Research Program, Project D-5, April 1999.

The number of fasteners required to constrain the broken rail from contraction is

(7) $$n_{Fstnrs} = \frac{P_{Longitude}}{R_{Fstnr}}$$

The effective rail length on one side of the break to constrain the broken rail end displacement is

(8) $$l_{rail} = n_{Fstnrs} Spcg$$

where

l_{rail} = The rail length to constrain the break, in (mm)
$Spcg$ = Fastener spacing, in (mm).

The constrained rail break gap is estimated using the longitudinal restraint of the fasteners, integrating the unit restraint over the rail length from the rail break to the point the rail is fully restrained longitudinally (*Figure 11*).

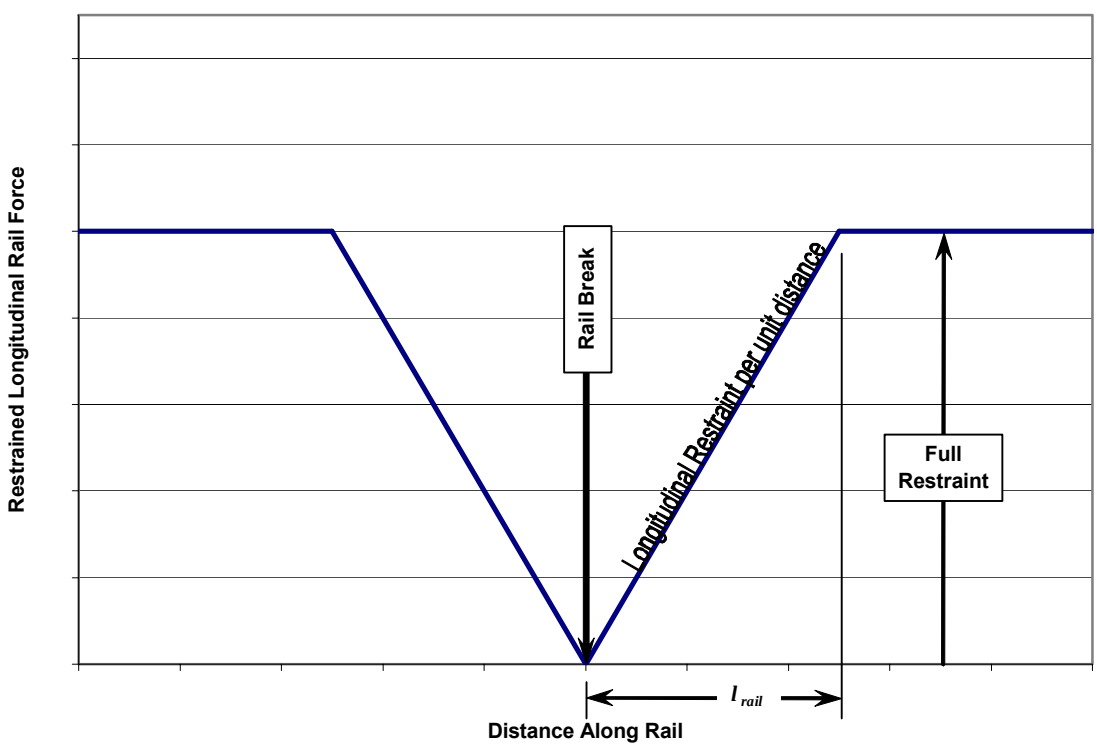


Figure 11. Rail Break Gap Determined by Rail Longitudinal Restraint

The rail break gap will be

(9) $$Gap = 2\Delta l = \frac{2}{EA}\left(2SpcgP_{Longitudinal} - \frac{(n-1)^2 r}{2}\right)$$

Variable meanings are the same as above.

This relationship produces broken rail gap estimates that are very small.

However, many rail break gaps are significantly greater than this relationship would lead us to expect. The reasons for this discrepancy can be attributed to loss of rail clip toe load and lower coefficient of friction than assumed (from ice formation on the rail, for example).

The upper limit of a broken rail gap occurs under the assumption that there is no longitudinal restraint over the length $\boldsymbol{l_{rail}}$.

The maximum rail gap uses this assumption and is

(10) $$Gap_{\max} = 2l_{rail}\alpha\Delta T$$

If rail break gap is excessive, the fastener spacing may be adjusted.

The fastener spacing to constrain the rail gap after a rail break is

(11) $$Spcg = \frac{Gap_{allowable}}{2n_{Fstnrs}\alpha\Delta T}$$

Where

Spcg = Fastener spacing (in)
$\boldsymbol{Gap_{allowable}}$ = The allowable rail gap (usually 3 in or less)
$\boldsymbol{\alpha}$ and $\boldsymbol{\Delta T}$ have the same meaning as above.

Rail break gaps that vary from the estimates in the foregoing equations are the result of inadequate longitudinal rail restraint. Some rail clips are known to lose toe load with exposure to service and repeated reapplication (for rail changes or other maintenance). Environmental conditions will alter the friction values between the rail clips and the rail, invalidating the estimates if a high friction coefficient is assumed. Some designers choose to vary fastener longitudinal restraint to reduce loads on structures (see following subsection).

The proper design practice is to

- Assume practical rail to clip friction values

- Reduce the nominal rail clip toe load by at least 20% for relaxation of elastic rail clips

- Specify uniform fastener restraint throughout a Direct Fixation track section.

If the resulting rail break gap estimate is excessive from these assumptions, the required longitudinal restraint to meet this requirement must be calculated and stated as the *minimum* longitudinal restraint in the specifications.

b) Track and Structure Longitudinal Interaction

For design purposes, the track and structure interaction is primarily from thermal forces. The potentially governing track force on structures is the rail break force, $P_{Longitude}$. This force will occur if the span is longer than the effective rail length, l_{rail}, with proportionately lower force when spans are shorter than the rail length to constrain the rail break force.

For a majority of practical conditions, the rail break force will not be the governing force for a pier design when the pier is no taller than about 20 ft (6m).

Under normal conditions (i.e., rail is not broken), track and aerial structure longitudinal transfer loads are through fastener longitudinal restraint. Although rail and a concrete (or steel) structure have nearly the same expansion coefficients, the rail will heat and cool faster than the more massive concrete aerial structure. However, the rail constrains all its thermal forces internally without movement (in CWR). Aerial structures typically are designed to expand and contract freely. Any differential force between rail and structure is created by the fasteners' rail clip longitudinal restraint.

The aerial superstructure will move easily against the rail clip longitudinal restraint. The loads introduced by track and structure interaction are small compared to thermal forces developed in the rail and may be ignored for design of the track or the structure.

Designs that attempt to control broken rail longitudinal force into aerial structure piers typically are counter productive, permitting conditions that may increase broken rail gaps and create undesirable distribution of rail stress along the rail. Varying the fastener longitudinal restraint strategically along a track, using rail anchors (rigid attachment of the rail to the structure), and deploying rail expansion joints have greater life cycle expense than specifying adequate, uniform fastener longitudinal restraint and increasing pier structure capacity if the broken rail force governs the pier design.

The structural design criteria and codes in North America will govern the structural design for piers about 20 ft tall or less, irrespective of rail break forces.

D. Track Response to Loads

Track responses to loads are rail deflections and rail stress. Methods and equations for evaluating track response are published by AREMA[12] (from Hetenyi[13] and Timoshenko and Langer[14]).

V. DIRECT FIXATION MATERIALS

This section reviews materials used in Direct Fixation track and fasteners and the engineering limits of those materials.

A. Rubbers and Synthetic Elastomers

Two types of elastomer are commonly used in ballastless track systems. They are natural rubber (NR) compounds and chloroprene (commonly referred to as a product trade name, Neoprene), a synthetic elastomer.

General physical, mechanical, and chemical resistance properties for different elastomers are summarized in Table C[15].

1. Rubber Chemistry and Manufacturing

Crude rubber is the substance harvested from rubber trees. It is a very stiff solid that is highly prone to oxidation, ozone and ultraviolet degradation. In its native form it is not “cross-linked”. That is, its molecules are not linked and have poor resistance to stress.

---

[12] *Manual for Railway Engineering*, American Railway Engineering and Maintenance-of-Way Association, Chapter 16, Section 10.11.1.

[13] M. Hetenyi, *Beams on Elastic Foundation*, The University of Michigan Press, copyright 1974 by M. Hetenyi (University of Michigan Studies, Scientific Series, Volume XVI). Vertical and lateral response: pp. 27–30. Rail rotational response: pp. 154–155 and pp. 127–136.

[14] S. Timoshenko and B.F. Langer, “Stresses in Railroad Track,” *Proceedings of the Annual Meeting of American Society of Mechanical Engineers*, Nov. 30 to Dec. 4, 1931, Paper No. APM-54-26, pp. 277–302. Republished in *Track Research Compendium*, Transportation Research Board in cooperation with American Railway Engineering [and Maintenance-of-Way] Association, 1982, Text #26, pp. 335–360.

[15] C.A. Harper, *Handbook of Plastics and Elastomers*, Second Edition, McGraw-Hill Book Company, 1985.

The process for making useful elastomer material from crude rubber begins with mechanically kneading or rolling the crude rubber to soften it, then mixing the raw material with additives. The mixture is then heated to a high temperature to make the finished elastomer. The heating process is called vulcanization.

In manufacturing bonded Direct Fixation fasteners, the elastomer is bonded to the fastener's steel plates during the vulcanization process.

Additives in rubber compounds improve the finished elastomer's properties, aid the processing or reduce the expense of the material. Typical additives and their purposes are shown in Table D.

Table C. Typical Properties of Elastomers

Property	Natural Rubber (cis-polyisoprene)	Butadiene-Styrene (GR-S)	Synthetic (polyisoprene)	Butadiene-acrylonitrile (nitrile)	Chloroprene (Neoprene)	Butyl (isobutylene-isoprene)
Physical Properties						
Specific Gravity (ASTM D 792)	0.93	0.94	0.93	0.98	1.25	0.90
Thermal Conductivity, Btu/(h)(ft^2)(°F/ft) (ASTM C 177)	0.082	0.143	0.082	0.143	0.112	0.053
Coefficient of thermal expansion, 10^{-5} per °F (ASTM D 696)	37	37	—	39	34	32
Electrical Insulation	Good	Good	Good	Fair	Fair	Good
Flame Resistance	Poor	Poor	Poor	Poor	Good	Poor
Min. Recom. Service Temp., °F	–60	–60	–60	–60	–40	–50
Max. Recom. Service Temp., °F	180	180	180	300	240	300
Mechanical Properties						
Tensile Strength, lb/in^2						
- Pure Gum (ASTM D 412)	2,500 – 3,500	200 – 300	2,500 – 3,500	500 – 900	3,000 – 4,000	2,500 – 3,000
- Black (ASTM D 412)	3,500 – 4,500	2,500 – 3,500	3,500 – 4,500	3,000 – 4,500	3,000 – 4,000	2,500 – 3,000
Elongation, %						
- Pure Gum (ASTM D 412)	750 – 850	400 – 600	—	300 – 700	800 – 900	750 – 950
- Black (ASTM D 412)	550 – 650	500 – 600	300 - 700	300 – 650	500 – 600	650 – 850
Shore A Hardness (durometer)	A30 – 90	A40 – 90	A40 – 80	A40 – 95	A20 – 95	A40 – 90
Rebound						
- Cold	Excellent	Good	Excellent	Good	Very Good	Poor
- Hot	Excellent	Good	Excellent	Good	Very Good	Very Good
Tear Resistance	Excellent	Fair	Excellent	Good	Fair to Good	Good
Abrasion Resistance	Excellent	Good to Excellent	Excellent	Good to Excellent	Good	Good to Excellent

Table C. (continued)

Property	Natural Rubber (cis-polyisoprene)	Butadiene-Styrene (GR-S)	Synthetic (polyisoprene)	Butadiene-acrylonitrile (nitrile)	Chloroprene (Neoprene)	Butyl (isobutylene-isoprene)
Chemical Resistance						
Sunlight Aging	Poor	Poor	Fair	Poor	Very Good	Very Good
Oxidation	Good	Good	Excellent	Good	Excellent	Excellent
Heat Aging	Good	Very Good	Good	Excellent	Excellent	Excellent
Solvents						
- Aliphatic hydrocarbons	Poor	Poor	Poor	Excellent	Good	Poor
- Aromatic hydrocarbons	Poor	Poor	Poor	Good	Fair	Poor
- Oxygenated, alcohols	Good	Good	Good	Good	Very Good	Very Good
Oil, Gasoline	Poor	Poor	Poor	Excellent	Excellent	Poor
Animal, vegetable oils	Poor to Good	Poor to Good	—	Excellent	Excellent	Excellent
Acids						
- Dilute	Fair to Good	Fair to Good	Fair to Good	Good	Excellent	Excellent
- Concentrated	Fair to Good	Fair to Good	Fair to Good	Good	Good	Excellent
Permeability to gases	Low	Low	Low	Very Low	Low	Very Low
Water-swell resistance	Fair	Excellent	Excellent	Excellent	Fair to Good	Excellent
Uses	Pneumatic tires and tubes; power transmission belts and conveyor belts; gaskets; mountings; hose; chemical-tank linings; printing-press platens; sound or shock absorption; seals against air, moisture, sound and dirt		Same as natural rubber	Carburetor diaphragms, self-sealing fuel tanks, aircraft hose, gaskets, gasoline and oil hose, cables, machinery mountings, printing rolls	Wire and cable, belts, hose, extruded goods, coatings, molded and sheet goods, adhesives, automotive gaskets and seals, petroleum- and chemical-tank linings	Truck and automobile tire inner tubes, curing bags for tire vulcanization and molding, steam hose and diaphragms, flexible electrical insulation, shock, vibration absorption

Table D. Rubber Additives and Purpose

Type of Compound	Typical Material	Purpose of Additive
Fillers	**Carbon black**	**Reduce product expense and improve mechanical properties**
Plasticizers	**Petroleum oils** **Unsaturated vegetable oils**	**Extenders, reduce product expense** **Processing aid, facilitate extrusion and calendaring (shaping by rolling) processes**
Age resistors		**Antioxidants, protect against oxidation and heat** **Antiozonants, protect against ozone** **Antiflex-cracking, retard cracking caused by cyclic deformation** **Antihydrolysin, retard deterioration caused by high humidity and water**
Vulcanizing accelerators	**Sulfur**	**Increase the rate of vulcanization**
Activators		**Increase the efficiency of accelerators**

Rubber ingredients and formulations are rarely published. Examples of rubber formulas for track applications are summarized in Table E[16]. The table explains the purpose of the various compounds in the rubber mixture to impart desirable properties in the finished vulcanizate and to improve the vulcanization process.

Table E. Example of Compounds and Properties of Bulk Rubber Used in Bridge Bearings and Rail Pads

Compound	**Purpose of Compound**	**Parts per Weight of Crude Rubber**	
		Bridge Bearings	**Rail Pads**
Natural Rubber (RSS or SMR-5)	Base material	100	100
Stearic Acid	Activator; increases the rate of the vulcanization process	1	2
Zinc Oxide	Activator; increases the rate of the vulcanization process	10	5
Dutrex R	Aromatic oil, a plastizer; used to make the product less expensive and, in the amounts indicated, as an aid to facilitate the manufacturing operations	2	3

[16] Morton, M., *Rubber Technology*, Second Edition, Van Nostrand Reinhold Company, 1977.

Compound	Purpose of Compound	Parts per Weight of Crude Rubber	
		Bridge Bearings	Rail Pads
	of the compounded rubber		
SRF Black	Carbon black filler; reduces the rubber cost, promotes ultraviolet light protection and provides reinforcement (increases tensile strength, tear strength and abrasion resistance)	35	—
MT Black	Carbon black filler; reduces rubber cost. Usually nonreinforcing.	—	60
China Clay	Non-black filler; reduces the rubber cost	—	20
UOP-88 (Antiozonant)	Age resistor; prevents surface cracks under tension caused by ozone	4	—
Age Rite Powder (or A.O. MB)	No information found; probably an antioxidant to protect the elastomer against oxidation and heat	1	1
Paraffin Wax	Places a protective film surface on a vulcanized component to protect against oxygen and ozone. Waxes are not a likely compound in Direct Fixation fastener elastomers because the film can break in dynamic applications.	—	1
Santocure (CBS)	A proprietary product; Santocure is a primary amine-based accelerator to increase the speed of vulcanization, and mitigates scorching during vulcanization.	0.7	1
Sulfur	Accelerator; increases the rate of vulcanization[17]. In these proportions, the intent is to produce a soft rubber. Lower proportions of sulfer will produce harder rubbers.	2.5	2.5
Total		156.2	195.2

Other antioxidant materials: DOPPD (di-octyl-paraphenylenediamine) and PBN (phenyl-Beta-naphthylamine)

2. *Synthetic Rubber Chemistry and Manufacturing*

Chloroprene rubber[18] is the most common synthetic material used in Direct Fixation fasteners. Typical formulations are shown in Table F.

An “activator” increases the effectiveness of the vulcanization accelerator.

[17] Vulcanization: The process of turning compounded rubber mixture into an elastomer by heating the rubber mixture and sulfur together at a high temperature.

[18] Another chloroprene rubber is produced under the name Baypren.

Table F. Example of Chloroprene (Neoprene) Formulations[19]

Material	Purpose	Common Ingredient	Quantity, Parts by Mass			
			1A	2A	1B	2B
Chloroprene Rubber	**Base material**		**100.0**	**100.0**	**100.0**	**100.0**
Stearic Acid	**Activator**		**0.5**	**0.5**		
Antioxidant	**Protects against oxidation**	**Octylated diphenylamine**		**1.0**	**1.0**	
Magnesium Oxide	**Vulcanization accelerator**		**4.0**	**4.0**	**4.0**	**4.0**
SRF Black	**Filler**	**Carbon black**		**30.0**		**30.0**
Zinc Oxide	**Activator**		**5.0**	**5.0**	**5.0**	**5.0**
Ethylene Thiourea (ETU) with binder	**Vulcanization accelerator**				**0.47**	**0.47**
			109.5	**139.5**	**110.47**	**140.47**

3. Stiffness and Fastener Geometry

The chemistry of the elastomer compound can be designed to reduce the stiffness of the fastener. However, the electrical insulation requirements for fasteners dictate that the elastomer cannot be much softer than the hardness shown in example products in Table G.

Table G. Properties of Example Elastomers

Compound	**Bridge Bearings**	**Rail Pads**
Cure Time and Temperature	20 min @ 285°F	15 min @ 307°F
Tensile Strength, psi	3050	2880
Tensile Strength (aged 7 days @ 158°F), psi	3200	2590
Percent Elongation	520	540
Percent Elongation (aged 7 days @ 158°F)	480	510
Shore A Hardness	60	66
Shore A Hardness (aged 7 days @ 158°F)	62	—

[19] "Product Description & Quality Control Report for Polycholoroprenes," Rubber Manufacturers Association, Technical Bulletin SP-310, Appendix A.

If a specification requires electrical insulation properties (bulk resistivity) above 1 x 10^9 ohm-in, fastener stiffness will likely increase significantly. The upper electrical resistance limit of compounds containing carbon black is about 1 x 10^8 ohm-in. Compounds containing carbon black must be avoided if very high resistance is required. In this case, silicone elastomers are the best to use.[20] Silicone elastomers have poor stiffness properties. Major applications of silicone elastomers include electrical insulators, ignition cables, gaskets, O-rings, static seals (dynamic seals are not recommended), food and medical grade tubing, and roll covers.[21]

The stiffness may be reduced by several approaches using geometry. The fastener can be made softer by increasing the elastomer thickness (depth), or the fastener may have designed voids and internal elastomeric walls to modify the fastener's stiffness.

There are obvious limits on the fastener height, with specifications defining the smallest practical envelope for the track. Fastener shape then becomes the primary means for controlling the fastener's stiffness. The stress and strain capacity of the elastomer material becomes critical in the design of the fastener's shapes.

Figure 12 shows the relationship between elastomer hardness and "shape factor," the ratio of loaded area to the free side area of a fastener. In a fastener designed to have internal walls, voids or chambers, the free side area is the area of all the walls within the shape that are able to flex. When subjected to compression loads, the available area for expansion determines the compression modulus.

Some ballastless track products use closed-cell microcelluar materials as elastomeric elements. These materials have internal "shape factors" as a result of the microcelluar material.

Other track materials have a combination of closed and open cell urethanes. The predominant application for this material is as tie pads.

[20] Khairi Nagdi, *Rubber as an Engineering Material: Guideline for Users*, Hansen Publishers, 1993, p. 36.

[21] Nagdi, p. 141.

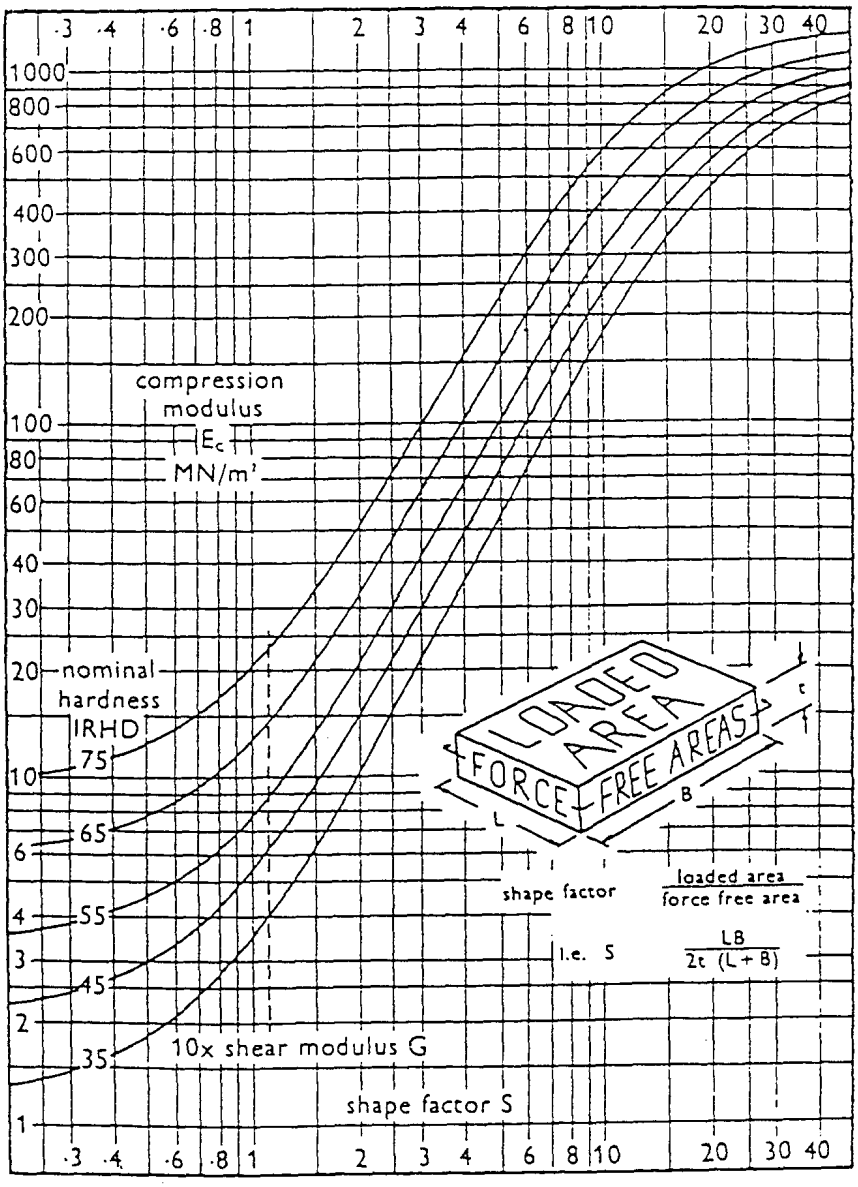


Figure 12. Variation in the Compression Modulus of Rubber with Shape Factor[22]

[22] The source of this graphic is obscure. The same information in a slightly different format is in *Engineering with Rubber*, ed. Alan Gent, Figure 8.4, p. 217.

4. Elastomer Fatigue

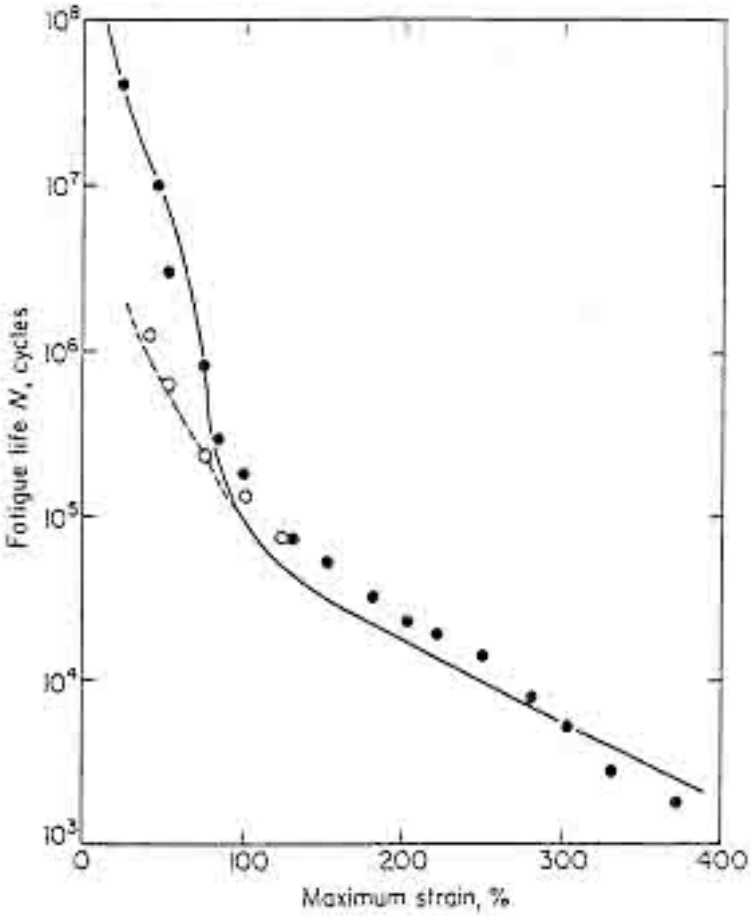
a) Influences on Elastomer Fatigue

Elastomer fatigue is influenced by internal flaws from manufacturing and surface cracks from an oxidizing environment. The stress and strain induced in the elastomer and the material's modulus establish the life expectancy under these influences.

A typical fatigue curve from dumbbell specimens using maximum strain (instead of stress as in traditional S/N curves) is shown in Figure 13[23]. Figure 13 shows that for low strains (<25%) the fatigue life of rubber typically exceeds 10^8 cycles. However, as shown in the figure, an oxidative environment can be expected to have a detrimental effect on the fatigue life and may reduce the useful service life by almost an order of magnitude.

Figure 14 shows the effects of additives to overcome the effect of ozone or oxidative environments on fatigue performance. Protective agents DOPPD (di-octyl-paraphenylenediamine) and PBN (phenyl-Beta-naphthylamine) were added to the vulcanizates in the figure, which show substantial increases in fatigue life of NR by a factor of 5 at low levels of strain (~25%).

[23] *Engineering with Rubber,* ed. Alan Gent, Hanser Publishers, figure attributed to G.J. Lake.



NOTE: Solid symbols represent laboratory atmosphere, open symbols represent ozone atmosphere.

Figure 13. Variation in Fatigue Life with Maximum Strain for Natural Rubber, a Vulcanizate (minimum strain equals zero).

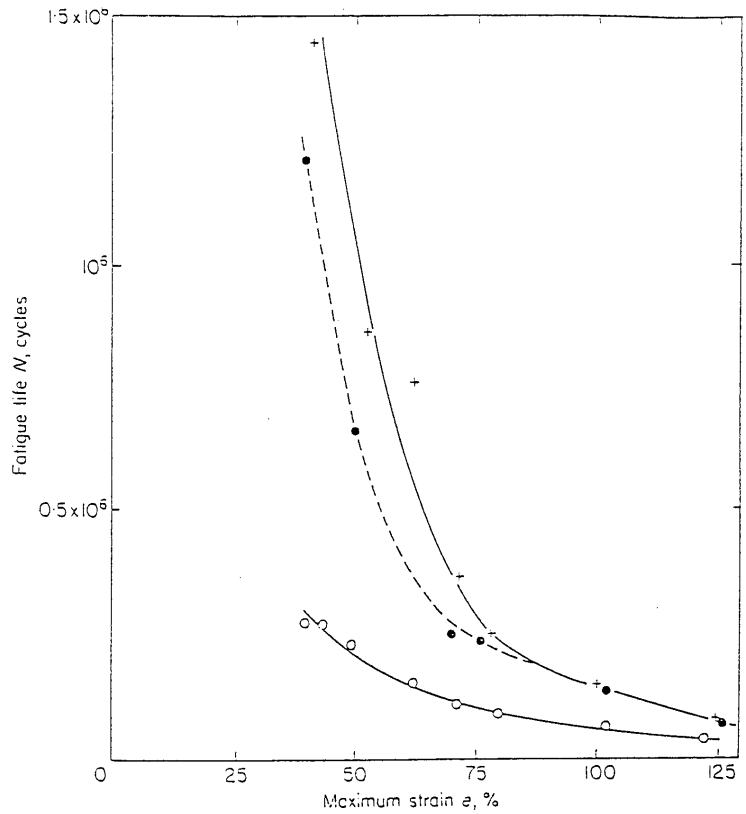


Figure 14. Fatigue Life of Natural Rubber in an Ozone Chamber Illustrating the Effects of PBN (solid symbols) and DOPPD (plus symbols) as Dynamic Antiozonates on the Unprotected Vulcanizate A (open symbols)

b) Fatigue Estimates

The following defines relationships for elastomers to meet the design criterion's life expectancy for allowable material stress or strain.

The estimates for elastomer fatigue are based on fracture mechanics[24, 25].

Criteria are presented separately for two levels of crack development:

1. Applied energy below which cracks never develop for an unlimited number of cycles ("infinite" life)

[24] *Engineering with Rubber*, ed. Alan Gent, Hanser Publishers, 1992.

[25] AA. Griffith, *Phil. Trans. R. Soc. London, Ser. A,* **221**, 163 (1920).

2. Applied energy at which cracks develop or grow with increasing load cycles (finite life)

The first level is an "infinite" life criterion, limited by a threshold tearing energy, G_o. The second level is a finite life criterion above the threshold tearing energy, G_o, and below a compound-dependent catastrophic failure limit.

Figure 15 shows the relationship of tearing energy to fatigue life. G_o is about 40 J/m^2 (0.286 in-lb/in^2) for most commercial rubber and rubber-like compounds.

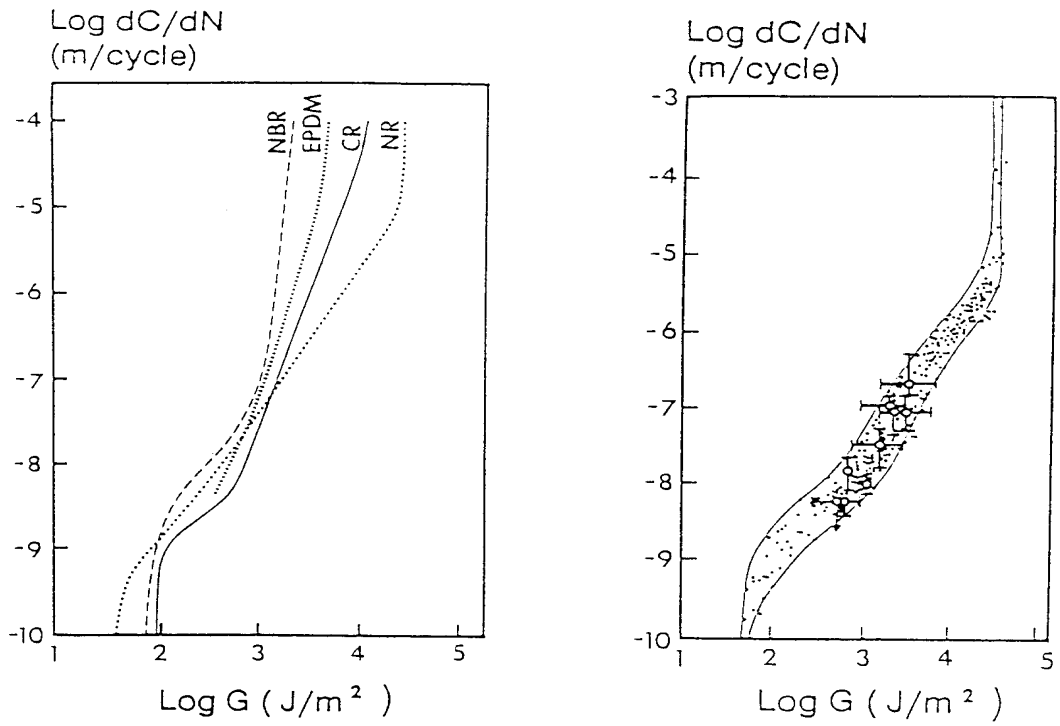


Figure 15. Fatigue Crack Growth Rate
(LEFT[26]: various elastomers; RIGHT[27]: simple extension test pieces and laminates of high shape factor under uniaxial compression)

[26] Gent, pg. 149, Figure 6.11
[27] Gent, pg. 161, Figure 6.20

Table H. Definition of Symbols Used in Fatigue Estimates

Symbol	Definition
B	Constant (material dependent coefficient in fatigue calculations)
G_o	Tearing energy threshold = 40 J/m^2
G_m	Shear modulus ≈ E/3 (kPa)
E	Young's modulus (tension) (kPa)
E_c	Young's modulus (compression) (kPa)
π	Pi
C, C_o, c	Initial crack length (cm)
ε	strain (cm/cm)
f(c/h)	= 0.40 ; for crack length less than 0.1 h
	= 0.0423 + (-1.14957)(c/h) + 1.512629 (c/h)^2 + (-0.55736) (c/h)^3 + 0.06691 (c/h)^4 ; for crack length between 0.1 h and 3.0 h
	= 1.0 ; for crack length more than 3.0 h
H, h	Specimen height, elastomer thickness (cm)
ϕ	Material compression modulus (see Table **I**)
N	Number of load cycles to fatigue failure
S	Shape factor: $S = \frac{Load\ Area}{Bulge\ Area}$; see *Figure 12*
τ	Shear stress (kPa)
σ	Tensile Stress (kPa)

(12) $$E_c = E\left(1 + 2\phi S^2\right)$$

Table I. Elastomer Material Properties[28]

Shear Modulus, G (kPa)	Estimated Hardness, Shore A	Young's Modulus, E_0, E (kPa)	Ratio of Tensile to Shear Modulus, E/G	Bulk Modulus, E_b, K (Mpa)	Material Compression Coefficient, ϕ (Dimensionless)
296	29	896	3.03	979	0.93
365	33	1,158	3.17	979	0.89
441	36	1,469	3.33	979	0.85
524	40	1,765	3.37	979	0.80
621	43	2,137	3.44	1,007	0.73
793	47	3,172	4.00	1,062	0.64
1,034	52	4,344	4.20	1,124	0.57
1,344	57	5,723	4.26	1,179	0.54
1,689	61	7,170	4.25	1,241	0.53
2,186	66	9,239	4.23	1,303	0.52

Elastomer Infinite Life Estimate

Infinite life is estimated assuming the stress or the strain in the material from a force creates elastic energy less than the material's threshold tear energy, G_o. The approach assumes an initial flaw of length C_o in the material. The result is an estimate of stress or strain below which the assumed flaw will not grow, thus the material will have infinite life.

The specific relations vary with tensile loading, shear loading and compression loading.

Tensile Limit for Infinite Life

Tensile limit in terms of strain, ε in tension:

$$\left(\frac{G_o}{E\pi C_0}\right)^2 = \frac{\varepsilon^4}{1+\varepsilon} \tag{13}$$

Tensile limit in terms of tensile stress, σ in tension:

$$\left(\frac{G_o 2E}{2\pi C_o}\right)^2 = \frac{\sigma^4}{1+\frac{\sigma}{E}} \tag{14}$$

[28] Gent, Table 8.1, p. 215.

Shear Limit for Infinite Life

Shear limit in terms of strain:

(15) $$\varepsilon_{shear} = \left(\frac{2G_0}{G_m h \left[f\left(c/h \right) \right]} \right)^{1/2}$$

[Note: A conservative value of ***f(c/h)*** is 0.4, a value representing normal porosity in elastomers.]

Shear limit in terms of shear stress:

(16) $$\tau = \left(\frac{2G_o\, G_m}{h \left[f\left(c/h \right) \right]} \right)^{1/2}$$

Compression Limit for Infinite Life

Compression limit in terms of strain, ε

(17) $$\varepsilon = \left(\frac{4G_o}{E_c h} \right)^{1/2}$$

Compression limit in terms of stress, σ

(18) $$\sigma = \left(\frac{4G_o E_c}{h} \right)^{1/2}$$

Elastomer Finite Life Estimate

When stress or strain is above the threshold tear energy G_o, but below a catastrophic failure value, the assumed flaw of initial length C_o will grow. The growth rate of the flaw depends on the stress applied to or strain experienced by the material, along with the material's properties.

The relationships are specifically for tensile stresses in the material but produce reasonable results in compression by substituting the appropriate compression properties (such as Young's compression modulus) in the formulas.

Tabular values for parameters in the relationships are listed in Table J and Table K.

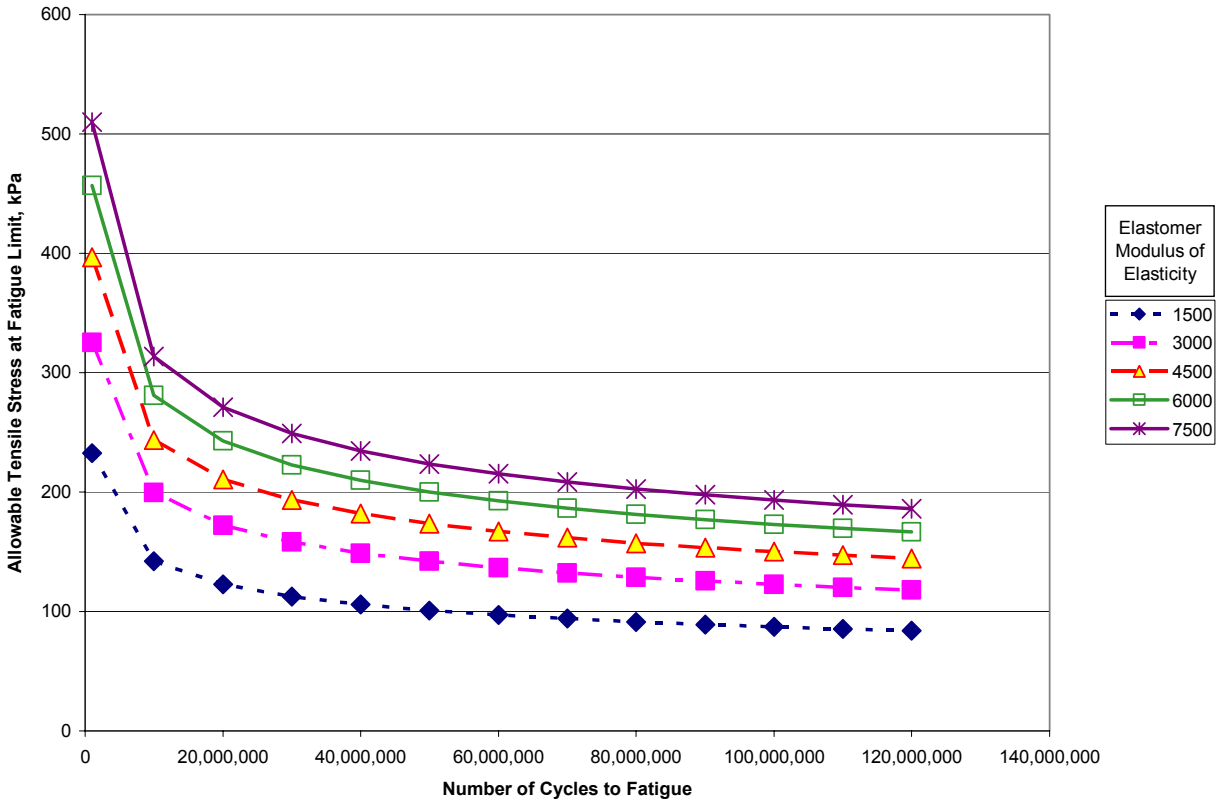


Figure 16. Allowable Tensile Stress at Fatigue for Practical Elastomers

Stress vs. Load Cycle Fatigue Life (plotted in *Figure 16*):

$$\frac{\left(1+\frac{\sigma}{E_t}\right)^{1/2}}{\sigma^2} = \frac{\pi}{E}\left[N(\beta-1)B(C_o)^{\beta-1}\right]^{1/\beta}$$

(19)

<u>Assumed Parameter Values</u>:

$\boldsymbol{B}$ = 5 x 10^{-8} m/cycle/kJ^2/m^4
β = 2.4
$\boldsymbol{C}_o$ = 0.002 mm.

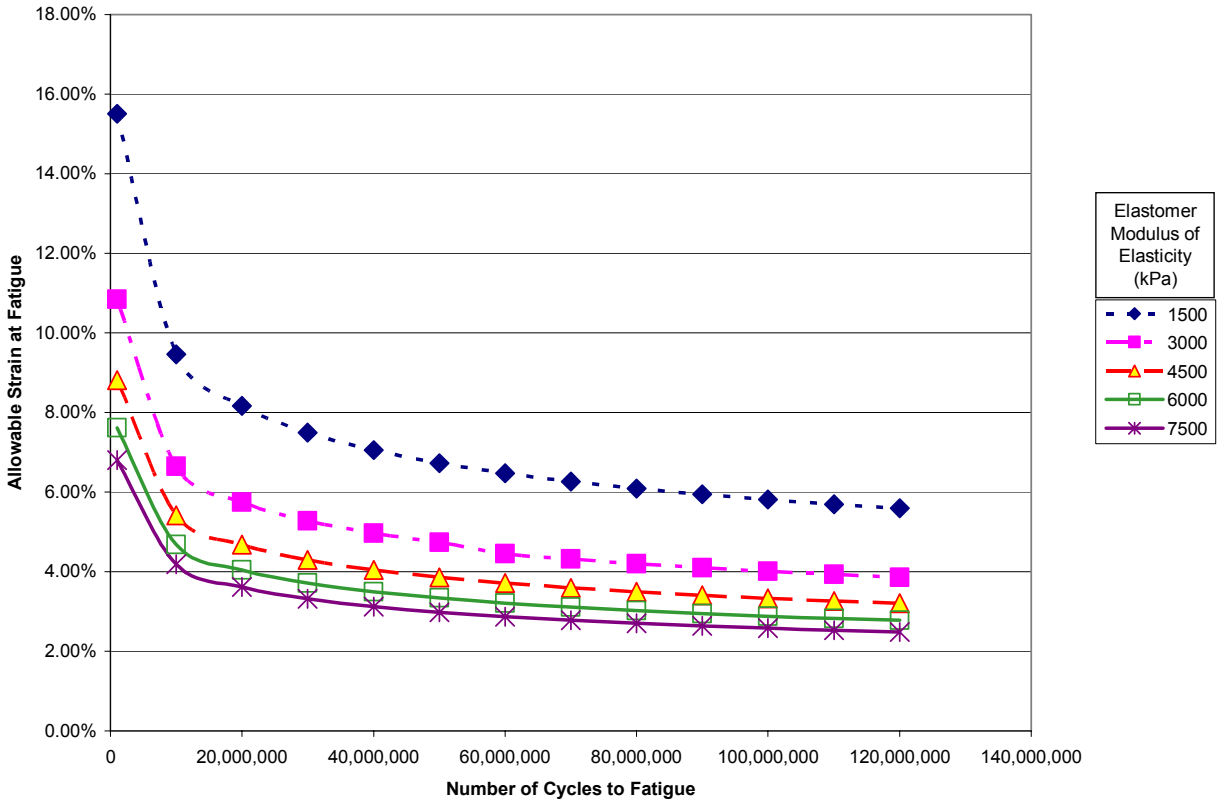


Figure 17. Allowable Strain at Fatigue for Practical Elastomers

Strain vs. Load Cycle Finite Life (Figure 17)

(20) $$\frac{(1+\varepsilon)^{1/2}}{\varepsilon^2} = \pi E\left[N(\beta-1)B(C_o)^{\beta-1}\right]^{1/\beta}$$

<u>Assumed Parameter Values</u>:

$\boldsymbol{B}$ = 5 x 10^{-8} m/cycle/kJ^2/m^4
β = 2.4
$\boldsymbol{C_o}$ = 0.002 mm.

Table J. Mechanical Properties of Typical Filled Rubber Compounds

(Source: Gent, Table 2, pg 327)

Rubber Type		Density	Carbon Black Content	Engineering Stress	Breaking Stress	Ultimate Strain
Acronym	Name	(Kg/m^3)	(wt per 100 parts of rubber)	(kPa at 300% strain)	(Mpa)	(%)
NR	Natural Rubber	1,130	50	15,400	28.1	490
IR	Synthetic Polyisoprene	1,130	50	16,800	30.7	510

Table K. Exponents of β values (for fatigue calculations)

(Source: Gent, pg 149, Table 6.1)

Rubber Acronym	Rubber Type	β Unfilled Rubber	β Filled Rubber
CR	Polychloroprene	1.70	3.40
NR	Natural Rubber	2.00	2.00

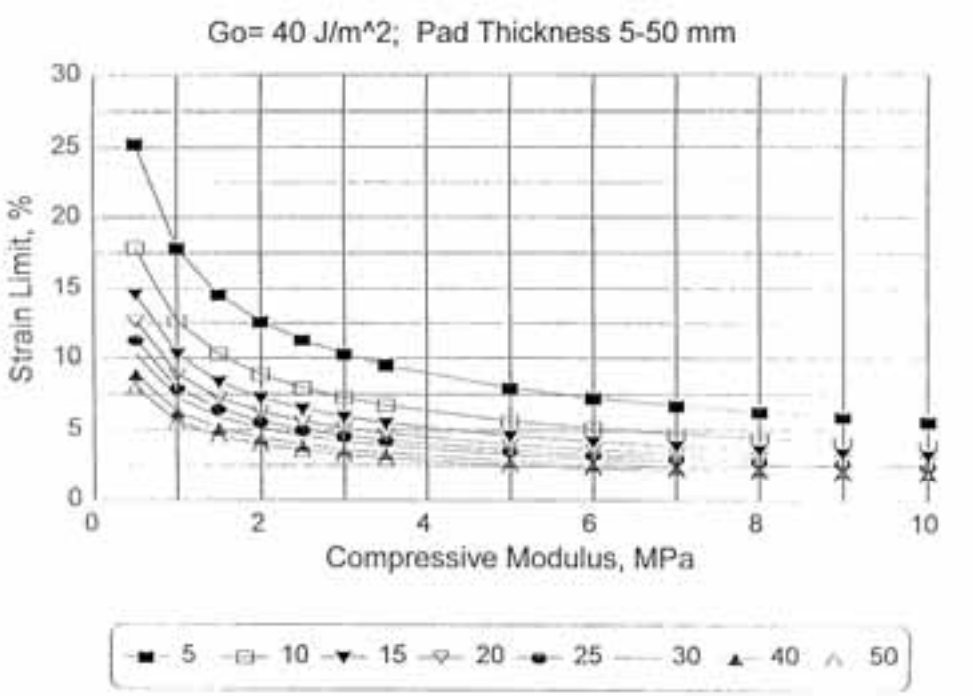


Figure 18. Fatigue Strain Limits in Compression

Figure 17 shows life expectancy with strain for different elastomers. Figure 18 shows compression strain limit variation with elastomer compression modulus and elastomer thickness. These figures indicate that the maximum allowable strain in a fastener should be between 6% and 10% for reasonable fastener life expectancy of materials normally selected for fasteners.

Many designers of elastomeric products for load applications such as track use 15% maximum strain as a rule of thumb. Since that rule of thumb is greater than the foregoing estimates, and elastomers in Direct Fixation fasteners rarely fail, it is useful to bear in mind that the foregoing relations produce estimates and are likely conservative.

Figure 19 shows an “infinite life” fatigue curve, number of cycles to failure versus maximum strain (in tension), for “unflawed” rubber. Use of this curve assumes that the behavior under tension is similar to that in compression. Development of the theoretical curve in Figure 19 to represent the experimental data is based on the assumption of G_o = 40 J/m^2 with an initial flaw length of 25 μm, typical of flaws found in “virgin” rubber.

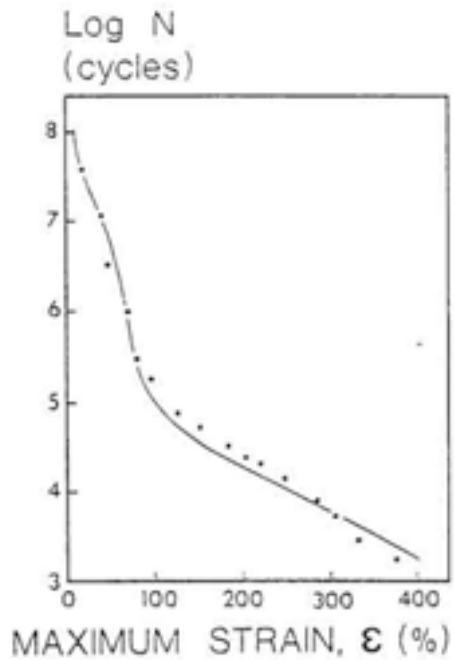


Figure 19. Tensile Fatigue Life N as a Function of Maximum Strain ε (minimum strain for each cycle is zero) for an NR Vulcanizate Tested in Air; each point is the average of 4 to 8 experimental results. The theoretical curve was derived from the crack growth characteristics, assuming a natural flaw size of 25 μm.

B. Reinforced Concrete Material

Concrete and related grout materials are typically the support materials for Direct Fixation fasteners.

This subsection goes beyond concrete materials because material issues are inherently intertwined with aspects of handling, placing, and curing concrete for different physical arrangements of the track support.

Issues dealing with pullout strength of the concrete for anchor bolts and anchor bolt inserts are in subparagraph VI.E.6, Design to Prevent Bolt Loosening.

1. General – Concrete Configurations

Supporting concrete plinth designs must be appropriate for the Direct Fixation application. The experience is that large continuous plinths can exhibit significant cracks emanating from anchor bolt inserts. Such Direct Fixation support can provide improper drainage, incur adverse plinth-structure interaction, and create tolerance accumulations unacceptable for Direct Fixation track.

Direct Fixation track concrete plinths should:

- Be as compact as practical. Configurations that integrate the anchor bolt inserts into the superstructure directly are the ideal. The anchor bolts should not be placed with the superstructure concrete because that concrete placement tolerance exceeds the precision required for Direct Fixation track.[29] Rather, troughs or pockets designed into the superstructure allow second pours in these troughs or pockets to position rail and fasteners precisely by the track contractor.

- Have less than 10 feet between expansion joints, preferably gaps at least 6 inches wide between adjacent plinth ends for drainage through the track. On cambered aerial spans (particularly long spans), plinth lengths of approximately 5 feet (actual length will be consistent with an integer of fastener spacing) are recommended.

- Not incur a significant fastener anchor bolt torque application until the concrete has cured to 28 day strength, or as stipulated in the applicable design criteria for full strength.

[29] Support structure concrete is expected to be finished to within 1/8” of the proper elevation, at best, but may be as much as 5” from the proper elevation due to survey error or post-construction settlement. Direct Fixation fasteners must be installed within 1/16” of the proper elevation with minimum shimming.

- Never create an uncertainty whether anchor bolt inserts will cut reinforcement bar or be in contact with reinforcement bar. Rebar must be clear of anchor bolt inserts for stray current reasons, preferably by the greatest distance practical.

2. *Concrete Issues*

a) General Characteristics of the Concrete Trackbed and Its Construction

The general character of the trackbed and its construction in any given portion of the alignment will be determined by multiple factors; the most important of which are:

i. The physical character and geometry of the alignment—at-grade, tunnel or aerial structure; curve, spiral, tangent, station grounds or special trackwork

ii. The structural supporting elements and their fundamental interfaces with the trackbed, and whether the track concrete also serves as a structural element, such as at-grade slabs

iii. Track elements chosen—rail section, welded vs. bolted, and required track appliances, special trackwork components, trip stops, derails, sliding joints, etc.

iv. The Support/Fastening (S/F's) system chosen for that particular portion of the alignment

v. The desired trackbed details and allowable dead load—slab at-grade, full-width slab, plinths, grout pads, etc., sometimes Owner-specified or dictated by other factors, such as a specialty track construction method[30]

vi. Required control and/or mitigation of wayside noise and vibration, special features such as floating slab construction

vii. Dynamic envelope of the trains and clearance interface with platforms, utilities, walkways, C & S components, etc. (see Drawing #2, Attachment 1B – showing a multitude of such elements)

[30] An example specialty track construction method is the slip-forming of the non-structural slab, wet-stabbing the rail clip shoulders in place, and providing a continuous, low-durometer pad under the foot of the rail. However, the basic idea has been used by the MBTA in the Boston vicinity, and a derivation of it in Los Angeles on the Blue Line Section 140-C, that were built by US contractors without McGregor's assistance.

viii. Derailment protection/guard rails and restraining rails

ix. Electric traction components, appliances, and requirements

x. Other factors—emergency egress, drainage, fire line, C & S, ventilation, lighting, etc. (see Drawing #2, Attachment 1B)

xi. Concrete placement methods—single-pour vs. two-pour methodology; most S/F systems discussed here are constructed with second-pour, "non-structural" concrete even though that concrete may be heavily reinforced

xii. Specific construction method (if known or specified)—top-down vs. bottom-up, or other, such as embedded block ties, often called "Resilient Ties" (RT) is always built top-down, with other S/F's it varies)

xiii. Access points for delivery of concrete, CWR or rails, construction equipment and OTM

xiv. Architectural / aesthetic requirements

xv. Local fire or other codes

xvi. Construction budget

xvii. Long-term maintenance requirements, including cleaning

Although the list above is normally well known by Track Designers, it is not unusual for one or more items to slip through the cracks, sometimes causing real problems during construction or later train operations.

The designer should be familiar with the various construction methods and options, and with due allowance to the other controlling factors, design the S/F-track concrete system to allow for and encourage the use of the most efficient methodology, which will usually result in a good quality outcome at a reasonable cost.

b) Physical Dimensions of Slab, Plinth or Grout Pad and Constructability Issues

The physical dimensions of the track concrete slab, plinths, or other trackbed detail vary for a variety of reasons and have a significant influence on the overall track concrete design, construction issues and methods, schedule, and cost. In this discussion, slab means a full-width slab covering most of the invert (see drawings #1 & #2, Attachment 1B) vs. plinths, which are two relatively narrow slabs under each rail and wide

enough to support the DF's (see drawings #3 & #4 in Attachment 1B). Several types of trackbed details and their attributes are discussed below:

i. Full-width slabs—both reinforced (Drawing #2, Attachment 1B) and unreinforced (Drawing #1, Attachment 1B), usually are fairly easy to build and when unreinforced, require little or no formwork, but do require frequent control joints to minimize cracking, more concrete and higher dead load than plinths; can be tricky to build top-down if depth is > 18 inches; DF slabs are normally reinforced, RT slabs are not reinforced where blocking concrete is in place (Drawing #1, Attachment 1B).

ii. Plinth designs are generally similar in width and depth, but vary in length: (1) continuous (> 40 ft between construction joint gaps); (2) medium length (10 to 15 ft between construction joint gaps—see Drawing #4, Attachment 1B); and (3) individual plinths (pedestals) for each S/F assembly. Continuous plinths have the drawbacks of frequent shrinkage cracking and needing conduits or blockouts for wiring and drainage and are usually used for bottom-up construction; medium plinths have the drawbacks of more labor to place rebar and forms, but are more user-friendly for top-down construction because the jig legs can fit in the voids between forms and they have fewer shrinkage problems; individual plinths are usually used for short DF jobs (< 100 ft) but are seldom used on big jobs because of the relatively high cost and long schedule. Most plinths use reinforced concrete, but there are some unreinforced designs, as well, which are usually placed in grooves cast into the structural support element.

iii. Grout pads—semi-continuous grout pads are shallow (usually < 2-in thick) unreinforced concrete pads (or epoxy grout) roughly 20- to 22-in wide, built bottom-up, and require that the anchor inserts be drilled and grouted into place, partially penetrating the invert. Because of the relatively high cost and long schedule time, few designs currently incorporate this detail. It does provide the lowest track profile of all the designs, where overhead clearances are an issue.

iv. The width of plinths has been standardized at 24- to 26-inches in most DF designs (see Drawings #3 & #4, Attachment 1B), which has some big advantages: (1) formwork can be standardized and re-used, (2) the width fits most commercial DF's with adequate side clearance, (3) it provides adequate structural support, and (4) it's a good match between structural requirements and dead load. However, there is one serious disadvantage: often the planned stirrup and rebar locations leave almost no tolerance to maintain the 2-in minimum cover specified, especially when the stirrups are

mislocated laterally because of wet-stabbing during the civil construction, resulting in cover of less than 1½-in in many cases. We suggest consideration should be given to: (A) changing the rebar/stirrup placement dimensions to allow more cover and installation tolerances or (B) increasing the width of the concrete by 2 in or (C) both. This could alleviate the severe problems a number of Owners have experienced from bare rebar corrosion exploding the plinth concrete. An additional benefit of widening the concrete section and increasing the rebar cover by at least 1 in on each side would be slightly easier placement and finishing of the concrete while only adding about 32 lbs of additional dead load per track-foot (0.0082 cyd of concrete/trk-ft).

v. The depth of the second-pour concrete, whether slab or plinth, is largely determined by the length of the anchor inserts used in the case of DF, or the minimum embedment depth of the RT blocks. Usually, it is in the 6- to 8-in range in tangent track; it can be considerably more when the track slab is also structural. For economic and dead load reasons, the depth is kept to a minimum.

vi. In fairly recent times, a plinth design has evolved which uses an integral, cast-in-place upstand on the gauge side of the plinths as a replacement for bolt-down bridge guard rails for derailment control. We would advise a cautious approach to this detail, as it is very difficult to form, reinforce, and place the concrete and also makes it very difficult to build top-down. In addition, it traps water under the DF's in superelevated curves and is a trash catcher. There is also the question of what to do if it is damaged: stop revenue service until it is fixed or what?

c) Type and Location of Shear Connections and Reinforcement, Constructability

Most second-pour concrete construction requires the use of shear connectors between it and the structural invert to transfer lateral, longitudinal, and uplift loads. The common practice in plinth design in North America is to use two rows of stirrups arranged longitudinally along the edges of the plinth section, quite often set out close to or on the 2-inch cover dimension. This can cause severe rebar corrosion and the cracking or spalling of the concrete, as noted above. There is also a problem with contractor's vehicles damaging the exposed stirrups prior to the trackbed construction. Some designs require drill-and-grout by the track contractor, but many jobs allow the civil to wet-stab the stirrups, often in the out-of-tolerance locations. An alternate is to use "L" bars or bars with threaded couplings flush with the surface of the deck or invert, which are much less susceptible to damage. In Europe, the stirrups are oriented laterally so they act as lateral rebar in addition to being the shear connectors. Some

thought should be given to this detail, as it is more troublesome and costly than it should be.

Resilient Tie (RT) construction does not require shear connectors, provided that the supporting structure includes a perimeter upstand to act as blocking concrete.

Most plinth designs are reinforced concrete, sometimes very heavily reinforced. Analysis indicates that very little reinforcement is actually required. For economic reasons, this aspect should be analyzed carefully so as to avoid over-reinforcing, which can be counterproductive as far as concrete life and durability are concerned. Regarding reinforcement corrosion control, see Section 4.

d) Corrosion Control, Drainage and Life-of-Concrete Issues

Corrosion control of the metallic elements embedded or attached to the concrete is a very important issue that must be addressed fairly early in the design stage, usually in conjunction with the Systems Engineering group. It is a fairly complicated subject and there are widely differing opinions, even in the corrosion control engineering fraternity, of how this is best accomplished. We are not qualified to discuss the merits of electrically common, bare rebar vs. isolated, epoxy-coated rebar vs. cathodic protection, etc. But almost all corrosion problems stem from uncontrolled water: i.e.. water where you don't want it and possibly for a long time. There are steps that the Track Designer can take that will mitigate the effects of uncontrolled water, such as:

i. Specify a concrete mix that has low permeability – this will reduce capillary water movement within the concrete; low-porosity mixes often require pozzolan and chemical admixtures; forbid the use of calcium chloride as an accelerator

ii. Consider the addition of fiber reinforcement to the concrete mix which helps to reduce plastic shrinkage cracking, which in turn makes the in-place concrete less permeable

iii. Make sure there are no "water traps" in the trackbed design, that all low and ponding sites are fitted with drains, and that those drains can actually be cleaned—good drainage is the best defense against uncontrolled water.

iv. All metallic fittings that are embedded in the concrete but partially exposed to the air should have appropriate corrosion protection applied

v. Make sure the plans and specs call for all control joints and random cracks that occur during construction to be effectively sealed with a suitable resilient compound

vi. Consider specifying the application of a concrete sealer / water repellant to the track concrete; this is seldom done, but can have great benefit when applied to somewhat permeable concrete, and areas where water ponding cannot be prevented

vii. Take extra precautions to protect against chloride intrusion where vehicles enter a structure from street-running, bringing road salt in the winter

viii. Install stray current monitoring stations to provide warnings if the rebar or other structural steel is at risk; this is a Systems Engineering issue, but will probably affect the details of the trackbed design

To summarize, most of the steps that make concrete "tighter" and more durable also help to inhibit water and ion intrusion and reduce potential corrosion, whether caused by stray current or environmental factors (see paragraph II.B.2 in this Section). Corrosion of the embedded metallic elements is the major cause of concrete failures in transit trackbeds; therefore, a relatively small investment during construction can pay off in greatly extended useful life. In typical plinth designs, there are approximately 0.086 cyd's of concrete per track-foot. If the delivered cost of concrete is doubled, say from $100/cyd to $200/cyd because of premium performance mix design and admixtures, the cost per track-foot is increased by less than $9.00! That's a bargain for the Owner, as it probably represents an increase in cost of the entire trackbed construction of slightly over 2%.

For additional helpful information on the topic of corrosion and life-of-concrete issues, we suggest a comprehensive ACI Report, #ACI-222.3R-03, "Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures." It is available from ACI, P.O. Box 9094, Farmington Hills, MI 48333-9094 (www.concrete.org). The Concrete Reinforcing Steel Institute (CRSI), 933 North Plum Grove Rd., Schaumberg, IL 60173-4758 (www.crsi.org) has a large library available of test reports, case histories, and research results related to rebar corrosion and its prevention.

e) Type and Location of Rail Supports / Fastenings and Anchorages

The type of Rail Support / Fastening system chosen will be dictated by cost and the various performance criteria and considerations in Sections

IV through VI of this document, which will also establish the desired spacing. These choices will establish the design criteria for the track concrete to support the unit loads of the S/F's and accommodate the mountings and anchorages, taking into account some additional factors:

i. The spacing of the anchorages, if of the insert type, will essentially dictate the rebar plan, as they need to be based on the same unit length increments; otherwise, there will be periodic conflicts between the inserts and rebar cage.

ii. RT is not normally encased in reinforced concrete, but if it is, then the rebar plan should allow a minimum of 2½ inches clear between the block pockets and the rebar, as there will be moisture in the pockets over time.

iii. Care should be taken to make sure the S/F's are not too close to the edge of the plinth, construction joints, or other interruptions in the track concrete, especially in high impact areas, such as sliding joints and special trackwork.

iv. The "edge effect" should be considered when designing for the required insert pullout resistance values when the inserts are roughly as close to the concrete edge as their embedment depth dimension (see Section V.E.6).

f) Type of Track Concrete, Mix Design and Control, and Use of Admixtures

The general topic of concrete mix design is too extensive to cover in detail in this discussion; however, it is very important to the project outcome that the concrete mix is designed to provide not only the necessary strength, but also long-term durability, which is even more important. Because the Specs may call for a relatively low-strength concrete for the trackbed, which is perfectly OK, it may be assumed by the contractor and the concrete supplier that practically any mix design will be OK. That is definitely not true. It is up to the Track Designer to make sure the mix will meet both the strength and durability criteria, which is done by controlling the water/cementitious material (w/cm) ratio, the aggregate "packing" criteria, and using admixtures that are beneficial in reducing permeability, shrinkage, rebar corrosion and weathering effects. In other words, it is "high performance concrete." It is vitally important that all stakeholders realize that the track concrete is by far the most costly track component to replace if it fails in service and can be a perpetual headache to the Owner. Rail, DF's and anchorages, and RT's can be readily replaced, when necessary, in relatively short track outages during regular maintenance windows; that is generally not true of the track concrete. Therefore, any

concrete failures can result in significant traffic interruptions as well as considerable ongoing expense and tying up scarce maintenance crews.

But without going into the specific details of the “best” mix design, as that is open to a great deal of debate in the concrete engineering and construction industry, we can offer rules [nlb1]that can be safely applied to track concrete with uniformly good outcomes, viz:

i. Make absolutely sure that the contractor and concrete supplier know the importance of using a closely controlled, repeatable mix design and that the supplier has the required materials always on hand and the ability to batch and mix them accurately

ii. Make absolutely sure the CM/Inspectors are aware that the mix is vitally important; don’t let slumps, cylinders, and w/cm tests slide or allow field practices that will be harmful to the long-term durability of the concrete, such as long drum times, water “tempering” on site, under compaction, improper curing, etc.

iii. Remember there are only two factors that control the ultimate strength and durability of a specific mix design after it is placed: (1) the w/cm ratio (the lower the better) and (2) proper curing (the longer kept moist, the better); these important points are frequently forgotten in the frenzy to meet schedules

iv. Make sure the mix design specifies top-size aggregate that will work with the formwork and rebar clearances to be found on this project

v. Spec must cover testing for and ruling out the possibility of alkali-aggregate reactivity

vi. Specify or allow the use of beneficial admixtures in the mix, which can reduce shrinkage, permeability, and workability problems, and improve durability at small cost

vii. Air entrainment is very important to preventing freezing damage to the track concrete in cold climates and should be specified; it also improves workability in warm climates and helps keep the w/cm ratio low

viii. Specify or allow the use of pozzolans in the mix, which can also reduce shrinkage and permeability and also improve durability considerably

ix. Make sure adjustments in the slump specified permit the use of high-range water reducers (super “P’s”) or other workability

enhancing admixtures, as they also reduce the w/cm ratio, which is highly desirable

There are a host of admixtures and pozzolans available in the market place. To help decide what to use, we've included a sample spec in Section 5, PART 2 – PRODUCTS, Sections 2.01.A through 2.01.L., which lists a large number of materials and admixtures in the spec that are typically used in the design of "premium performance" concrete and its sealing and protection after placement. This gives a good idea of the products that are available for this purpose; the only thing missing is a shrink-reducing admixture (SRA), which is probably not included as they are relatively new in the industry. We suggest the Track Designer look this over to see the range of products available and familiarize himself with their effects, both good and bad. However, a word of caution—when more than one admixture is used in a mix, the results can sometimes be surprising and not what's desired at all. All mix designs should be reviewed by experts and thoroughly tested for admixture compatibility and other properties prior to the work.

Although the Track Designer may defer to other concrete experts in specifying a particular mix design, he should be able to assess reasonably well the mix design submitted by the contractor and concrete supplier and look for the attributes that will result in the most durable concrete, as quite likely experts may not be available during the often hurried submittal review process.

To gain additional knowledge, we suggest further reading, such as an in-depth treatment of mix design and control in the Portland Cement Association's Engineering Bulletin "Design and Control of Concrete Mixtures," Thirteenth Edition, available from Portland Cement Association, 5420 Old Orchard Rd, Skokie, IL 60077-1083 (www.portcement.org) and again we recommend the previously cited ACI Report ACI 222.3R-03, which has a lengthy discussion of admixtures and pozzolans and their effects. Also, the ACI Report ACI 201.2R-01 "Guide to Durable Concrete" is an excellent resource; the ACI documents can be obtained from ACI, P.O. Box 9094, Farmington Hills, MI 48333-9094 (www.concrete.org).

3. Grout Pads

For grout pads, the grout material must have the same coefficient of expansion as the base concrete.

4. Construction Method, Formwork and Concrete Delivery

There are generally two methods used for most trackbed construction in North America: top-down and bottom-up. In top-down the running rail or a surrogate is in place on the guideway, with the S/F's or surrogate templates attached to it, including the anchor inserts, and sometimes fitted

with “slobber plates,” all supported by some type of adjustable jigs or horses that allow the skeletonized “track” to be placed at the proper geometric relationship to the PGL, with the rails properly canted, gauged, and at the correct vertical and horizontal alignment. When the rebar and forms are in place, the concrete is placed and finished. The reasons for using this method include:

i. The track can be set using only the survey hubs set usually 20-ft OC in tangent, 10-ft OC in curves and a track level and tape to excellent accuracy.

ii. Any places in the track that look “funny” can be corrected before the concrete placement, avoiding survey busts, in some cases.

iii. It makes embedding the anchor inserts at the correct locations very easy. The preferred top-down construction method also employs slobber plates, which facilitates providing the desirable flat mounting seats for the DF’s.

iv. Usually the formwork is placed quickly, as it actually references to the rails, rather than survey marks and stringlines.

v. It makes obtaining the correct grade, cant, and slope of the DF mounting seats or locating the RT’s properly more or less automatic, usually eliminating any shimming or adjusting to obtain the correct track geometry during final assembly and de-stressing.

vi. In most cases, the rails and OTM are then already on site for final assembly.

vii. The method works with virtually any type S/F: DF, RT, whole ties, etc.

viii. With adjustable support jigs, setting the superelevation is easily done in curves and spirals, even if there is also an underlying vertical curve.

ix. In computer language: WYSIWYG.

There are drawbacks to the top-down method, such as:

i. The rails and OTM have to be on site, which is sometimes difficult because of access problems.

ii. In DF construction, often large air/water voids are left under the slobber plates, requiring extensive patching.

iii. Even with care during concrete placement, significant effort is required to clean the track components prior to final assembly.

iv. Swings in ambient temperature or sun heat can disturb the accuracy of the geometric set-up and require re-adjusting, even during concrete placement.

v. Sometimes the rebar is hard to place and tie properly in such tight confines.

vi. The support jigs require an investment, perhaps not justified on small jobs.

In the bottom-up method, the formwork is the primary reference, set up to survey hubs and stringlines for longitudinal and lateral dimensions, and the grade line set with the surveyor shooting in the elevations so that the chamfer strip can be nailed (or adjusted) by the carpenters to obtain the correct grade, cant, and slope strike line for the concrete. In some cases, there are templates to hold the anchor inserts in place to be wet c.i.p.; in other cases, they are drilled in and grouted later. The advantages to the bottom-up method are:

i. No track materials need be on site during concrete placement, no access problems

ii. Less interference with placing and tying rebar

iii. Top finishing of concrete is not restricted by rails and OTM in the way

iv. Little or no investment in jigs or other specialized equipment is required

v. No track knowledge or handling equipment is required on site during set-up

There are also drawbacks to the bottom-up method, as well:

i. It is difficult to get the DF mounting seats exactly right, regarding flatness, cant, slope, and position of anchorages; usually requires extensive shimming and/or grinding during final track assembly

ii. Surveying in the elevations in curves and spirals, especially on vertical curves, is very time-consuming and error prone, difficult to execute within tolerances

iii. A survey bust is not necessarily obvious before placement of concrete

iv. Not adaptable to installation of RT or whole ties

The preponderance of jobs in North America in recent years have used top-down; however, there are some commercially available forms on the market that take some of the tedious survey work and possible errors out of the bottom-up method, and it is very often appropriate for short (< 200 ft), tangent track constructions. The choice is usually up to the contractor, but the specs can and should encourage the use of the fastest, most accurate method, as some Owners have had ongoing maintenance problems with track that required excessive shimming or didn't have mounting seats that were flat enough to keep the DF pads from rocking and loosening the anchor bolts.

In addition to the two methods discussed, there are other methods, such as slip-forming and also using a combination of pre-cast elements then embedded in cast-in-place concrete, but these are usually proprietary, and of only limited interest in this discussion.

The formwork to be used is generally either wood, built on site or prefab, or metal, usually adjustable and reusable. Normally the biggest problem with the formwork is interference with the jigs supporting the track in top-down construction, or poor quality and bad fit-up that allow the concrete to leak out during placement and vibrating. Forms that are too high make it difficult for the finishers to do their work properly, as they can't see the strike line very well, and the finish is usually pretty sloppy. Proper cleaning and oiling of the forms will prevent unsightly "pullouts" during stripping and leave a better finish on the concrete.

The transport of the concrete can be an important element in the concrete QA/QC process, because consistently long drum times, caused by traffic or bad scheduling, usually are handled in the field (or at the plant) by adding more water than the mix design allows. This has two bad effects: (1) it lowers the in-place strength and (2) it reduces the durability. In consultations with the contractor and concrete supplier, this is an important point to stress—they must work out a timely transport method or the quality of the concrete is potentially compromised. This can be handled, if the equipment is available, by doing the water-mixing on site, although this is not as good as batch-plant mixing. Or a batch plant can be set up on site or close by, if the job size permits. In any event, this is an issue that should be addressed and resolved timely.

If the work plan calls for pumping, especially long distances, be aware that the air-entrainment will be partially lost (as much as 50%). Also, the contractor usually orders a wet mix for pumping; the w/cm ratio should be monitored closely. The mix design may be adjusted to help compensate for these problems, or the use of a re-mixer specified, to keep the in-the-form properties of the concrete consistent with the specs.

We suggest that additional reading of interest on these topics can be found in two ACI Reports: ACI 304R.00 "Guide for Mixing, Measuring, Transporting, and Placing Concrete" and ACI 304.2R-96 "Placing Concrete by Pumping Methods"; both can be obtained from ACI at the address shown above.

5. *Placement, Finishing and Curing of the Track Concrete*

The proper placement, finishing and curing of the concrete is where the outcome of the project is determined. The best mix design cannot do what it was intended to do unless it is properly installed. Probably one reason there has been a history of problems with installing track concrete is that the responsible personnel have approached the job as a "small" structural concrete job rather than as the "architectural" concrete job, which is more like close-tolerance pre-casting, that it really is. The similarities to architectural concrete are striking: (1) the sections are often relatively small but finely detailed, (2) they are exposed to view, in stations anyway, so that the finished appearance is important, and (3) degradation of the surface is undesirable and usually signifies some internal degradation, as well. That means architectural concrete requires extra attention and care during installation to perform as desired.

In most specs, the placement, finishing and curing are simply passed off by referring to appropriate ACI spec sections; please note the detail covered in Section 5, PART 3 – EXECUTION, 3.01 through 3.07, which covers the various executions of the work parameters in considerable detail. This level of detail reduces the possibility of misunderstanding on the contractor's part of what is acceptable and what is not. This also provides agenda items for the "Pre-Concrete Conference" of the stakeholders, where all the concrete items can be reviewed and sorted out well before the work begins.

In our opinion, the most common violations of good practice that occur in the field are:

i. Unauthorized addition of mix water on site, or "tempering" partially set concrete during finishing

ii. Improper vibration and consolidation—often, the vibrator head is 13 inches long and the slab or plinth is only 8 inches thick; the vibrator is inserted at an angle, which simply adds more air to the mix,

which contributes to the bughole problem; a shallow slab vibrator head should be used for this work, and the vibration should be applied long enough to expel excess mix air

iii. Finishing too green—not waiting for the bleed water to evaporate and troweling it back into the surface, ruining the cement paste and inducing map cracking and later scaling

iv. Stepping on the S/F's during finishing, causing them to make depressions in the plastic concrete that won't recover, especially true in RT installation; work platforms should be used to prevent this from happening

v. Poor finishing of DF mounting seats regarding flatness, cant and slope, especially in bottom-up construction

vi. Improper curing—on most jobs, curing is not done properly or long enough; as proper curing is one of the two big influences on the durability of the concrete, this is an area of the spec and of the inspection process that should be especially clear and tight to make sure it's done correctly

vii. Premature application of curing membrane—quite often, the spray-on membrane is applied before the bleed water has evaporated, trapping it in the surface layer and destroying the strength of the cement paste, resulting in map cracking and eventual scaling

viii. Lack of adequate monitoring and inspection of the concrete work

Although the use of spray-on curing membranes is generally accepted and allowed, it should be noted that they are: (1) not necessarily properly applied timely and in the required thickness, especially after the side forms are removed and (2) the subject of some debate about whether the resulting concrete is as durable as that which is truly moist cured for 7 days or more. This is an area of research that is needed, especially for non-ballasted tracks exposed to frequent freeze-thaw cycles.

An item not mentioned previously is bonding agents, which are often specified (usually the epoxy type, although many others are available). We suggest that the Track Designer look very carefully at their use, and make sure that the right type is specified, as there have been some unfortunate outcomes in this area.

It is not expected that the Track Designer will monitor and control all field conditions, but the Designer can and should make sure that the plans and specs address these and other important issues in such a way that both the contractor(s) and the inspectors will have a clear understanding before the commencement of work of what is desirable and acceptable and what

is not and plenty of time to straighten out any problems. Bear in mind that the specs are the inspectors' "bible" and the inspectors can only make the contractor do or not do what a reasonable interpretation of the spec says.

Any submitted work plans should be carefully reviewed to make sure the contractor has not only the right materials, equipment, QA/QC plan and schedule in mind, but the well-trained and experienced people to make it happen. Any discrepancies or differences of opinion as to the proper methodology can be addressed during a "Pre-Concrete Conference" or similar meeting mentioned earlier, which should be held well ahead of the planned work.

Regarding the inspection issue viii, above, this is caused primarily, we believe, by the inspector(s) having expertise in track construction, but not necessarily in concrete construction. The inspector(s) should be well versed in all aspects of the concrete portion of the Work as well as the track and preferably be ACI Certified.

A very useful reference to help set up appropriate specs for placement, finishing and curing is the ACI Seminar Course Book "Troubleshooting Concrete Construction," publication SCM-17(03). The book describes the case histories of concrete failures, with the reasons they failed. It also contains ACI Report ACI 308R-01 "Guide to Curing Concrete," which is extremely helpful. It is available from ACI at the address listed earlier.

6. *Construction Tolerances: Dimensions, Voids, Flatness, Rebar Cover, etc.*

Construction tolerances for the bearing seats in the track concrete vary considerably among projects for no discernible reason, as they often are using the same S/F's. For DF's, there are five critical dimensions for the bearing seat, in what we believe to be their order of importance: (1) flatness, (2) elevation, (3) cant or cross-slope, (4) longitudinal grade slope, and (5) the anchor insert locations and elevations. The reason that flatness is most important is that it is "non-adjustable" by practical means, other than a grout overlay or grinding, and it can affect the integrity of the mounting. If it is either high or low in the center by about 0.060 in, there is the risk of breaking the bottom plate of the DF, or else the potential for rocking on the anchor bolts making them hard to keep tight. Therefore, that dimension should be kept within a tight tolerance of within 0.030 in of truly flat when measured with a straightedge placed diagonally from corner to corner of the bearing seat. The other tolerances as recommended in paragraph 3.09 of Section 5, Example Concrete Specification, applicable to both DF and RT construction, should work for most projects, unless the S/F's chosen require tighter tolerances.

Bearing seat elevations should be held within the tolerances referenced above, as it is shim adjustable; however, if plastic shims are used, the thinnest shim that is practical is 0.060-in thick. Metal shims can be made

in any thickness, but are subject to corrosion, even if galvanized, unless made from stainless steel. Therefore, the grade tolerance should be related to the shim material specified for the job, but the "within ± 0.060-in of the adjacent bearing seats" is OK[31] for almost all cases in DF construction and readily achievable with top-down construction.

There is an alternate approach worth considering that can help solve the shimming quandary: use a 0.090-in thick low-density polyethylene shim under every fastener, which will help to stabilize the DF's on slightly uneven concrete. The same material is also available in 0.060- and 0.125-in thickness, allowing an adjustment either way of 0.030 to 0.035 in, which provides the fineness of adjustment desired by the DF and spring clip manufacturers. HDPE shims can be added, if a thicker shim pack is needed, but with a note of caution – the LDPE and HDPE have very low coefficients of friction, so the anchor bolts have to withstand all the longitudinal and lateral rail forces.

If the contractor is using slobber plates in conjunction with top-down, the slobber plates should be large enough to make a flat bearing seat that will allow the DF to be adjusted within its full lateral range without bearing on rough concrete.

The acceptability of voids in the bearing seat area is another topic of lively discussion and widely varying tolerances among projects, from "no voids" to "left to the judgment of the RE." The "Example Specification" calls out 90% good bearing and a ½-inch maximum void diameter. That may be a bit too tight; perhaps 85% good bearing with a maximum individual void not to exceed 1-inch in the longest dimension would be considered acceptable and practical. If the concrete is a good mix, properly placed and vibrated, it will likely meet those criteria; if it's not, probably all the bearing seats will have to be parged.

Regarding rebar cover, please see the discussion in paragraph V.B.2. The authors' general opinion is that effort should be made to maximize rebar cover in the design of reinforced track concrete as rebar corrosion is the principal failure-causing mechanism of that concrete.

7. Inspection Criteria and Methods, NDT Testing

It is usually assumed that the inspectors will interpret the spec's language and the plan drawings properly and implement the proper inspection procedures. In many recent projects there have been conflicts between

[31] A tolerance of 1/32" is stated later in this report to avoid damage to rail clips. In practice, measuring and actually achieving a 1/32" tolerance is difficult. With the understanding that clips may be vulnerable to a tolerance larger than 1/32", the maximum allowable deviation should be 1/16".

the plans and specs, or criteria that were too vague to interpret solidly. This leaves the inspectors somewhat in a quandary; the Track Designer can help clear up this situation by making sure that ambiguities and/or conflicting requirements are cleared up timely and early during the pre-construction meetings, if it can't be done in the plans and specs prior to NTP.

For instance, in the "Example Specification," the DF bearing seat elevation tolerance is called out at 0.060-in relative to the adjacent bearing seats, but doesn't actually say how this relates to the theoretical dimension from the PGL; however, the language can be changed to read, "The design dimension of x.xx-inches from top of rail to any individual bearing seat shall be held within ± 0.060-inch, and the difference in elevation between any bearing seat and the two adjacent bearing seats shall not exceed a total of 0.060-inch." The question is: how will the inspector actually measure these dimensions? If the DF's have been removed and the rail jacked up, it is no longer a valid measuring reference. If the supporting jigs are still in place, the rail can be put back to the proper geometry and used as the measuring reference, but the contractors usually drift those jigs ahead as soon as possible to the next setup, so they may not be available to the inspector. In the case of bottom-up construction, the rail isn't there, anyway, to be used as a measuring reference, so some other way must be found to do this measuring. It can be done by instrument, but that is slow and barely accurate enough, given the division size on the stadia rod, and is difficult to do in spirals and curves. Some projects have specified using a stringline for this purpose, which works OK in tangent track, but not very well in curves. Probably the best solution is to use a purpose-made measuring straightedge that is at least 10-ft long, so that it can span a minimum of five rail seats and be measured from the hubs or benchmarks, in the case of full-width slabs. The same problems exist regarding measuring cant and slope. The point here is that provisions need to be made in advance for the inspectors to be properly equipped to do their job, or the project will suffer. Although this problem is not the direct responsibility of the Track Designer, he can help solve it by working with the RE to devise ways to both achieve and measure the track concrete accuracy that is required.

A suggested procedure to remedy these difficulties is to stipulate that the contractor will survey the formwork adjacent to each fastener in bottom-up construction, or top of rail in top-down construction, and deliver the survey notes to the Engineer prior to a required in-process Engineer inspection. The pour should not proceed until the Engineer's inspection is complete and all deficiencies are removed.

Such an inspection is recommended in any case, particularly in top-down construction, to check for epoxy coating nicks and gouges (fastener

inserts and rebar) that inevitably result from the construction process, along with rebar clearance from the inserts.

Few projects require non-destructive testing, but it is now becoming more common, as more devices such as impact reflectometers, ultrasound devices and ground-penetrating radar are available for doing this. It is an area that needs investigation to determine the best method applicable to track concrete (Ref: ACI 228R), but we suggest that some form of NDT is highly desirable to prevent undiscovered internal defects from causing serious problems later on.

8. Repair Methods and Rework of Out-Of-Spec Concrete

The "Example specification" covers the general repair of defective anchor inserts in Section 4, paragraph 3.10. The replacement inserts are usually installed with either epoxy or acrylic grouts intended for that purpose. Any repair plan submittal that proposes to use a grout that is not intended for this purpose (i.e. where the annular clearance is > 0.060 inch) should be rejected, as some grouts creep over time when the annular clearance is too great.

The repair of voids, spalls, and damaged concrete can be accomplished with a multiplicity of quick-set cementitious, epoxy-based, and other polymer-based products on the market, with this note of caution: the cementitious-based products should be cured the same way the substrate concrete is, or cracking and peeling may be excessive. The epoxies and polymers normally don't need to be cured and may be preferable for that reason. It is probably wise to allow both types, but require curing for the cementitious materials.

Out-of-tolerance bearing seats are fairly common in bottom-up construction, both high and low. In the "Sample Specification" it calls for the anchor inserts to be set below the concrete bearing seat surface by 0.187-in, which allows for grinding, if it is required, without damaging the inserts. The setting of the inserts low is a good idea, if bottom-up is going to be used.

It should be kept in mind that if the flaw to be repaired is a result of excessive water, excessive drying, or other cause that has created unsoundness in the concrete surface, then it is imperative that the damaged concrete be removed down to sound concrete, or the applied patch will simply slough off over time.

ACI has a number of reports dealing with concrete repairs, among them ACI 332R, ACI 546R, and ACI 555R; all are available from ACI at the address listed above. In addition, there are chemical specialty companies who offer repair manuals that can be helpful.

9. Summary of Most Important Concrete Issues

The most important concrete issues that have been cited above as problems largely result from lack of knowledge or inattention to the key details and interfaces required to install concrete successfully.

This is brought about, the authors believe, by the fact that concrete is so familiar it is taken for granted by the track design engineering groups, who are largely concentrating on the fine and complicated points of track and its construction above the concrete. This Commentary is intended to point out to the Track Designer that the often-times general language in Sections 03300 and 03301 of the spec, or similar, may not adequately cover the track concrete topic and result in a successful installation. The Sections that the Track Designer controls, both in the plans and specs, will have to address those items that are key to having the track concrete installed successfully. The highly specialized requirements for track concrete mean that all the steps involved—mix design and control, transport, placement and finishing, curing, and inspection—must be executed properly for the in-place concrete to reach its design strength, to meet the dimensional accuracy specified, and to be durable so as to provide a long, trouble-free service life. For any given mix design, strength and durability are tied closely together, and it is important to remember what was mentioned previously—that there are only two factors that influence strength and durability: (A) the w/cm ratio and (B) the length and method of curing. Essentially, everything else is "details," but important details. The Track Designer would do well to become familiar with those details, as their proper execution will largely determine the outcome of the project.

This review has deliberately avoided reviewing and commenting on concrete specs and details that generally are covered and executed properly. Their omission means they are well covered in current practice, and the mission here is to highlight those concrete items that most frequently fall through the cracks.

Mentioned above are several publications that can be very helpful to the Track Designer. Additional strongly recommended resources are: the ACI "Concrete Primer" Fifth Edition, Publication SP-1, which has a wealth of information on all aspects of concrete; the ACI "Field Reference Manual" Publication SP-15, which contains ACI 301 "Specifications for Structural Concrete" plus other ACI and ASTM references. ACI 301 has a "checklist" that is a great reminder that all the spec bases have been covered, which is a big help. Both SP-1 and SP-15 are available as separate publications from ACI at the address listed previously. All the other ACI documents mentioned in this Commentary are contained in the ACI Manual of Practice 2004. Another reference that is valuable is the CRSI "Manual of Standard Practice," Publication MSP-2-01, available from CRSI at the

address listed previously, which has a great deal of useful information regarding steel rebar.

10. Managing Concrete – Scopes

This Commentary is aimed at all the stakeholders in the track concrete construction process, who are:

a) The Track Designer

The Track Designer is responsible for all the track design, including the supporting concrete, in most cases, and whose scope regarding the concrete specifically will normally include:

i. The detail track concrete design interfaces with the S/F's and other track appliance, including all mounting dimensions and finishing details

ii. All specs and plans to cover the concrete construction, usually in concert with the structural engineering group and Systems Engineering

iii. Technical review of the contractors' submittals regarding materials and methods

iv. Resolution of conflicts arising from conflicting or ambiguous specs or plans

v. Coordination with the CM/Inspectors regarding spec and plan interpretation and methods of inspection

vi. Responsible for technically reviewing change orders or changing the plans to avoid conflicts

b) The Civil Contractor and/or the Track Installation Contractor

The Contractors cited are responsible for planning, scheduling and executing the track concrete construction in agreement with the plans and specs; in some cases, one or more may also be responsible for the structural concrete, as well. These parties need to be in the information loop regarding the important concrete issues involved.

c) The CM/Inspectors and Contractor QA/QC Personnel

Inasmuch as there are myriad steps involved in mixing, transporting and placing the track concrete, it is vital that these stakeholders are fully informed and cognizant of the high-sensitivity items that must be adequately planned, controlled and inspected, and if necessary, repaired or replaced. The CM/Inspectors should be part of the design process, as

well, since methods and specialized equipment may be required to allow for proper inspection procedures. Please note prior discussion comments regarding inspection and qualifications in paragraphs V.B.5 through V.B.7., above.

d) All Other Stakeholders in the Non-Ballasted Construction

There are other stakeholders in the trackbed concrete construction, which include:

i. The Owners Maintenance Department, which will be responsible for maintaining the trackbed after the warranty, and will be hard pressed if excessive maintenance is required

ii. The Owner's Operations Department, whose train operations will suffer if the track is not durable and requires excessive maintenance, resulting in outages or delays

iii. The Suppliers of the S/F's, which may not perform properly if there are problems with the supporting track concrete, which may induce warranty claims

iv. Other contractors whose schedule or access may be delayed if the track concreting completion is delayed by slow construction or excessive re-work

v. Transit Customers - the traveling public will suffer if excessive maintenance requirements interfere with revenue service and timetable operations

Certainly the Owner's Maintenance Department should be part of the design review process, as the Department may have had prior experience with track concrete problems that will help guide the Track Designer in his development of the plans and specs. The Contractor(s), once on board, can also be helpful in resolving potential problems before they happen, especially if there is a "Partnering" relationship built into the contract.

Lastly, the Track Designer would do well to seek advice from experienced track installation contractors during the design phase to get their input on "best practices" and to avoid traps.

C. Metallic Components

The metallic components of Direct Fixation fasteners are the plates internal to the fastener, the anchor bolts and their inserts, rail clips, and any associated washers or plates in a particular design arrangement.

Materials for bolts[32] and washers[33] are common industrial materials covered by ASTM specifications, with no further discussion needed here. For bolt grade and steel requirements, please see Section 2, Direct Fixation Fastener Example Procurement Specification (for example, see paragraph 2.01.L for anchor bolts).

Anchor bolt inserts generally are ductile iron castings with machined internal threads[34]. Steel and plastic inserts are also available.

Elastic rail clips usually are special high strength, treated steels to develop as much toe load as practical. The properties and tolerances of rail clips are covered in other sections of this report.

The following discussion applies only to steels used in the plates and frames integral to the fastener, and to rigid rail clips.

Plates for fasteners can be ductile iron, cast steel or rolled plates. Casting allows unique shapes. Rolled products can offer higher strength per volume of material and economy in mass production.

1. Ductile Iron Castings

The fastener specification for ductile iron top and bottom plates (and any other cast iron product such as rigid rail clips) is ASTM A536-84(2004), Standard Specification for Ductile Iron Castings, with the minimum of Grade 65-45-12. The 65-45-12 grade designation refers to specification minimum values for tensile strength, yield strength and elongation, respectively.

The required ductile iron chemistry is shown in Table **L**.

---

[32] ASTM A-325 Specification for Structural Bolts, Steel, Heat Treated; dimensional standards are in ASME B18.2.1.

[33] ASTM F436.

[34] ASTM A-325 or ASTM A-490; thread standards are in ASME B18.2.6.

Table L. Ductile Iron Chemistry Requirements[35]

Carbon	3.20 – 4.10%
Silicon	1.80 – 3.00%
Manganese	0.10 – 1.00%
Phosphorus	0.050% max.
Sulfur	0.035% max.
Magnesium	0.025 – 0.060%

The required hardness of ductile iron is between 156-217 Brinell Hardness Number (BHN)[36], measured in accordance with the procedures in ASTM E10. Using the Tabor estimate[37] for yield stress from Brinell hardness, the material can have a yield stress between 37,000 psi and 51,400 psi, consistent with the stipulated iron grade.

Direct Fixation specifications require ductile iron to have fracture energy of 3 foot-pounds in the Charpy or Izod impact tests, ASTM E23. This requirement specifies the minimum allowable impact capacity of the material under the notched test condition. The nature of the test also establishes whether the material will perform in an elastic-plastic[38] mode if it develops cracks. For comparison, the same test without notching the test specimen will measure fracture energy of 60 ft-lb, on average, for this grade of ductile iron[39].

To illustrate where these requirements place fastener plates among other ductile irons, Table M provides typical strength and fatigue properties for common grades of standard ductile iron.

[35] SAE J434, Table A1, pg. 9

[36] SAE J434, Table 1, pg. 2, for SAE grade D450 (equivalent to ASTM grade 65-45-12).

[37] D. Tabor: *The Hardness of Metals* (Claredon Press, Oxford, U.K., 1951) p. 174.

[38] Many steel and, to a lesser extent, iron materials exhibit metal flow and elongation when stress is greater than the yield stress. The material retains its ductility and integrity for stress ranges above the yield stress but in a work-hardened state. The mechanics are called elastic-plastic behavior, to distinguish from brittle behavior.

[39] SAE J434, Table A2, “Charpy Un-notched Impact Energy,” for SAE grade D450.

Table M. Typical Mechanical and Fatigue Properties of Ductile Iron (1 MN/m2 = 6.9 ksi)

Classification	Ultimate Strength, ksi	Yield Strength, ksi	Elongation (in 2 in., %)	Hardness (BHN)	Unnotched Fatigue Strength, ksi
60-40-18	60 – 80	40 – 55	18 – 30	149 – 187	28 – 30
80-55-06	80 – 100	55 – 75	6 – 10	179 – 248	38 – 40
100-70-03	100 – 120	70 – 90	3 – 10	217 – 269	43 – 45
120-90-02	120 – 175	90 – 150	2 – 7	240 – 300	48 – 50

2. *Rolled Steel Plates*

The fastener specification for rolled steel plates is ASTM A36/A36M[40] steel as a minimum.

Table N. Chemical Requirements for Fastener Steel Plates[41]

Product	Plates		
Thickness, in. [mm]	To ¾" [20], Incl	Over ¾" to 1 ½" [20 to 40], Incl	Over 1 ½" to 2 ½" [40 to 65], Incl
Carbon, max, %	0.25	0.25	0.26
Manganese, %	...	0.80–1.20	0.80–1.20
Phosphorus, max, %	0.04	0.04	0.04
Sulfur, max, %	0.05	0.05	0.05
Silicon, %	0.40 max	0.40 max	0.15–0.40
Copper, min, % when copper steel is specified	0.20	0.20	0.20

Rolled steel plates are required to have a fracture energy of at least 15 foot-pounds in the notched impact test, ASTM E23.

Table O. Tensile Requirements[42] for Rolled Steel Plates Used in Direct Fixation Fasteners

Tensile strength, ksi [MPa]	58–80 [400–550]
Yield point, min, ksi [MPa]	36 [250] c
Elongation in 8 in. [200 mm], min	% 20
Elongation in 2 in. [50 mm], min	% 23

[40] ASTM A36/A36M-04 Standard Specification for Carbon Structural Steel
[41] ASTM A36/A36M, Table 2.

[42] ASTM A36/A36M, Table 3.

3. *Fatigue in Fastener Plates*

In most metallic alloys, if the load and stress variations are relatively constant, there is a stress range below which fatigue failures will typically not occur; this stress level is called a fatigue limit or endurance limit.

As an example the fatigue curve for ductile iron Grade 65-45-12[43] is shown in Figure 20.

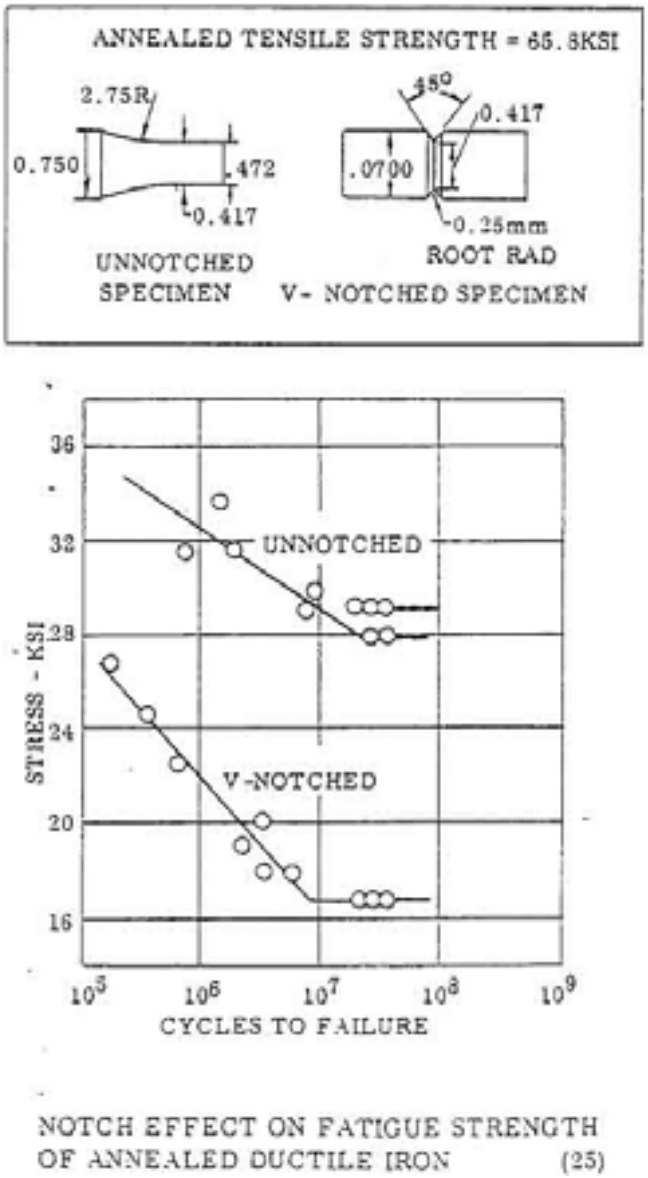


Figure 20. Fatigue Curve for Ductile Iron ASTM-536 Grade 65-45-12

[43] This grade is typically specified for metal plates in Direct Fixation fasteners.

Factors that influence the fatigue behavior of metallic materials are surface roughness, the nature of stress application (fully reversed, or unidirectional), and the environment (corrosion).

The roughness of the surface of a metallic component can have an appreciable effect on its fatigue strength. The fatigue strength of metallic components tends to increase as the roughness of the surface decreases, especially when the direction of final machining or polishing is parallel to the principal applied stress, rather than perpendicular to it.

Figure 21 illustrates plate fatigue limits for various steels and roughness[44].

The results shown in Figure 21 represent a stress condition called fully reversed, in which the maximum and minimum alternating stresses are equal, and the mean of the stress cycle is zero.

The fatigue strength of specimens with more practical engineering surfaces, such as rough-turned machined surfaces or as-forged surfaces tended to be about 35 percent of the material's tensile strength. The fatigue strength of many steels (for fully reversed cycling conditions) is approximately 50 percent of the material's tensile strength when the specimen surface was highly polished.

[44] Houdremont, E. and Mailänder, R., "Bending Fatigue Tests on Steels", Stahl und Eisen, Vol. 49, 1929, pp. 833.

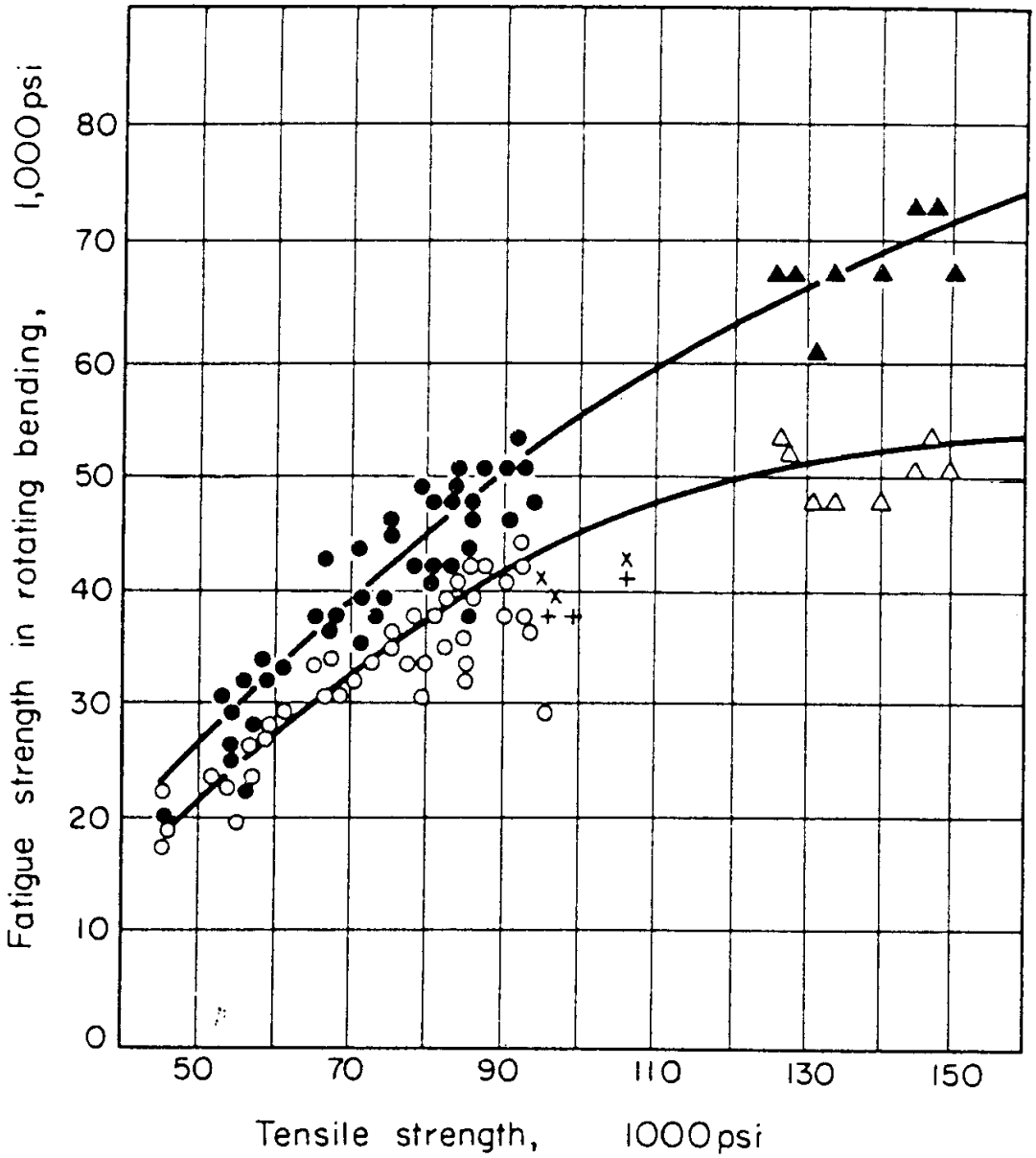


Figure 21. Relation Established by Houdremont and Mailänder [65] Between the Fatigue Limit of Various Steel Alloys and Their Tensile Strength.
(Solid symbols indicate polished specimen surfaces, open symbols, pluses and crosses indicate rough-turned specimen surfaces.)

For non-fully reversed stress cycles, in which the mean stress is greater than zero, as illustrated in Figure 22, modest increases in the estimated fatigue strength can normally be introduced, as follows[45].

$S_f = 1.41\ S_{max}/(1 - R)^{0.5}$, where the stress ratio $R = S_{min}/S_{max}$.

Table P summarizes the approximate impact that stress ratio and mean stress [$S_m = (S_{max} + S_{min})/2$] could be expected to have on a metallic material's fatigue limit[46, 47].

Table P. First Order Approximation of the Effect of Cyclic Stresses at Different Stress Ratios on a Material's Fatigue Limit.

Maximum Stress, ksi	Minimum Stress, ksi	Mean Stress, ksi	Stress Ratio	Fatigue Limit, S_f, ksi
S_{max}	$S_{min} = - S_{max}$	0.0	- 1.0	S_{max}
$1.2 * S_{max}$	$0.6 * S_{min}$	$0.3 * S_{max}$	- 0.5	$1.2 * S_{max}$
$1.4 * S_{max}$	0.0	$0.7 * S_{max}$	0.0	$1.4 * S_{max}$
$2.0 * S_{max}$	$1.0 * S_{max}$	$1.5 * S_{max}$	0.5	$2.0 * S_{max}$
$S_{max} < S_u$	S_{max}	S_{max}	1.0	No fatigue damage predicted

For example, Table P suggests that a loading spectrum that produces a constant amplitude stress cycle with a stress ratio of 0.50 and maximum stress of X at a critical location in a fastener system would be equally as safe (relative to the material's fatigue limit) as another spectrum that produces a fully reversed constant amplitude stress cycle (R = -1.0) with a maximum stress of about 1/2 X.

[45] MIL-HDBK-5, "Metallic Materials and Elements for Aerospace Vehicles and Structures," Revision G, Change Notice 2, pp. 9-83, April 1997.

[46] Walker, E.K., "The Effect of Stress Ratio During Crack Propagation and Fatigue for 2024-T3 and 7075-T6 Aluminum," Effect of Environment and Complex Load History on Fatigue Life, ASTM STP 462, 1970, pp.1-14.

[47] Rice, R.C. and Jaske, C.E., "Consolidated Presentation of Fatigue Data for Design Applications," SAE Paper No. 740277, Society of Automotive Engineers, 1974.

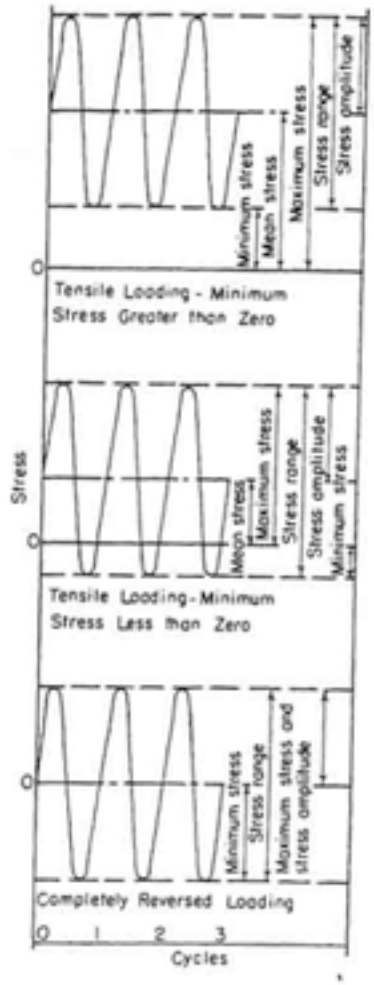


Figure 22. Typical Fatigue Loading

The environment is another potentially important factor that should be considered in establishing long-life stress limits for metallic components. Fatigue life prediction based on modeling of the interaction between environments and materials subjected to cyclic loads is very complex and has been the subject of research for many years. However, as a first approximation, some general guidelines can be discussed.

Figure 23 illustrates percent reduction to the fatigue limit of various metals due to exposure of a component to a corrosive environment prior to fatigue loading.

An active corrosive environment during cyclic loading, such as in service, obviously is a more severe environment than shown in Figure 23, creating corrosion fatigue.

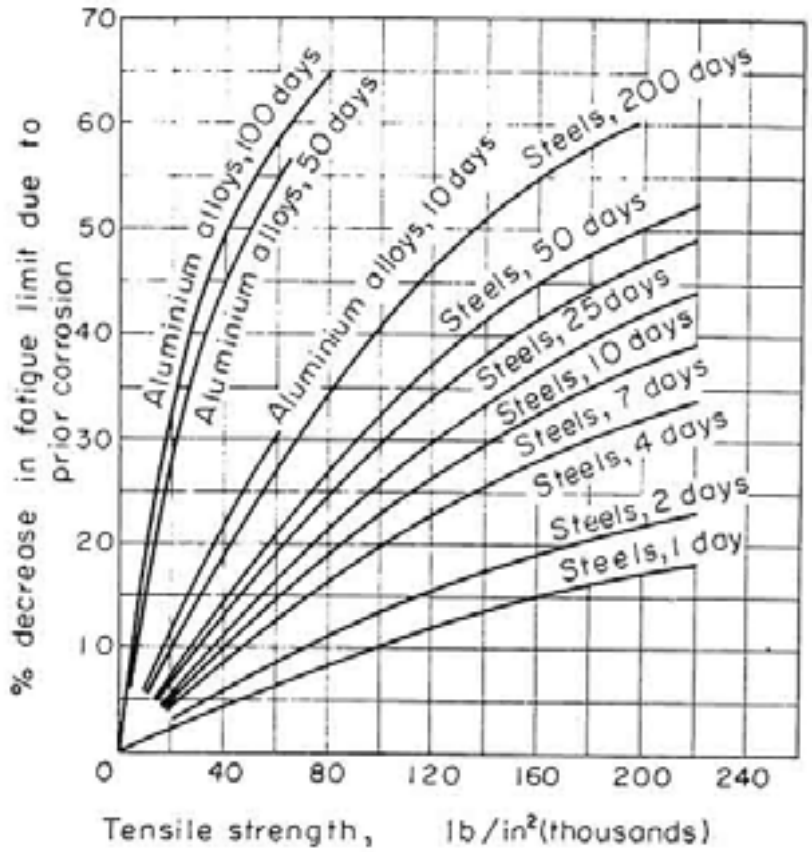
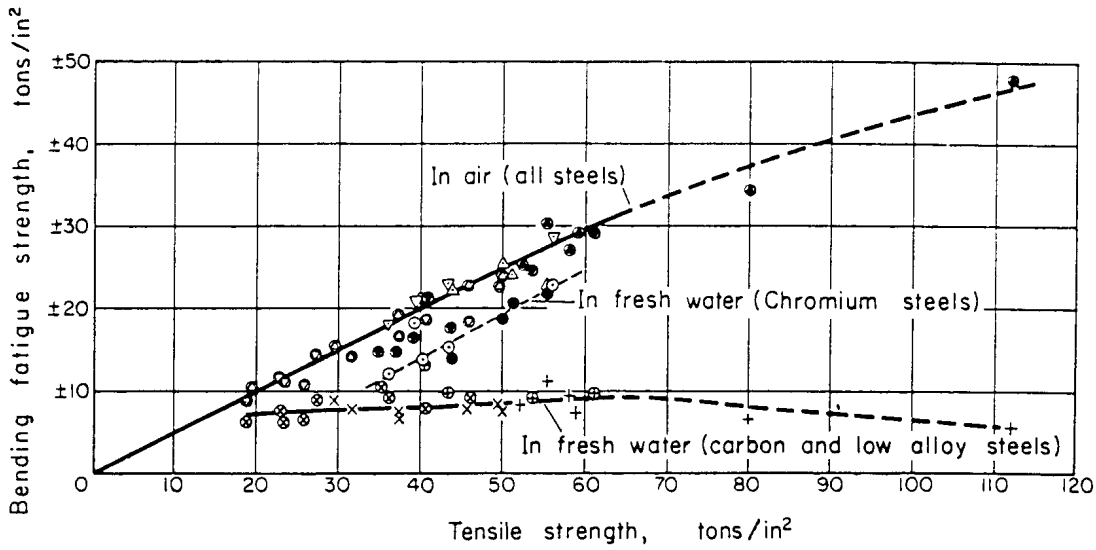


Figure 23. Relation Between Tensile Strength and the Percentage Decrease in Fatigue Limit of Steels and Aluminum Alloys Due to Stress-Less Corrosion

Figure 24 shows the effect of heat-treatment and chemical composition on the corrosion fatigue strength of various steels.



Rotating bending fatigue strength
(20 × 10⁶ *cycles*, 1450 *cycles per min*)

	Heat-treated material tested in air	Annealed material tested in air	Heat-treated material tested in fresh water	Annealed material tested in fresh water
Carbon Steels	⊘	⊘	×	⊗
Low Alloy Steels	◐	◐	+	⊕
Chromium Steels	△	▽	●	⊙

Figure 24. The Influence of Heat-Treatment and Chemical Composition on the Corrosion Fatigue Strength of Steels

The stress limits outlined earlier will serve as useful guidelines for near infinite life design of the metallic components. Clearly, the ultimate choice between one type of fastener system and another may not come down to the one that can reliably withstand the highest stresses or the one with the greatest margin of safety. For example, the choice between a plate fastener and an embedded block fastener system may be based on their relative need for adjustment. Or the choice could be based on the relative comfort level that has been established, based on prior usage in critical applications; prior experience provides the best testimony as to the performance of a product.

VI. FASTENER DESIGN

A Direct Fixation fastener functions as a rail restraint device, as a mechanical filter for impacts and vibrations, and as an insulator. The attractiveness of Direct Fixation fasteners is their compactness. Their challenge is to succeed in all functions within limited geometry under significant loads.

A. General Considerations

Bonded fasteners allow more corrosion protection where all exposed edges are covered with elastomer. The rail-to-support stray current path can be longer with bonded fasteners.

Non-bonded fasteners allow greater opportunity for in-service inspection for wrought or cast iron metallic component degradation (visible physical damage, wear or deformation, corrosion damage, and fatigue cracking) than bonded fasteners that have external surfaces covered by elastomer.

Fasteners with anchor bolts through only the bottom plate avoid arrangement complexities dealing with elastomer compression and anchor bolt insulation.

Bolted rail clips generally require additional maintenance compared to elastic (boltless) rail clips, although there are successful bolted rail clip designs with no more maintenance demand than boltless rail clips.

Bolted rail clips provide higher toe loads than elastic rail clips, with some bolted rail clips producing double the longitudinal restraint of boltless clips.

Embedded block ties may offer construction economies over Direct Fixation fasteners (i.e. plate-type fasteners) in a variety of circumstances. The Resilient Tie designs offer double insulation and a very long stray current path from rail to support.

Rail cant is required. Whether the cant is achieved in the fastener design or by the support is a consideration. Some agencies prefer the support to have the required cant. This allows the fastener to be symmetrical, eliminating the possibility of installing the fastener the wrong way. With most track maintenance performed at night with poor lighting conditions, a non-canted, symmetrical fastener is beneficial.

Designing the track support to have the cant also promotes drainage away from the fastener, important for stray current and corrosion issues.

If the support will be surfaced with the rail cant angle, the expectation should be the angle will be formed with less accuracy. The construction tolerance for rail cant in this case must reasonably reflect concrete working tolerances and the ability to measure cant deviations.

For example, the specification requires the support concrete to be formed with a rail cant of 1:40. The ability to finish concrete to the correct cant is on the order of 1/32", at best, across the fastener bearing surface. The ability to measure cant from a plane across the bottom of both running rail is 0.005", at best[48]. The combination would have the allowable deviation measurement of cant to be ±0.081" which would allow the actual cant to be between 1:25 and 1:100. Cant variation of this magnitude would cause the track gauge to be out of tolerance. In practice, track gauge takes precedence over rail cant, making the issue of rail cant value somewhat moot. If rail cant values become an issue during construction, more cant is better than less cant for most wheel profiles. Rail cant accuracy is a relatively minor issue for agencies with cylindrical wheel profiles.

Direct Fixation fasteners for special trackwork (turnouts, restraining rail configurations, and possibly guard rail and other special track appliances) are best judged by a design that restrains running rail, switch rail, frogs and guarding rail to position as a primary safety criterion. Electrical isolation is the second criterion. Fastener dynamic properties are a distant third criterion because the stiffness that frogs, switches, guard rail and other appliances impart to the track override much if not all mitigation fasteners may provide for impacts and ground-borne vibration.

B. Fastener Mechanical and Electrical Properties

1. Fastener Static Stiffness

Under static loading, elastomers behave much like a spring where the deflected fastener returns to its original shape. The solid acts in accordance with Hooke's Law, $F = kx$, where F is a force that moves the top fastener plate a distance, x, proportional to the fastener's stiffness, k. The top plate returns to its original position when the load is removed.

Inherently, Direct Fixation fasteners have non-linear load-deflection curves. The correct definition of fastener stiffness is the "tangential stiffness" at a stated load. Figure 25 illustrates the definition. Static stiffness is load dependent.

[48] The measurement is the field edge elevation of the rail base from a straight edge held against the gage side bottom of both rail.

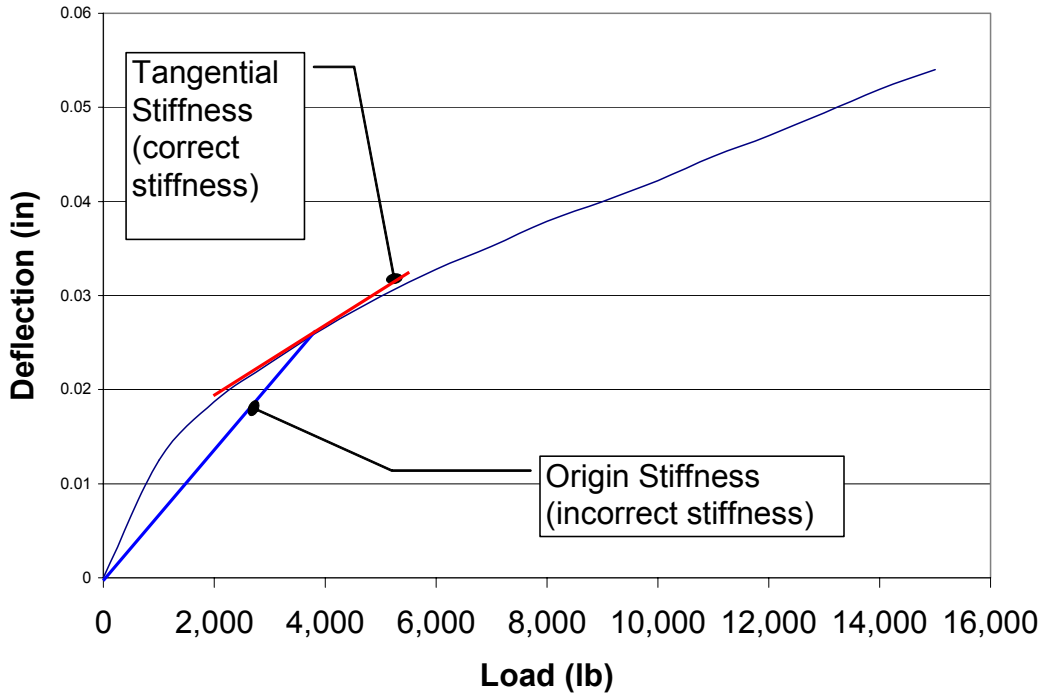


Figure 25. Tangential Stiffness, Correct Direct Fixation Stiffness Definition

Figure 26 is the static load-deflection data for 4 fasteners. Fasteners A and B are the same fastener model. Fasteners F and M are different designs from different manufacturers.

Figure 27 shows the tangential stiffness (the slope of the Load-Deflection curve) at each load for the data in Figure 26, demonstrating how the stiffness increases with load.

Figure 28 views the same information as in Figure 27 but narrowed to the typical transit load range.

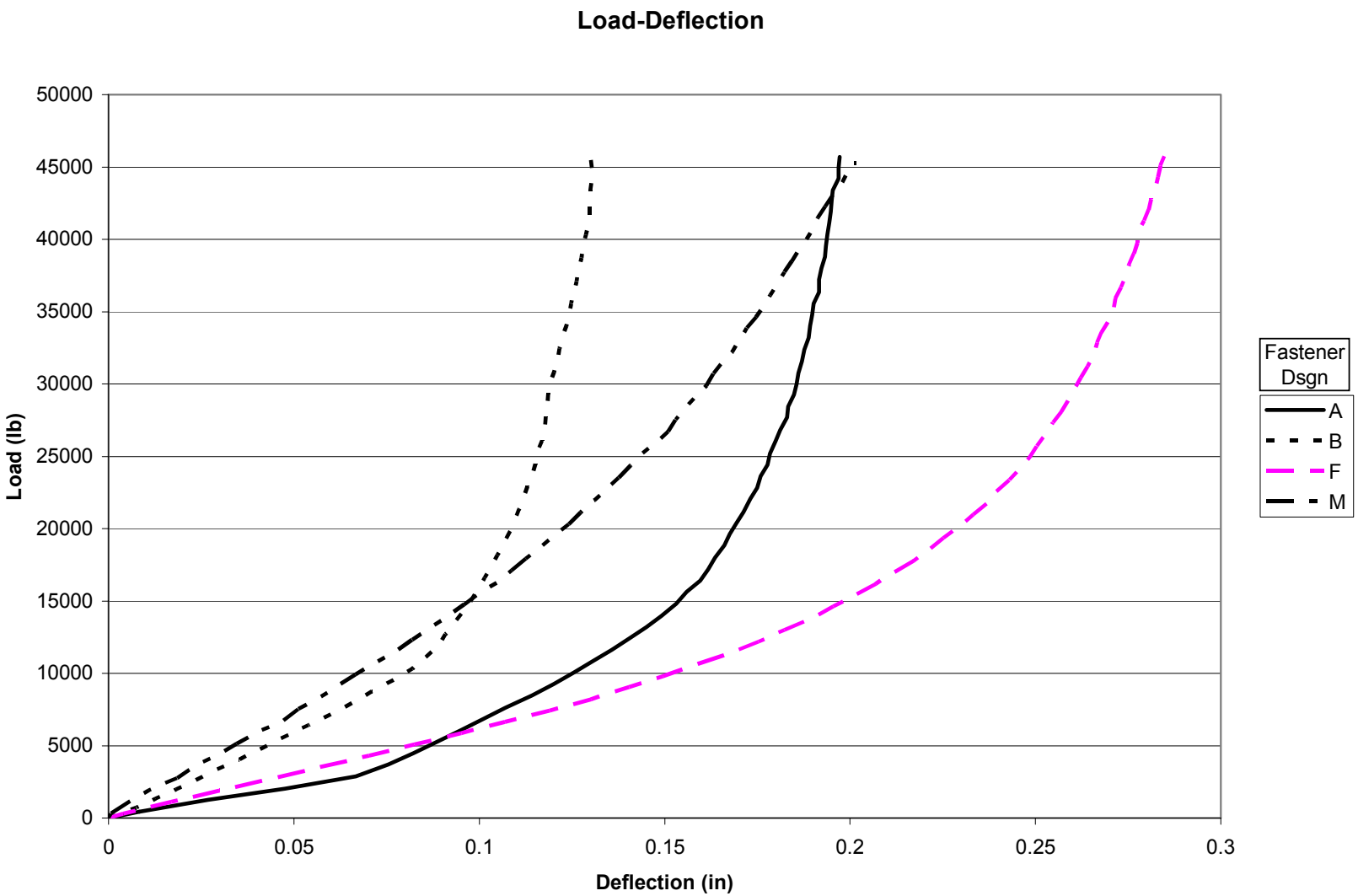


Figure 26. Load Deflection Data

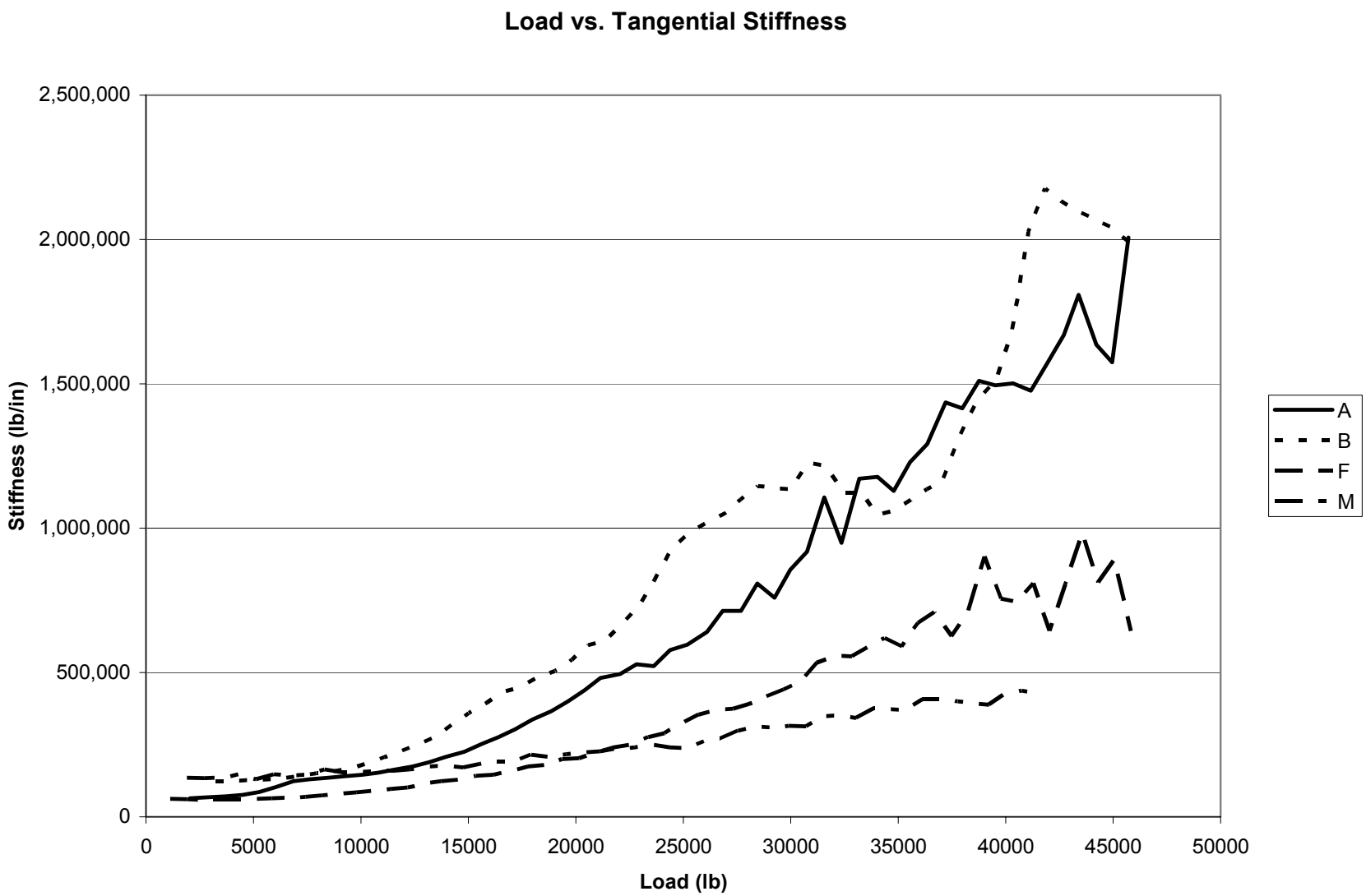


Figure 27. Fastener Tangential Stiffness versus Load

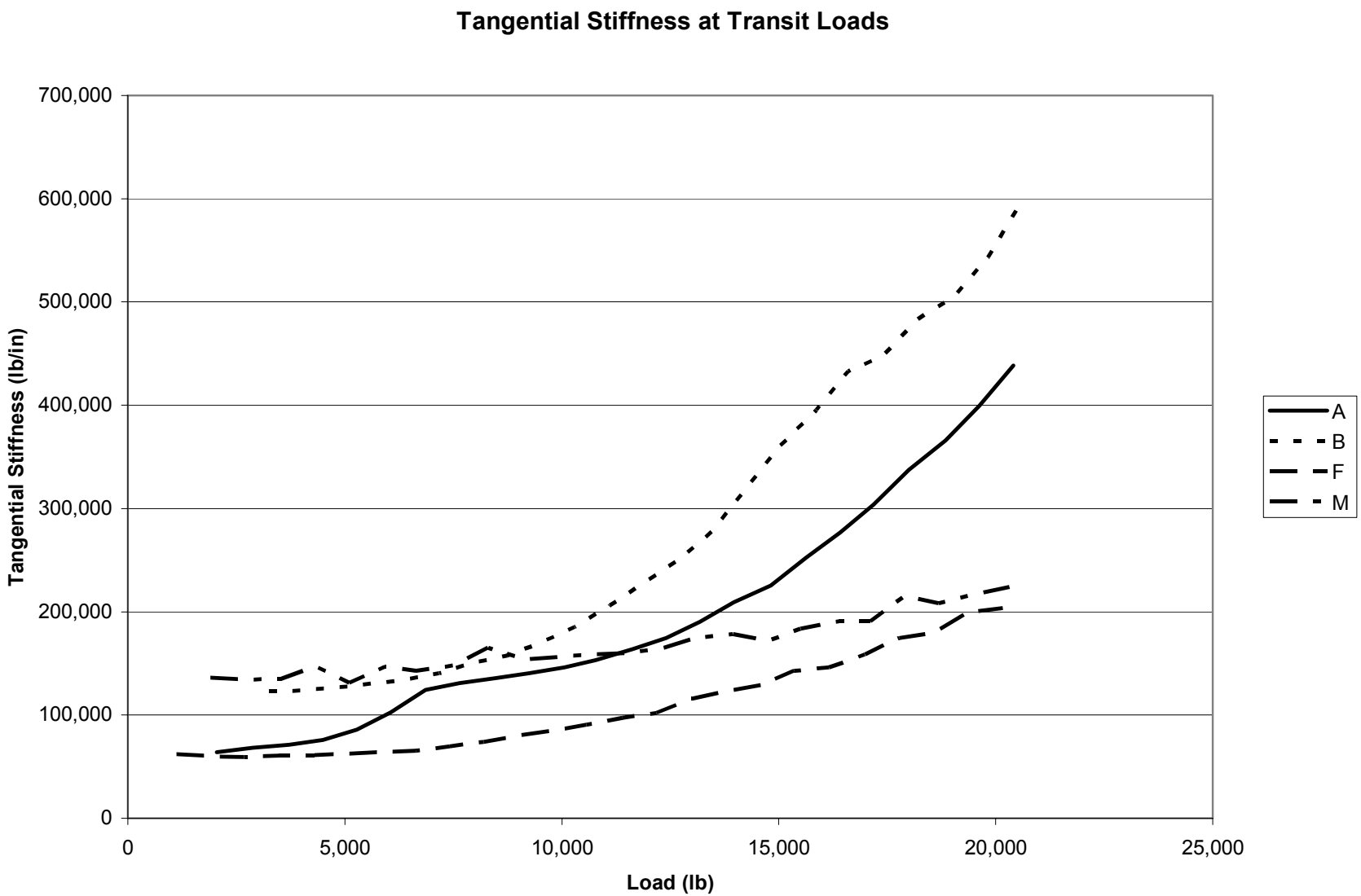


Figure 28. Fastener Stiffness Increase with Load at Transit Load Levels

2. *Fastener Dynamic Characteristics*[49, 50, 51]

It is important to understand a fastener's dynamic response because that is the response that will be exhibited in track. The fastener is a component of a dynamic system composed of the fastener, a portion of the rail, and a wheel and half an axle (when present).

Fastener dynamic characteristics are its dynamic stiffness, damping coefficient, critical damping coefficient, resonance frequency and loss factor. These characteristics interact with the inertial mass of wheel, half axle, and rail to define the system's resonant frequency.

The response of elastomers under time-varying loads (dynamic loads) is neither as an ideal Hookean elastic solid nor as an ideal liquid (dependent on time and rate of loading, has no memory, and does not recover when a deforming force is removed), but rather something in between termed viscoelastic behavior.

Viscoelastic behavior can be modeled as a spring-damper system (Figure 53, page 132). The derivation of relationships for the fastener dynamic response is in Attachment 1E.

The spring-damper model is useful within its limitations. The model's limitations are that it represents a single fastener only and it ignores dynamic interactions with the vehicle (including only the unsprung mass of a wheel and portion of an axle). These limitations do not invalidate the results if BOEF models are employed for multiple fastener response using characteristics from these tests, and the vehicle motions are near a steady state behavior, which is useful over a very broad range of applications.

a) Phase Shift: Measuring Dynamic Stiffness and Damping

Dynamic characteristics (dynamic stiffness, damping) are determined from the measured phase shift of the deflections from an oscillating load. In any dynamic system other than a pure spring, the deflections of the system will occur after the load is applied. The delay between load

---

[49] A.N. Kent, W.W. Scott, *Engineering with Rubber*, Hanser Publications, copyright Carl Hanser Verlag 1992, Ed. Alan N. Gent, pp. 77 – 79.

[50] *Standard Guide for Dynamic Testing of Vulcanized Rubber and Rubber-Like Materials Using Vibratory Methods*, American Society for Testing and Materials (ASTM) D 5992 – 96 (Reapproved 2001).

[51] *The Measurement of the Dynamic Properties of Elastomers and Elastomeric Mounts*, Society of Automotive Engineers, Inc, copyright 1973 by the Society of Automotive Engineers.

application and deflection response is called the "phase shift". The phase shift is illustrated in Figure 29 from a dynamic test of Fastener F.

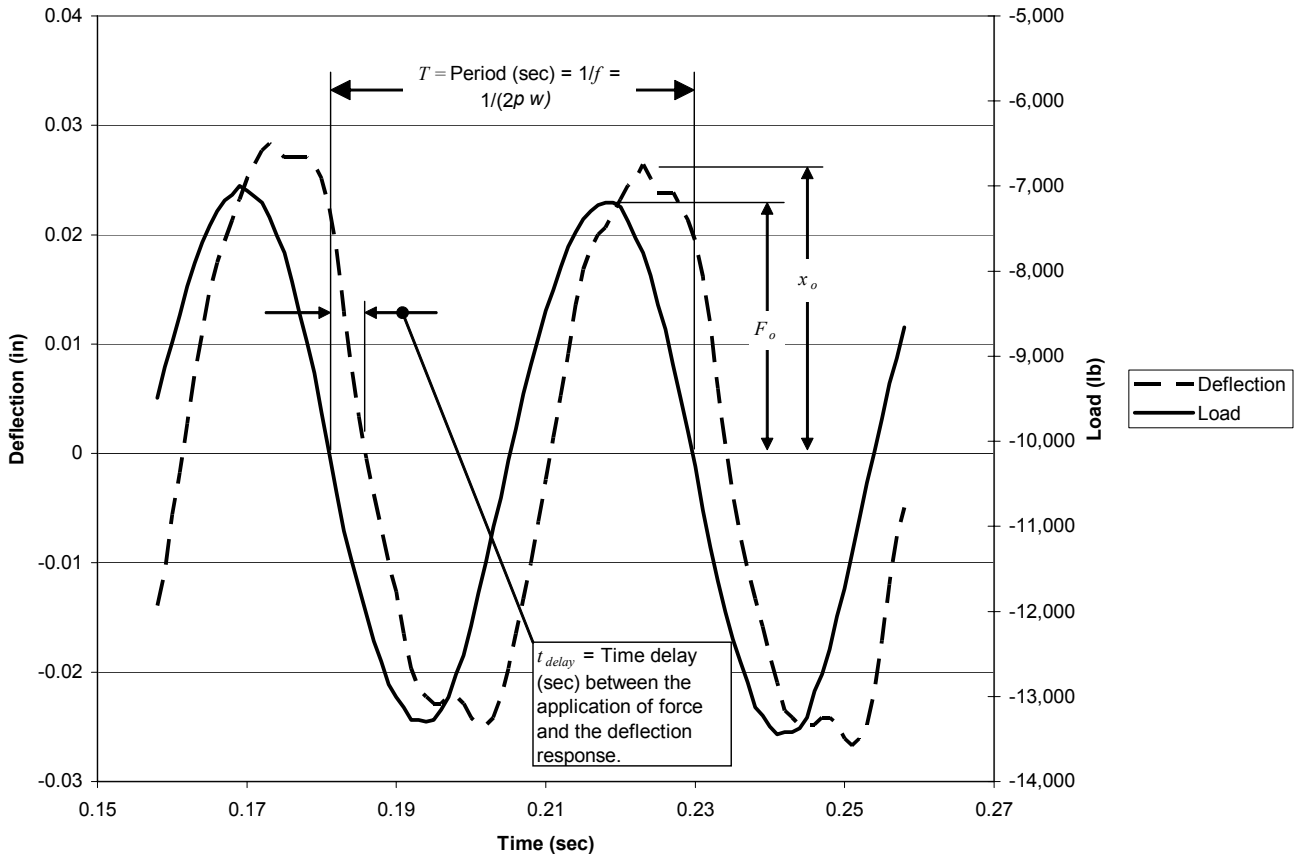


Figure 29. Phase Shift Measurement (Fastener F using 10,000 lb preload, 3,000 lb amplitude oscillating load applied at 20 Hz)

(21) $$Tan\,\psi = \frac{T}{t_{delay}}$$

where ψ = Phase shift angle (radians)
T = Period (sec)
t_{delay} = Time delay (sec)

The relationships between the phase shift angle and dynamic stiffness, damping coefficient and critical damping are presented in Attachment 1E. Again, these calculations use the system mass, meaning fastener stiffness and damping coefficient are dependent on mass.

b) Dynamic Stiffness

An oscillating load will produce less deflection because of damping, compared to the same load applied quasi-statically. The fastener stiffness

under dynamic loading is therefore greater than the stiffness under static loading.

Dynamic stiffness is dependent on the load, and the load's oscillating frequency.

The dynamic stiffness characteristic is illustrated for three of the four foregoing fasteners in Figure 30.

Measurements[52] were performed on 16 fasteners of 7 different fastener designs. For each fastener, separate measurement runs were made for pre-loads of 10,000 lb, 20,000 lb and 30,000 lb. For each load, separate measurement runs were made at the frequencies of 1 Hz, 5 Hz, 10 Hz and 20 Hz.

The following only presents results from the 10,000 lb pre-load measurements because that is the most appropriate data set for transit applications. The results are for the test mass (piece of rail and fastener top plate).

Figure 30 shows dynamic stiffness variation with test frequency for fastener B, as expected. The other fastener designs have less frequency dependence.

Fastener F is clearly dynamically softer than the other fastener designs.

[52] *Performance of Direct Fixation Track Structure, Final Report*, James Tuten III, Principle Researcher, Battelle, April 1999, under TCRP funding.

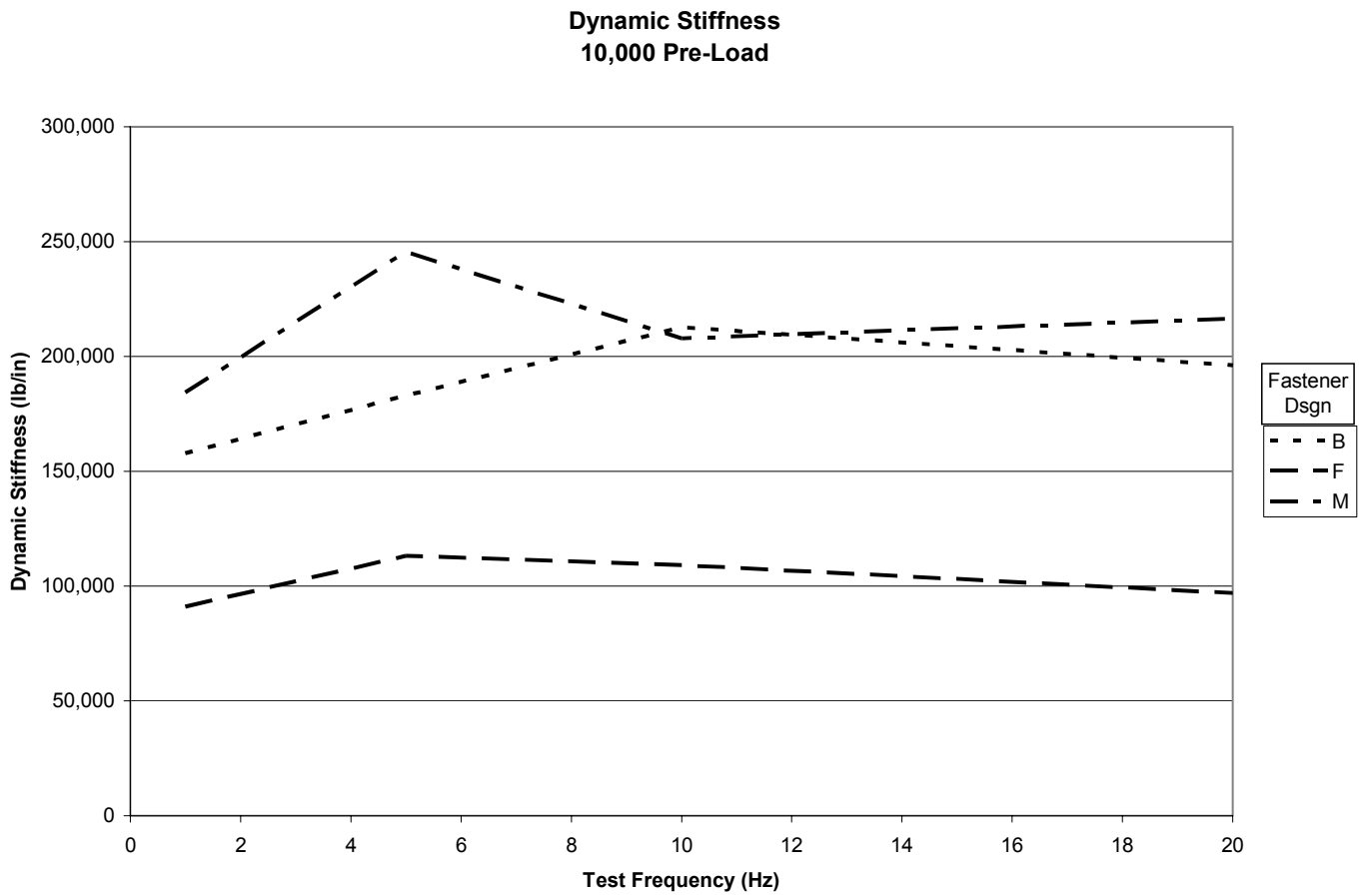


Figure 30. Dynamic Stiffness Results at 10,000 lb Preload (mass = rail + fastener top plate)

The dynamic stiffness values are somewhat higher than the static stiffness values shown in Figure 28 (at the 10,000 pound load level), typical of all fasteners.

c) Damping

Damping in fasteners is treated as if the elastomer material is viscous, like oil, for engineering purposes. While elastomers are far from oil or other fluid, "the … response in rubbery solids is internal viscosity between molecular chains."[53] That is, molecular chains slip relative to one another during loading.

A viscous fluid dissipates energy of motion through a different molecular process than an elastomer, but the effects are similar enough to be useful.

[53] Gent, p. 85.

In elastomers, the elapsed time under load determines how much inter-molecular slippage occurs. A slowly oscillating load will produce more molecular slippage than a rapidly oscillating load. This means that higher viscosity, or damping, will occur at the lowest frequencies. The damping coefficient is therefore dependant on load oscillation frequency.

Damping test results for the fasteners are shown in Figure 31 through Figure 33 for the damping coefficient, critical damping and the damping ratio. The mass in these plots is the test mass (the test rail and the fastener top plate).

Critical damping is the value at which vibration behavior ceases. The damping ratio is the damping coefficient divided by the critical damping coefficient.

The damping coefficient Figure 31 is much higher at low frequencies, as expected.

The fasteners with higher dynamic stiffness (fasteners B and M) generally have higher damping coefficients at most test frequencies.

These results are affected by temperature. The test data did not include temperature variations, so there is no supporting illustration. The importance of temperature is noted because the fastener characteristics may be sufficiently different at different times of the year to affect wheel-rail interaction or other mechanics that seemingly have no explanation. While the effects of temperature on the basic characteristics are known, quantification of the in-service effects requires research.

For example, elastomers will have a much higher stiffness at cold temperatures which may encourage rail corrugation mechanics. Ground vibrations may be more noticeable at low temperatures from higher fastener stiffness.

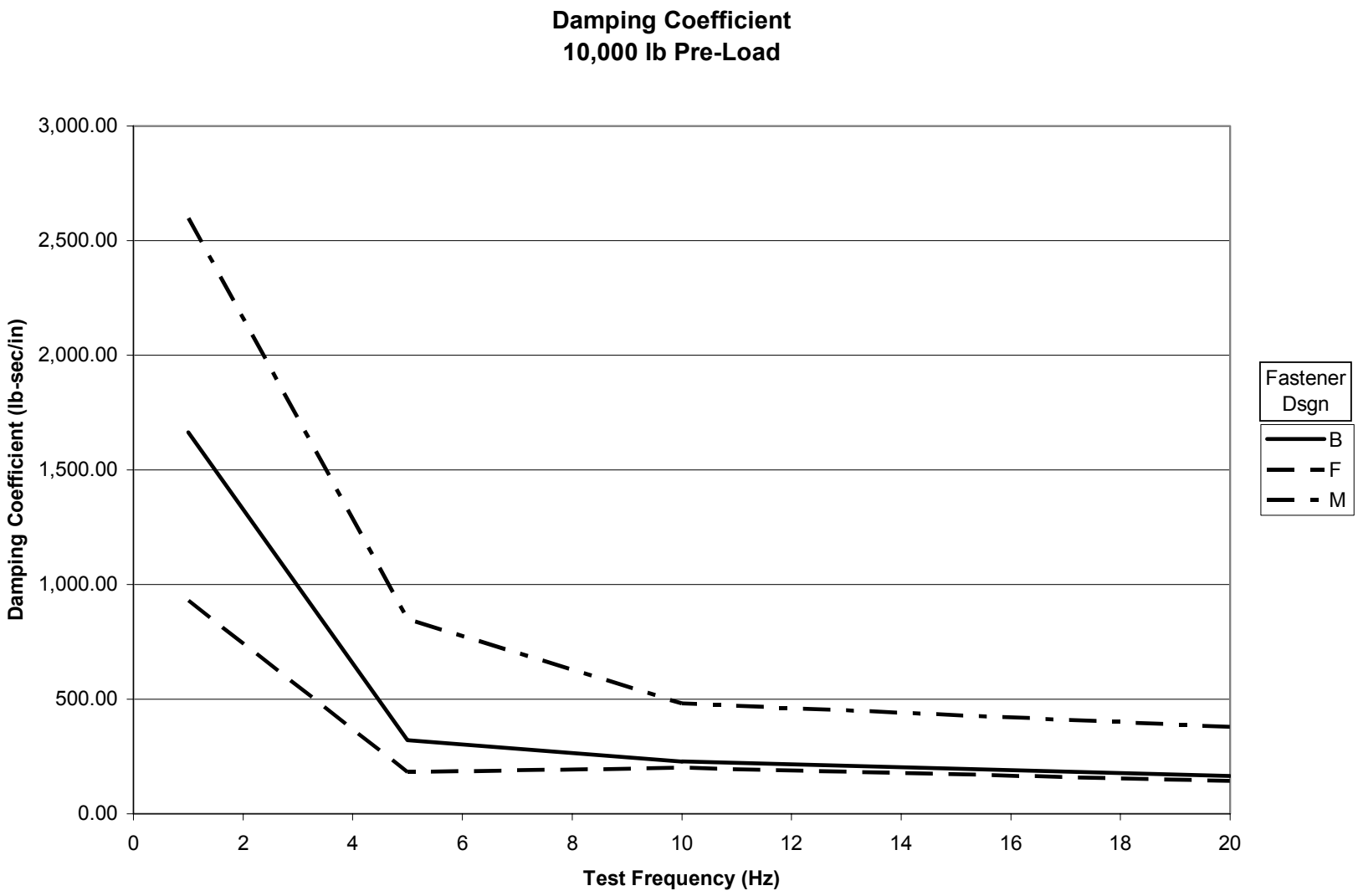


Figure 31. Damping Coefficient vs. Applied Frequency at a 10,000 lb Preload

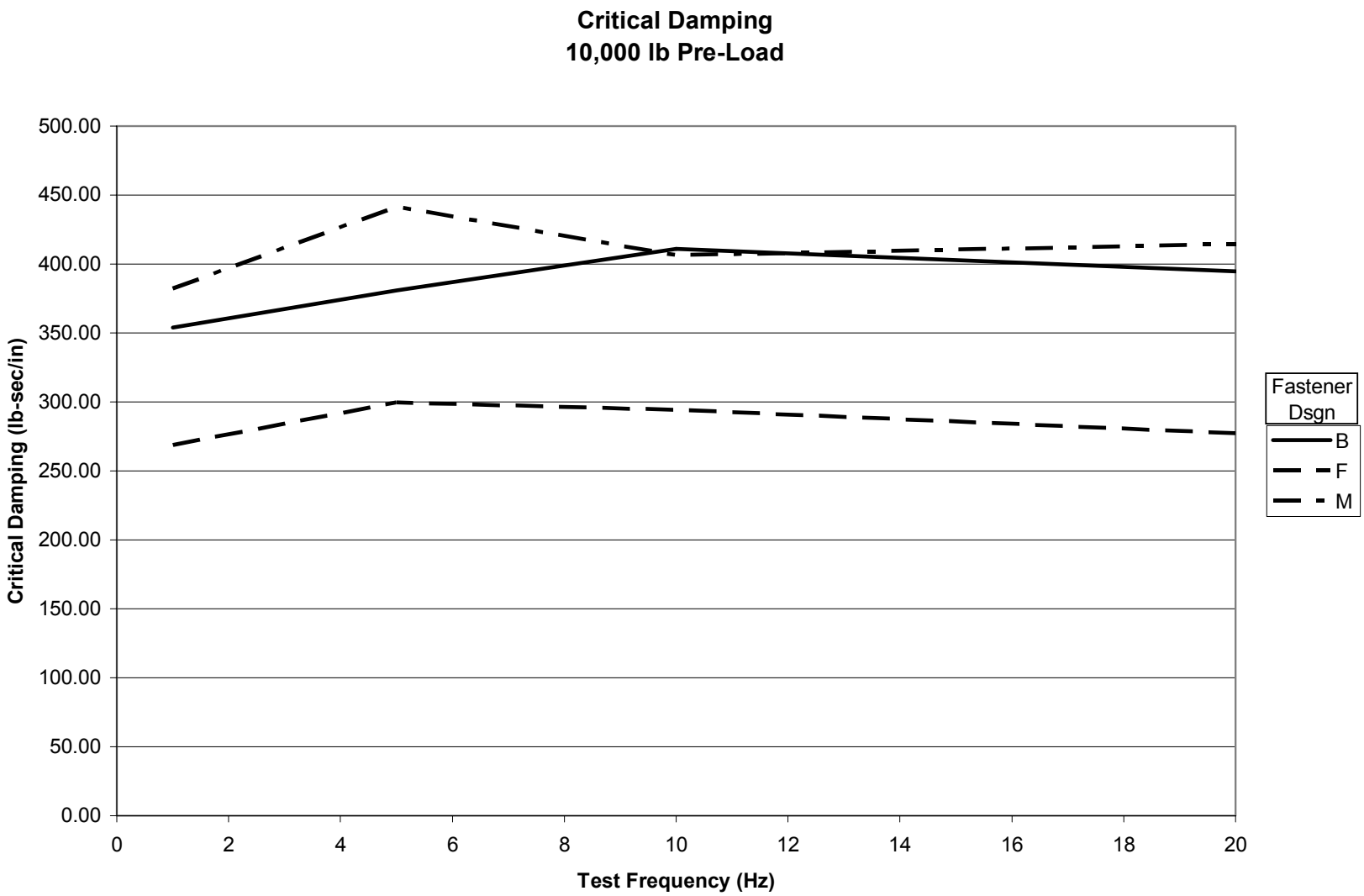


Figure 32. Critical Damping Values vs. Frequency at a 10,000 lb Preload

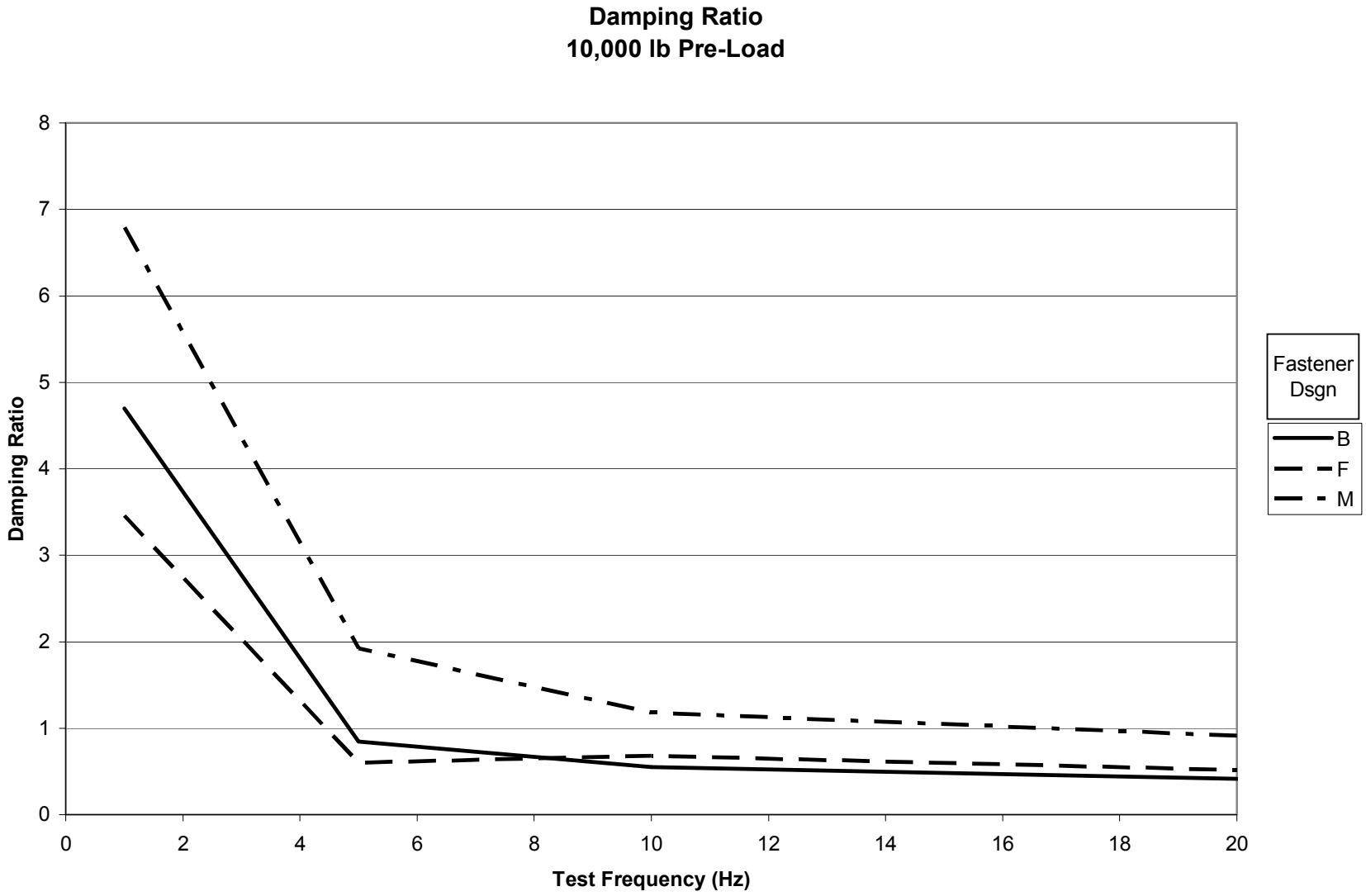


Figure 33. Damping Ratio vs. Frequency at a 10,000 lb Preload

d) Resonance Frequencies

The resonance frequencies of a fastener system are the key characteristic of interest for vibration issues. A fastener will filter vibration frequencies higher than the resonance frequency and will not filter frequencies below the resonance frequency. The fastener system may amplify vibrations that are very near the resonance frequency, depending on damping ratio[54].

The system resonant frequency is affected by effective mass[55] on the fastener. That means the resonance frequency will change as a wheel approaches and departs a fastener. The interest is in two conditions: (1) with no wheel present and (2) with a wheel directly over a fastener. The fastener system resonant response will be between these two conditions.

Figure 34 shows the resonance frequencies with no wheel present, including only the rail weight on the fastener, about 80 pounds for 115 RE rail and fasteners spaced at 24 inches. This condition produces the highest system resonance frequencies

[54] The vibrations amplification will increase as the damping ratio decreases below a ratio of 1. For example, there will be very little amplification if the damping ratio is 0.7. There will be significant amplification if the damping ratio is 0.1.

[55] "Effective mass" is the mass of weights that are supported by the fastener and are free to move. If no vehicle is present, the mass is that of a portion of rail supported by the fastener (some include the fastener top plate). When a wheel is directly over a fastener, effective mass is the rail, the supported weight of a wheel and half of an axle, called the "unsprung mass" of the vehicle. These are the only masses that can be affected by the fastener's dynamic response. The rest of the vehicle is above its suspension, isolating those weights from dynamic interaction with the fastener. Note that the weights of the wheel and axle are the only weights for mass consideration. The load on the wheel from the vehicle is not included, because that load has no effect on vibrations.

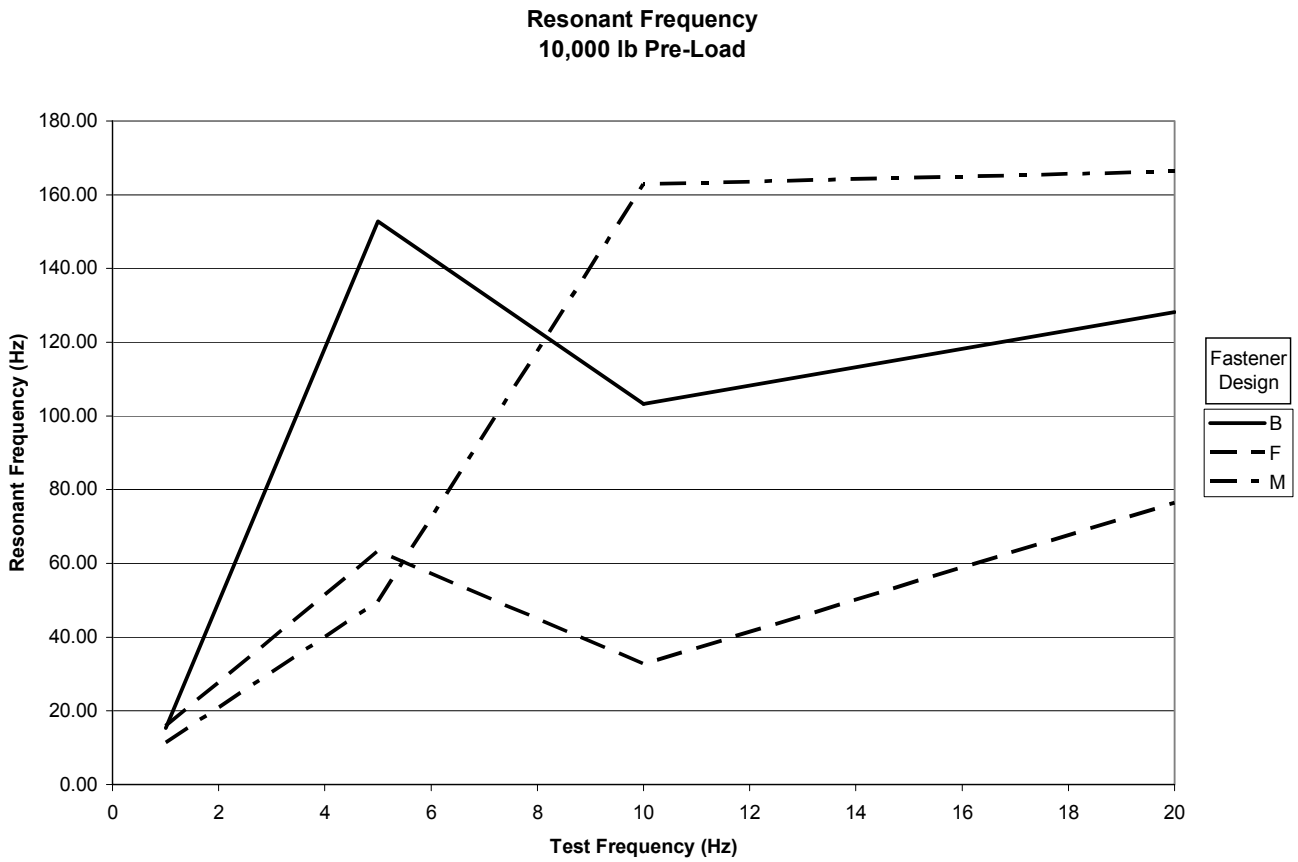


Figure 34. Resonant Frequency vs. Test Frequency Without a Wheel Load (rail mass only)

Figure 35 shows the resonant frequency under a wheel load, which is about 500 pounds including a typical transit wheel, half an axle and the rail supported by the fastener[56]. This condition produces the lowest resonant frequencies.

[56] The wheel and axle weight included in the values is actually the distributed weight because several fasteners will share the load.

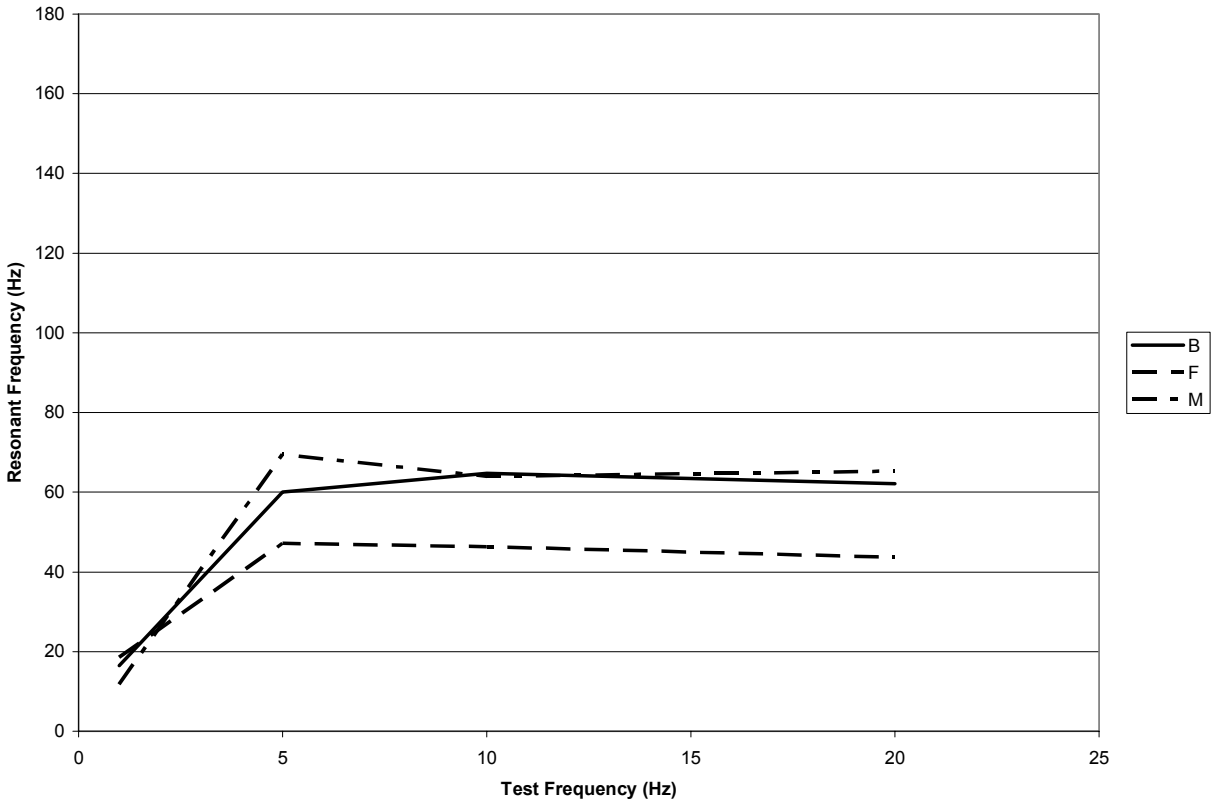


Figure 35. Resonant Frequency Expected Under Service Conditions (wheel, half axle and rail mass)

The relationship for the resonance frequency is different depending on whether the damping ratio is much less than 1, near 1, or much greater than 1. Please see Attachment 1E for the relationships. Please see Section 3, Direct Fixation Fastener Example Qualification and Production Test Specification and Commentary, paragraph 4.03.N for test procedures and application notes.

e) Loss Factor

The loss factor measures the elastomer material's irreversible energy dissipation from mechanical hysteresis. A high loss factor means the elastomer material will absorb energy in the form of increased internal elastomer temperature or permanent deformation. This energy is irreversible (lost) energy. A low loss factor means the elastomer material behaves more like a spring which stores energy and then releases it when the load is removed by restoring the fastener to its original shape. Stored energy is reversible.

The loss factor is independent of mass, where the dynamic stiffness, damping coefficient and critical damping coefficient include the system mass. It is useful to know the effect of these parameters without the influence of mass. The loss factor is therefore a direct measure of the elastomer dynamic characteristic without system mass influence.

Comparing loss tangent to phase shift, the phase shift is given by equation (47) and the loss tangent is given by equation (56), both repeated here:

Phase shift, ψ: $$\tan\psi = \frac{c\omega}{k - m\omega^2}$$

Loss Tangent: $$\tan\delta = \frac{\omega c}{k}$$

where

ψ	=	phase shift angle, radians
c	=	damping coefficient, lb-sec/in
ω	=	oscillating force frequency, radians per second
k	=	dynamic stiffness, lb/in
m	=	system mass, lb-sec^2/in
δ	=	angle of the loss tangent, radians.

At low frequencies and where the dynamic stiffness, k, is much greater than $m\omega^2$, the loss factor (loss tangent) is equivalent to the tangent of the phase shift angle. At high frequencies, the mass term becomes dominant in the phase shift and damping has more influence on the loss tangent.

For low values of phase shift angle, the angle and tangent of the angle are numerically the same. These equivalencies apply to this data.

Figure 36 presents the phase shift angle, equivalent to the loss tangent for this data, for the different fasteners for different frequencies.

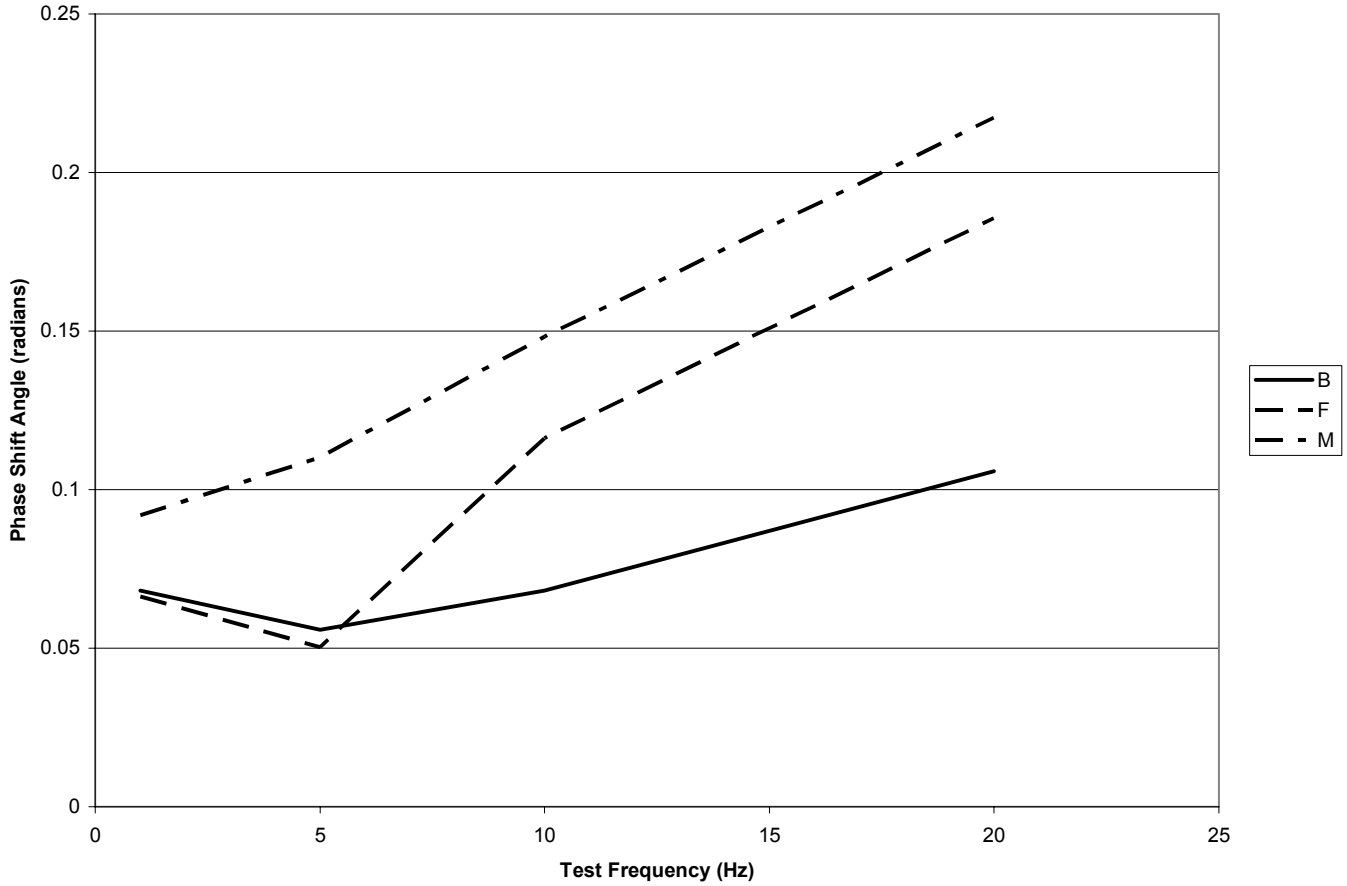


Figure 36. Loss Factor (Phase Shift Angle for this data) with Frequency

f) Dynamic to Static Stiffness Ratio

The Dynamic to Static Stiffness Ratio is the test currently used in specifications to indicate fastener dynamic response. The ratio is, as the name indicates, the dynamic stiffness divided by the static stiffness. The dynamic test procedure for the Dynamic to Static Stiffness Ratio is identical to the tests portrayed in this section, except the tests Dynamic to Static Stiffness Ratio tests are performed only at one test frequency, with less test data analysis.

The specification for the Dynamic to Static Stiffness Ratio test sets an allowable upper limit for the ratio.

Table Q
Dynamic to Static Ratio Test Results

Frequency (Hz)	Fastener Design		
	B	F	M
1	1.08	1.30	1.12
5	1.26	1.53	1.60
10	1.46	1.48	1.36
20	1.27	1.33	1.42

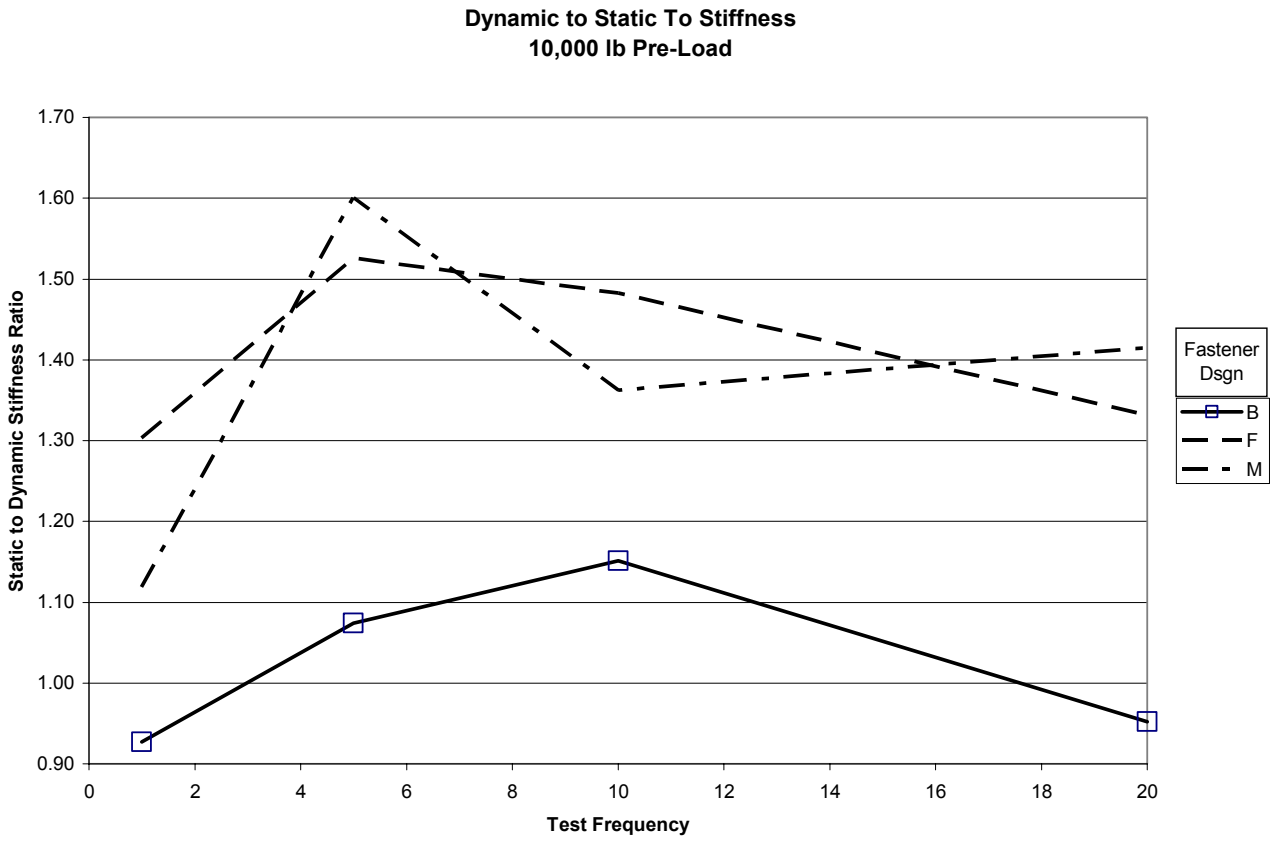


Figure 37. Dynamic to Static to Stiffness Ratio Results

The static stiffness used in Figure 37 is from Figure 27 at the test pre-load value.

Figure 37 shows that the dynamically softer fastener F has a dynamic to static stiffness ratio that is much higher than the stiffer fastener B.

The Dynamic to Static Stiffness Ratio is an indirect measure of the energy losses (damping) inherent in the fastener and an indication of how close a fastener design acts like a pure spring (which will always have a ratio of one). Direct Fixation fasteners are spring-like, but are very different in their mechanical behavior and must be treated differently. Fastener designs should not be judged by Dynamic to Static stiffness ratios.

The current practice is to test the fastener at one frequency. As seen in the foregoing results, the fastener characteristics will vary with the test frequency. A fastener should be tested over a range of frequencies and, preferably, loads that are expected in revenue service to provide insight on expected fastener performance.

The Dynamic to Static Stiffness Ratio test does not produce the damping values that can be important to determining the fastener system's resonance frequency, a very useful engineering value for design and evaluations.

The example specifications (Section 3) replace the Dynamic to Static Stiffness test with a Dynamic Characterization Test.

3. *Fastener Electrical Properties*

a) Stray Current Resistance[57]

For systems with DC traction power, the fastener serves as an insulator for rail current leakage to ground, causing corrosion in the transit's facilities and nearby metal objects, such as structural steel, rebar and pipelines.

A model for estimating the leakage of traction return current to earth through rail fasteners is shown in Figure 38.

The relationship for rail to ground resistance from that model is:

(22) $$R_L = \frac{R_F s}{L}$$

where

R_L	=	Leakage resistance (ohms per standard track length)
R_F	=	Fastener resistance (ohms)
s	=	Fastener Spacing (ft)

[57] *Joint Trackwork Electrical Design Guidelines*, R. Clemons, Chairman, Task Force on Joint Trackwork-Electrical Guidelines, American Public Transit Association, September 1980.

L	=	Standard track length (ft) = 1,000 feet
r	=	Rail resistance per unit length (ohms)
R_F	>>	r

Note the model assumes that the fastener resistance, R_F, is much greater than the rail resistance, r.

Double track will produce half the resistance of a single track; three parallel tracks will produce one-third, and so on.

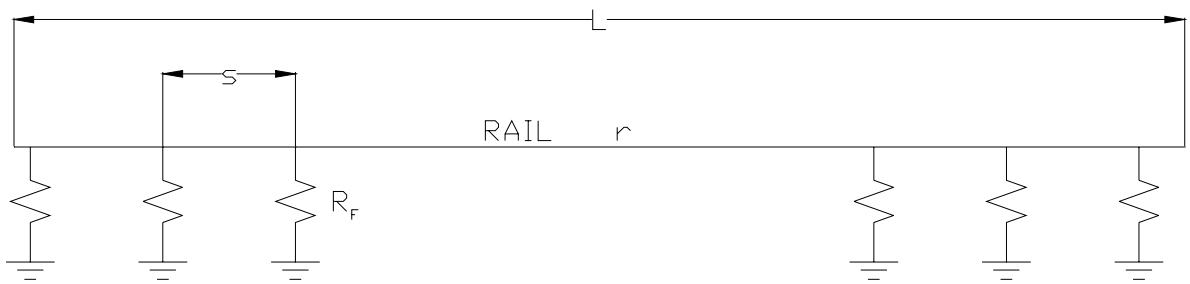


Figure 38. Traction Power Stray Current Model

The current leakage to ground is given by:

(23) $$I = \frac{V_{DC}}{R_L}$$

where

I	=	leakage current (amps)
V_{DC}	=	Traction power voltage (VDC)

The leakage and criteria for acceptable leakage from one specification are shown in Figure 38 over a range of fastener resistance values. The leakage from a dry fastener is well under the cited criteria, and leakage for a wet fastener is under the short term criteria. However, double track fails the short term criteria, for the assumed voltages and fastener spacing.

The leakage current will be closer to the wet condition if dirt and debris are allowed to accumulate around a fastener. Direct Fixation track benefits from periodic washing to minimize current leakage and corrosion. Like all other track types, proper drainage is imperative, but a purpose for Direct Fixation is to minimize corrosion from current leakage.

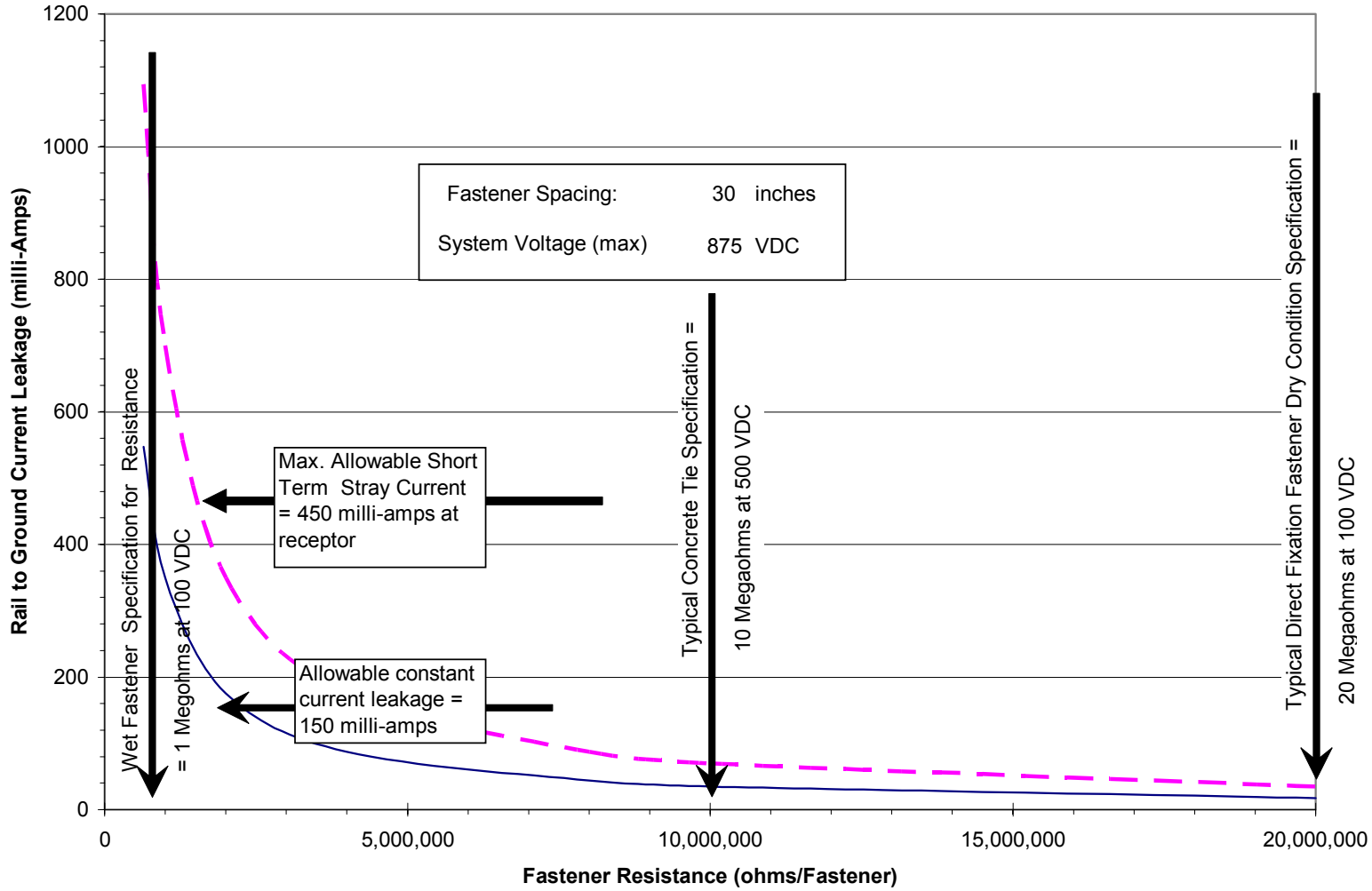


Figure 39. Current Leakage through Fastener
(allowable current leakage values in this plot are Santa Clara Valley Transportation Authority design criteria)

b) Impedance

Impedance is the resistance to AC current. The fastener impedance is important to allow track circuits to function properly. For this purpose, the impedance is measured between the running rails.

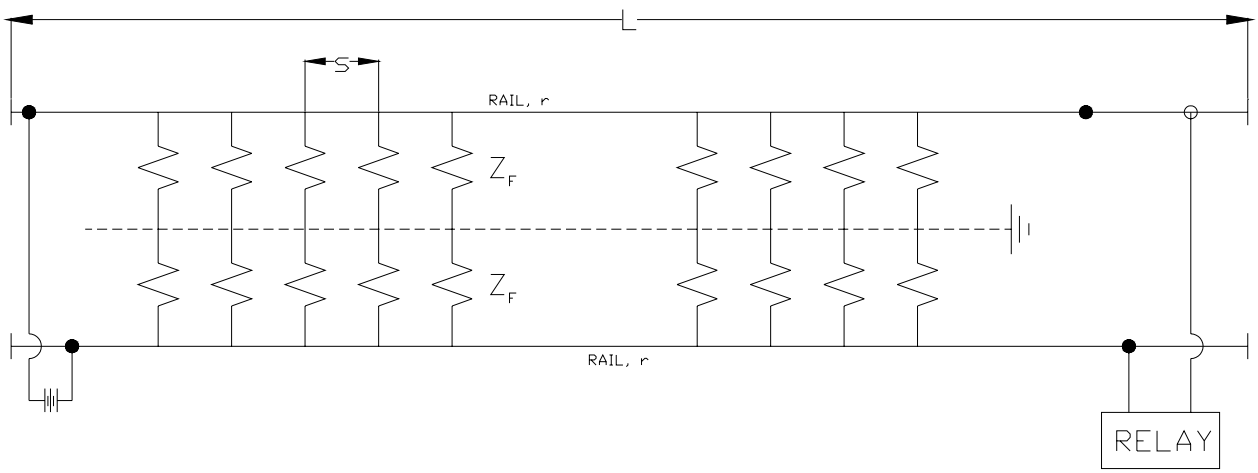


Figure 40. Model of AC Current Model

The schematic in Figure 40 represents rail-to-rail AC impedance model.

The relationship for the resistance between rails is:

(24) $$R_b = \frac{2Z_F s}{L}$$

where

R_b	=	Rail to Rail resistance (ohms) = "ballast resistance"
Z_F	=	Fastener impedance (ohms)
s	=	Fastener spacing (feet)
L	=	Standard Length (feet) = 1,000 feet

The rail to rail resistance is called the ballast resistance. The AAR Signal Manual states that the ballast resistance should preferably be not less than 2 ohms per 1,000 feet. Accepted practice is to use a higher value of 5 ohms per 1,000 feet for new construction.

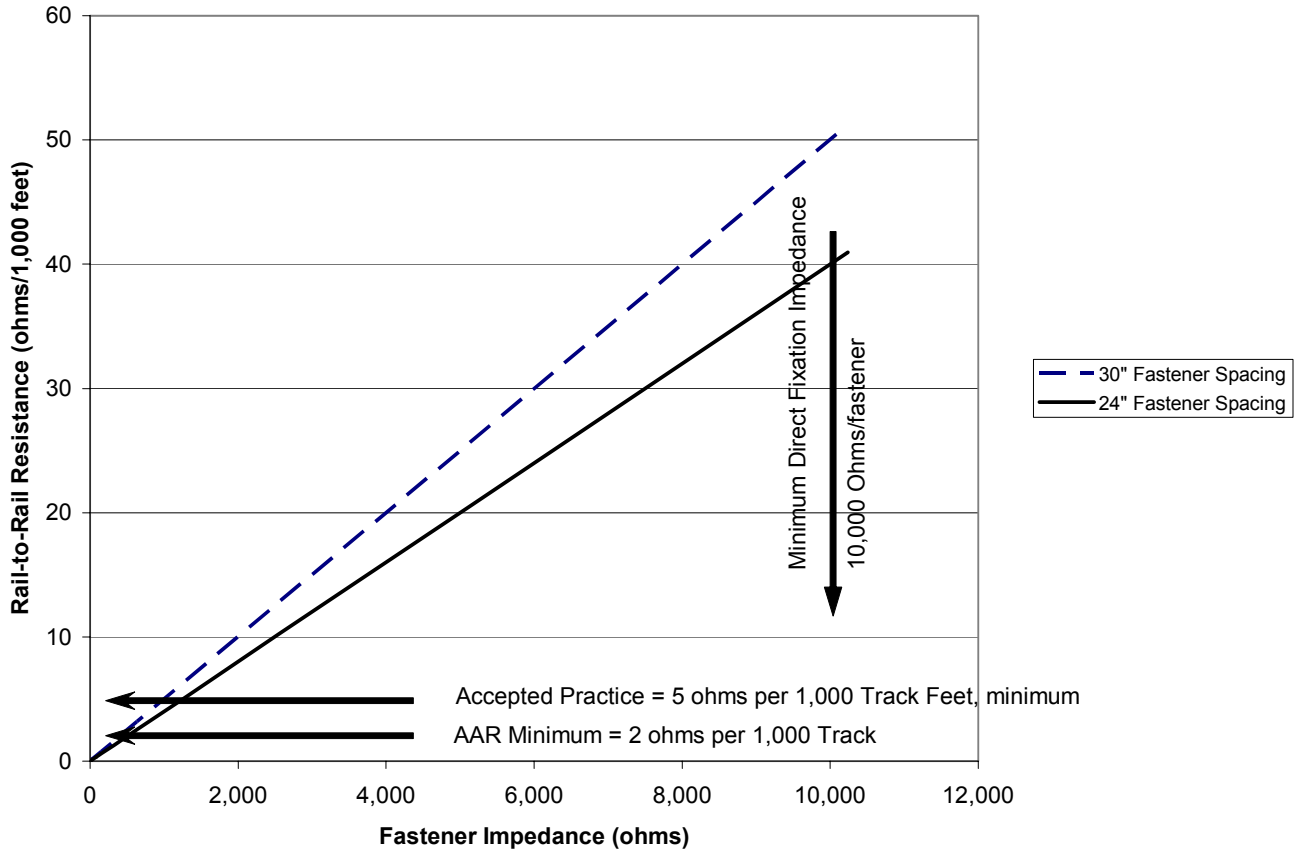


Figure 41. Fastener Impedance and Rail to Rail Resistance

Although the schematic and calculation is based on a DC circuit, the approach is generally considered applicable for AC impedance as well as DC resistance. A substantial safety factor must be applied to the minimum resistance of a new fastener to allow for service conditions (wetting, contamination, etc.).

C. Lateral Fastener Stiffness and Gage Retention

A vertically softer fastener will be laterally softer also, meaning rail lateral deflection and rotation will be greater than that of a stiffer fastener.

Figure 42 illustrates measured Direct Fixation lateral load-deflection for different vertical loads. The larger deflections with no vertical load reflect the reduction in lateral fastener stiffness with reduction in vertical stiffness (remembering that it is load dependant for static tests). This (no vertical load) condition exists with every wheel pass in the vertical precession wave. At that point, there is sufficient lateral force to generate gage widening.

The design procedure assesses lateral rail deflection and roll for proposed fastener stiffness values. The process calculates the vertical and lateral deflection waves.

The Direct Fixation specification for vertical and lateral deflections must reflect lateral rail head deflections for the test loads and the anticipated vertical and lateral fastener stiffness values. For example, a vertically stiff fastener will be tested to the same vertical and lateral loads as a vertically softer fastener, but the allowable deflections, particularly the lateral and rotational deflections, for each fastener must have different specified limits. If there are a softer and stiffer fastener in the same procurement, it is strongly recommended that there is a separate specification for the two fasteners.

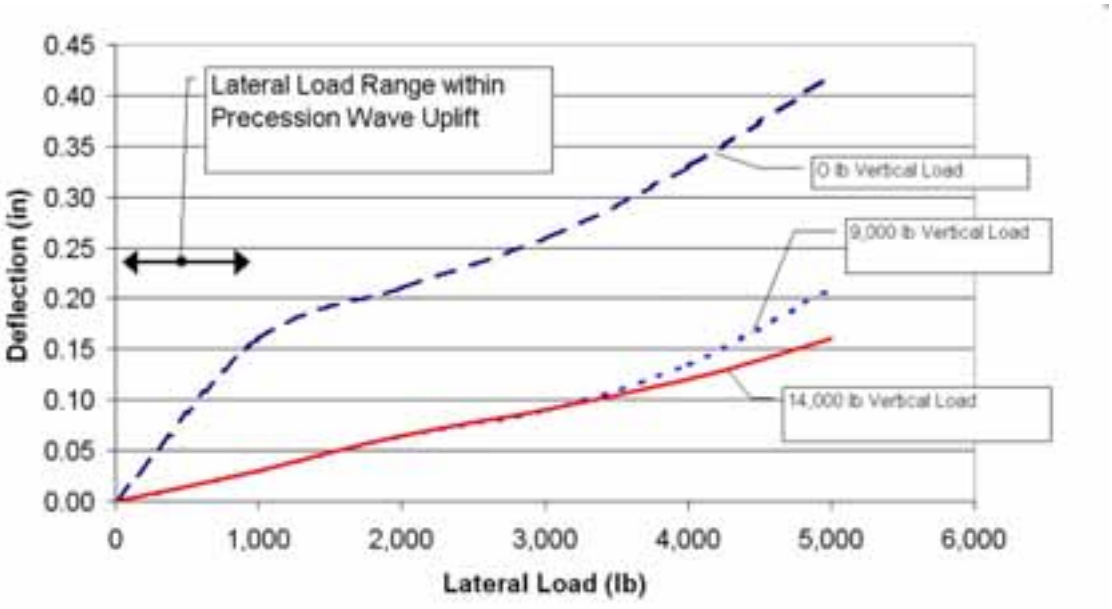


Figure 42. Lateral Stiffness versus Load

D. Fastener Stiffness Variation

Fastener stiffness is often stated as a singular value for a specific fastener design. Fastener stiffness is load dependent as noted previously (Figure 25). Any fastener will have a range of stiffness values depending on the load applied. Fastener stiffness also can vary from manufacturing, sometimes significantly within the same manufacturing lot. This section explores fastener stiffness variation and the implications of the variation in track performance.

The repeatability of fastener stiffness between fasteners of the same design is shown in Figure 7 for a single fastener design. Figure 7 shows that the actual

stiffness of any fastener at the same load may be significantly different from others in the same manufacturing lot, particularly at transit loads.

The inconsistency in stiffness translates into varying rail deflections, and fastener resonance frequency along the track. As an example, *Figure 43* shows resonance frequency variation with load for different fastener designs by different manufacturers including the previous fastener group. Some fastener designs have more consistent properties than others. In *Figure 43*, we note that the resonance frequency variability with load of most fastener designs span a wide frequency range, disallowing significant distinctions between most designs.

The variations in fastener stiffness created by manufacturing are greater than the stiffness variations between different fastener designs. This may have several implications:

a. The specifications should include production testing of fastener stiffness with limits on variance of stiffness from the qualification fastener stiffness.

b. The performance of one fastener design over another may not be discernable.

c. A track built to specification may create poor wheel/rail dynamic interaction from transitioning through fasteners of significantly different stiffness.

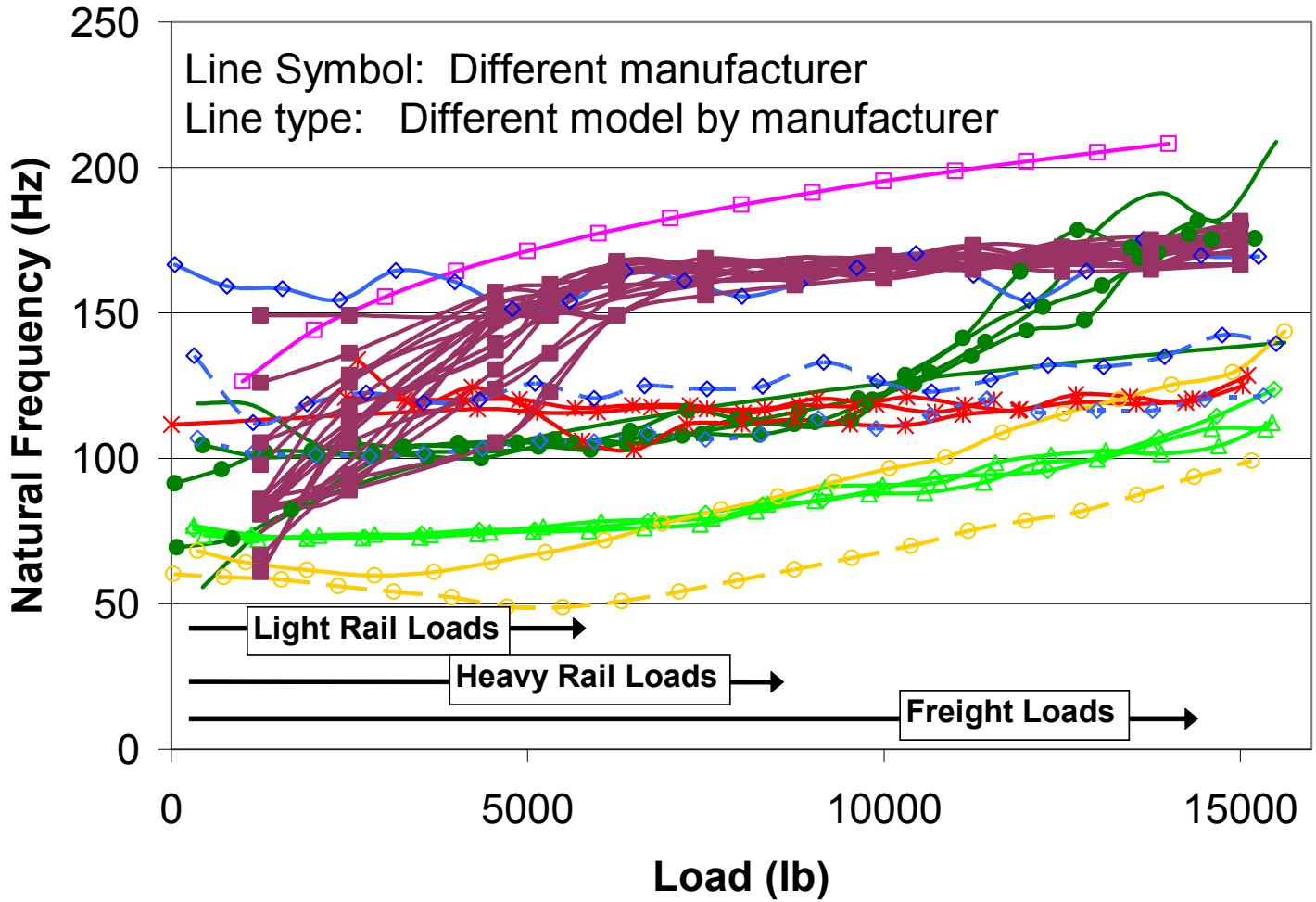


Figure 43. Resonance Frequency Variation Between Fastener Designs and Between Fasteners of the Same Design. Matching symbols are by one manufacturer, different line types for the same manufacture's symbol indicate a different fastener model or design for that manufacturer.

E. Anchor Bolts

The anchor bolt holds the fastener to gage and line. It is the primary lateral restraint component for the fastener. As a result, a prudent anchor bolt design factor or safety factor is higher than that for other components.

The anchor bolt primarily provides lateral restraint to loading by the bolts' clamping force, the "pre-load" on the bolt, where the fastener resists lateral load by friction between the concrete support and the fastener and any installed shims. The design of the bolt therefore is based on the friction force required to resist the maximum lateral load.

The bolts are designed to be redundant in the event one bolt loosens or fails. Usually there are two anchor bolts per fastener, one on the rail's gauge side and one on the field side. The bolt design assumes one bolt will safely hold the full lateral force acting in shear on the bolt. Some fastener designs employ 4 anchor bolts per fastener, a recommended configuration for Direct Fixation fasteners within special trackwork.

Anchor bolt design considerations are:

- Tensile strength of the bolt to apply the proper clamping force,
- Tensile strength to resist rail overturning moment,
- Adequate concrete embedment to resist pullout against bolt clamping tension and moments from rail forces,
- Adequate concrete restraint for bolt torque,
- Washers integral to lateral fastener adjustment, and
- Spring and lock washers to maintain a minimum bolt tensile loading that prevents bolt loosening.

1. *Anchor Bolt Size*

The large majority of anchor bolts for direct fixation fasteners are 7/8 inch (22 mm) in diameter, which meets the foregoing requirements for transit loading.

2. *Clamping Force*

The required clamping force is (assuming two anchor bolts):

(25) $$F_{clamp} = \frac{F_{Lat}}{\left(\frac{\mu_{concrete}}{2}\right)}$$

where

F_{clamp} = Load by two bolts to clamp the fastener to its support
$\mu_{concrete}$ = Coefficient of friction for the concrete/fastener interface or concrete/shim interface
F_{Lat} = Lateral fastener load

(26) $$F_{Lat} = F_{Vert} * L / V$$

F_{Vert} = Vertical force on the fastener
L/V = Lateral to vertical load ratio

In the clamping force estimate, the wheel load is ignored although it will increase the lateral fastener load resistance when fully over the fastener.

3. Insert Pullout Force

The minimum pullout force for the anchor bolt insert is calculated assuming the vertical and lateral rail forces leverage about the outer rail base to lift on the anchor bolt.

(27) $$R_{pullout} = SF\left\{\frac{F_{Lat}\left(H_{rail} - 0.5F_{Vert}w\right)}{d_{bolt} + 0.5w}\right\}$$

where

$R_{pullout}$ = Required bolt pullout restraint
SF = Safety factor
F_{Lat} = Lateral fastener load
H_{rail} = Rail height
F_{Vert} = Vertical load on the fastener
w = Rail base width
d_{bolt} = Bolt distance from the rail base edge (center of rail rotation)

The required insert pullout is specified much higher than estimated by the foregoing relation because the actual bolt tension created by the bolt torque is uncertain. Please see the following paragraphs.

4. Total Required Bolt Tensile Load

The total load on the anchor bolt is the sum of the load required to clamp the fastener to the support and the load imposed by the wheel load.

(28) $$T_{bolt} = F_{clamp} + R_{pullout}$$

where T_{bolt} = Total tensile load on the bolt.

5. Bolt Torque

The required bolt torque is that to generate the required tension in the bolt, T_{bolt}, is based on mechanics for forces on a slope where the thread progression is the slope.

(29) $$T_{torque} = T_{bolt}\frac{d_m}{2}\left(\frac{l + \pi\mu d_m \sec(\alpha)}{\pi d_m - \mu l \sec(\alpha)}\right) + T_{bolt}\mu_c\frac{d_c}{2}$$

where

T_{torque}	=	Bolt torque, ft-lb (m-N)
T_{bolt}	=	Required bolt tension, psi (Pa)
d_m	=	Mean diameter of the bolt, inch (mm)
d_c	=	Diameter of head bolt or washer, inch (mm)
l	=	Thread lead = 1/(No. of threads per inch)
μ	=	Thread friction
μ_c	=	Bolt head or washer friction on fastener
α	=	½ the thread angle = 30 degree for standard North American bolts.

The torque to remove the bolt is lower than the torque to install. Bolt removal torque is given by the following relation:

(30) $$T = F\frac{d_m}{2}\left(\frac{l - \pi\mu d_m \sec(\alpha)}{\pi d_m + \mu l \sec(\alpha)}\right) + F\mu_c\frac{d_c}{2}$$

The conventional practice is to use a dry thread friction value of 0.60 to calculate torque. However, the actual tension that is imparted to the bolt by the calculated torque can not be known with any certainty. Typical results from (27) are about 8,000 lbs. The bolt torque for dry friction is about 225 ft-lb. However, bolts often are supplied with an oil rust inhibitor for shipment, or the construction may be during wet conditions. The actual bolt tension from a 225 ft-lb torque may be 16,000 to 20,000 lb because the thread friction is reduced, possibly as low as μ = 0.07. The anchor bolt and anchor bolt insert must be designed for these higher loads.

Also, the specification must contain specifications for anchor bolt insert testing at these elevated loads to allow for the inadvertent occurrence of low thread friction values.

At the same time, the torque may produce less tension in the bolt than anticipated if the insert is skewed, there is debris on the threads, or the threads are not formed properly. These effects will create resistance that result in the bolt tension less than required at the specified torque value.

The countermeasures to assure proper bolt tension are construction specification stipulations to clean the bolt threads and the insert threads at the time of installation, and stipulations for plumb insert alignment with the fastener.

6. Design to Prevent Bolt Loosening

The principle for preventing a bolt from loosening is to assure that the bolt always is in tension. Track is a high vibration environment, routinely delivering shock loads to the anchorage system. Unreported vibration measurements from the Transportation Technology Center[58] show rail and track fasteners routinely endure vibration forces on the order of 100g in good track. By contrast, airplane designers become worried if vibrations approach 1g.

At these shock levels, bolt vibration can momentarily unloaded the bolt even with 12,000 to 30,000 pound tensile preload (the intended clamping force range). The result is micro slip in the bolt threads towards loosening (keeping in mind that bolts use slope mechanics and a bolt under tension will move “down-slope” towards loosening if given the chance).

The bolt themselves are incapable of maintaining bolt tension under these conditions. Lock washers and lock nuts do not have the capacity to assure tension in the bolt under all track conditions, providing false comfort against bolt loosening.

The anchorage arrangement needs to include a supplemental feature that will maintain some tensile load in the bolt under all circumstances. Successful anchor bolt arrangements either reduce shock loads to the anchor bolt or have a very significant spring washer that can maintain tensile loads on the bolt during vibration.

Configurations meeting these requirements use elastomeric washers and elastomeric sleeves about the bolt to dampen shock and vibration forces, or use helical spring washers. Several designs use both. These elements should include one or more flat washers. Lock washers may be included in the arrangement but are considered to have limited utility in this application.

[58] Association of American Railroads research facility located in Pueblo, Colorado. A “g” is a measure of acceleration where 1 times gravitation (1g) is double the static weight of an object. Force applied to an object is directly proportional to its acceleration by Newton’s relation F=ma where F is the resultant force of an object accelerated at a rate of “a” and has a mass of “m”.

7. *Insert Pullout Resistance*

The anchor bolt insert develops its resistance to pullout using the tensile strength of a conical section of concrete. The insert depth is the primary factor in developing the insert pullout resistance strength.

$$depth_{insert} = \frac{-(C\%)f'_c\,\pi d \pm \sqrt{((C\%)f'_c\,\pi d - 4((C\%)f'_c\,\pi)(-P)}}{2((C\%)f'_c\,\pi)} \quad (31)$$

where

$depth_{insert}$	=	Insert length. Insert embedment length in the concrete
$C\%$	=	Allowable concrete tensile stress as a % of concrete compressive strength
f'_c	=	Concrete compressive strength
d	=	Outside diameter of the female insert at the bottom
P	=	Required pullout force

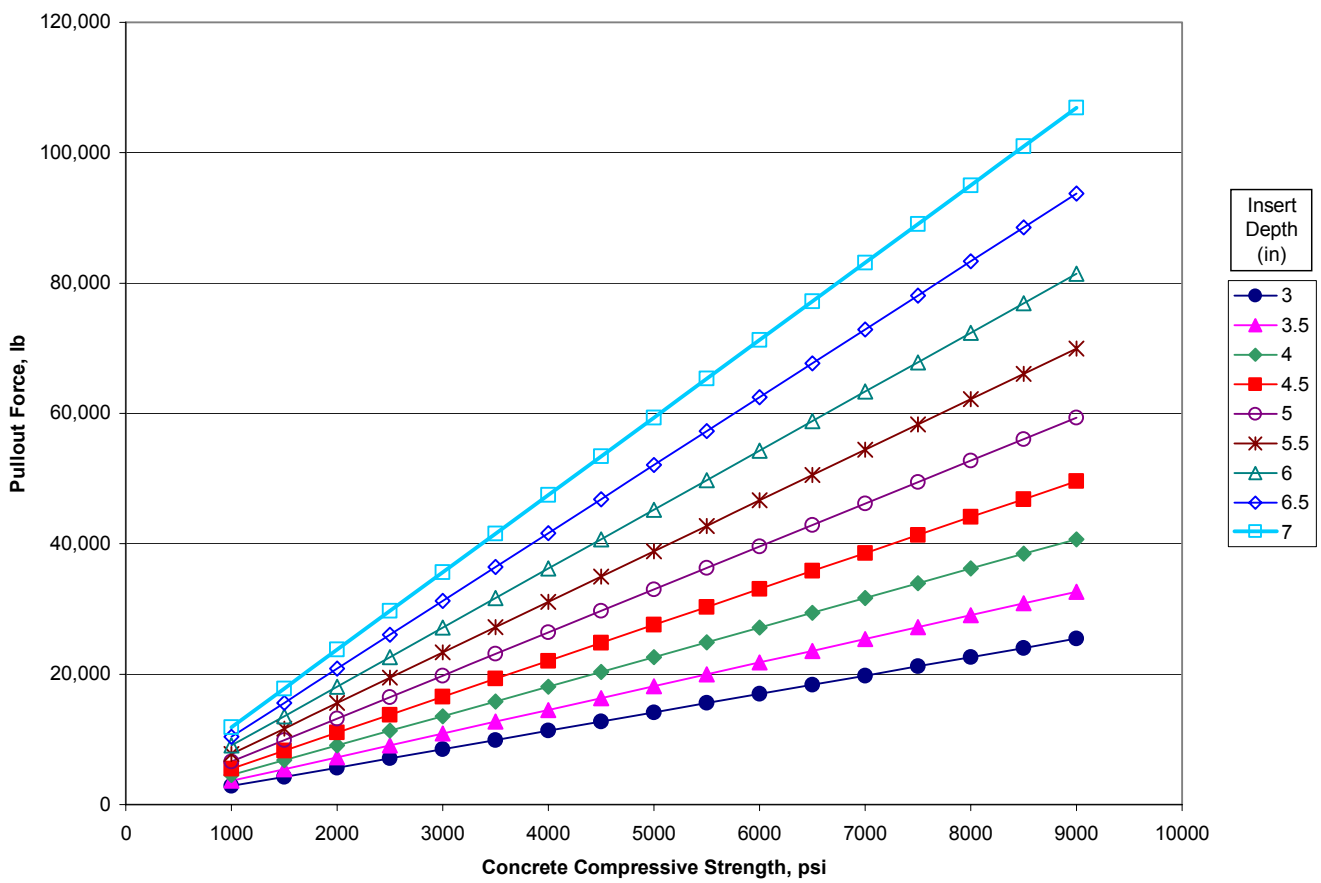


Figure 44. Example of Relationship Between Bolt Pullout Resistance, Insert Depth and Concrete Strength

VII. FASTENER SPACING

Fastener Spacing is determined by one or a combination of the factors chosen from Table R.

Table R. Determining Fastener Spacing

Issue	Criteria	Evaluation Method
Broken rail gap	The gap created by a broken rail must be no greater than stipulated in the design criteria (usually 3”)	Use equations in section IV.C.2 to determine the maximum allowable fastener spacing.
Curve rail offset for broken rail	Broken rail must not be offset laterally enough to derail a train	Calculate the lateral offset between the rail gage at one fastener to a line tangent to the curve from the middle of the adjacent fastener. Reduce the fastener spacing if that distance is more than ¼”.
Excessive traction force	Traction force at an individual fastener must be less than the fastener longitudinal resistance	Conduct train performance calculations with decreased fastener spacing. If spacing is less than desired or allowed, incorporate supplemental longitudinal rail restraint or require higher rail clip toe load on the rail in the specifications.
Aerial structure pier load relief	Reduce broken rail loads into fixed piers in aerial structures such that broken rail loads do not govern the pier design	Requires detailed analysis to balance broken rail gap criteria, fastener resistance and fastener spacing for the aerial span(s) in question.

VIII. TRACK TRANSITIONS

Track transitions for this discussion are those points in track where the track form changes from Direct Fixation to another track type, such as ballasted track. The track design attempts to make the track stiffness vary from one track type to the other over a distance, rather than abruptly, to reduce track maintenance and improve ride quality.

There are several methods to achieve a proper transition. These will be reviewed briefly.

A. Approach Slabs

Approach slabs typically are slabs 12” to 24” below the bottom of the tie for the 15 feet in ballasted track approaching the Direct Fixation track.

B. Asphalt Underlayment

Similar to approach slabs, asphalt underlayments are 6 inches to 9 inches thick for the 15 feet in ballasted track approaching the Direct Fixation track. The top of the asphalt underlayment is also 12” to 24” below the bottom of the tie.

C. Track Beams

Track beams as used in this discussion are vertical reinforcing beams attached to the top of ties and the Direct Fixation trackway. An example of this application is shown in Figures 45 – 47.

Figure 45. Transition Track Beam

Figure 46. Transition Track Beam

Figure 47. Transition Track Beam

D. Vary Direct Fixation Fastener Spacing and Tie Spacing

The track stiffness of Direct Fixation track can be reduced by increasing the fastener spacing or reduced spacing to make the track stiffer. Equations to adjust the track stiffness by varying the fastener spacing are provided in Attachment 1A.

This method may conflict with other longitudinal rail restraint issues (rail break gap parameters, etc.). Decreasing tie spacing may conflict with track surfacing equipment or create a conflict with third rail insulator spacing.

IX. DIRECT FIXATION CONSTRUCTION TOLERANCES AND SPECIFICATIONS

A. Construction Specification Comments

Constructing track to precise tolerances with full bearing on the supporting concrete is the single most important contribution to Direct Fixation track performance. While the specifications are generally disallowed from defining means and methods of construction, track designs compatible with top-down construction methods provide the highest confidence that the critical tolerances will be achieved. In this method, the rail, fasteners, rail clips, anchor bolts and inserts are fully assembled and placed at final position using jigs. Then the second pour concrete is placed.

In top-down construction, the only goal is to place the anchor bolt inserts to their correct final position.

The concrete bearing surface will never be correct. The specification must include stipulations that (1) the contractor provide a procedure for fastener bearing surface repair and (2) every fastener will be removed after the second pour is sufficiently cured. The minimum bearing surface repair includes removal of surface latent material (by scabbling, for example), recoating the insulation on the insert top (damaged by scabbling), placing repair grout, and placing the fasteners. The repair procedure should include the repair material design. The best repair material is a cementitious grout using fine sand. Epoxy grouts should be avoided because their coefficient of expansion is significantly different from the base concrete.

Track designs requiring bottom-up construction methods inherently have difficulty meeting required tolerances. Correction processes can attain the required tolerance although experience indicates the processes are costly.

Construction specifications typically:

- Include random anchor bolt pull-out testing. Some would favor a pull-out test to failure to determine the anchor design's safety factor.
- State the maximum plinth or grout pad height
- State the maximum shim height

Stipulations that are frequently absent from Direct Fixation construction specifications, but are critical to track performance, are:

- Establish quantifiable measures for full bearing of the rail, fastener and concrete on their mating surfaces.
- Require grout material to have the same coefficient of expansion as the base concrete.

If Direct Fixation track is installed on a new aerial structure, the owner should plan for resurfacing the Direct Fixation track at the first anniversary of the structure's completion. Aerial structures settle in unpredictable ways from changes in camber of spans and from pier settlement.

B. Direct Fixation Tolerances

Direct Fixation tolerances between adjacent fasteners' rail seats should ideally be within 1/32" of the plane of an adjacent rail seat. This tolerance is required to develop the designed toe load without exceeding the allowable stress in the elastic rail clips. Figure 48 illustrates a typical rail clip design load-deflection curve. The rail clip's installation deflection to develop the design toe load is shown, along with the range produced by allowable manufacturing tolerances of the clip and rail. The clip's allowable yield stress is shown to be 1/32" from the top of the clip installation range. This illustration is typical of most current rail clips.

While stating this ideal tolerance, it is acknowledged that it is difficult to achieve and somewhat difficult to measure in practice. This tolerance is stated as 1/16" in the example specifications and elsewhere in this report for this reason.

The reference plane for the foregoing rail seat tolerance is defined by the adjacent fastener rail seats either side of the fastener under consideration (in practice, place a straight edge between the adjacent fastener rail seats and measure the elevation deviation from the straight edge at the intermediate fastener, with measurements across the width of the rail seats). Deviations from the reference plane are elevation difference from the reference plane, rotation about the longitudinal axis of the reference plane, and rotation about an axis perpendicular to the longitudinal axis. Rigid rail clips are less vulnerable to clip stress problems from excessive deviations, but generally will have degraded performance from installation tolerance violation in about the same time frame as occurs with elastic rail clips.

When the fastener has cast-in shoulders or otherwise fixed lateral restraint, the fasteners on tangent track must be parallel to the adjacent fasteners within 1° to avoid binding the rail base between adjacent fasteners. Exceeding this tolerance may create longitudinal constraint that transfers loads larger than design loads between the structure and rail.

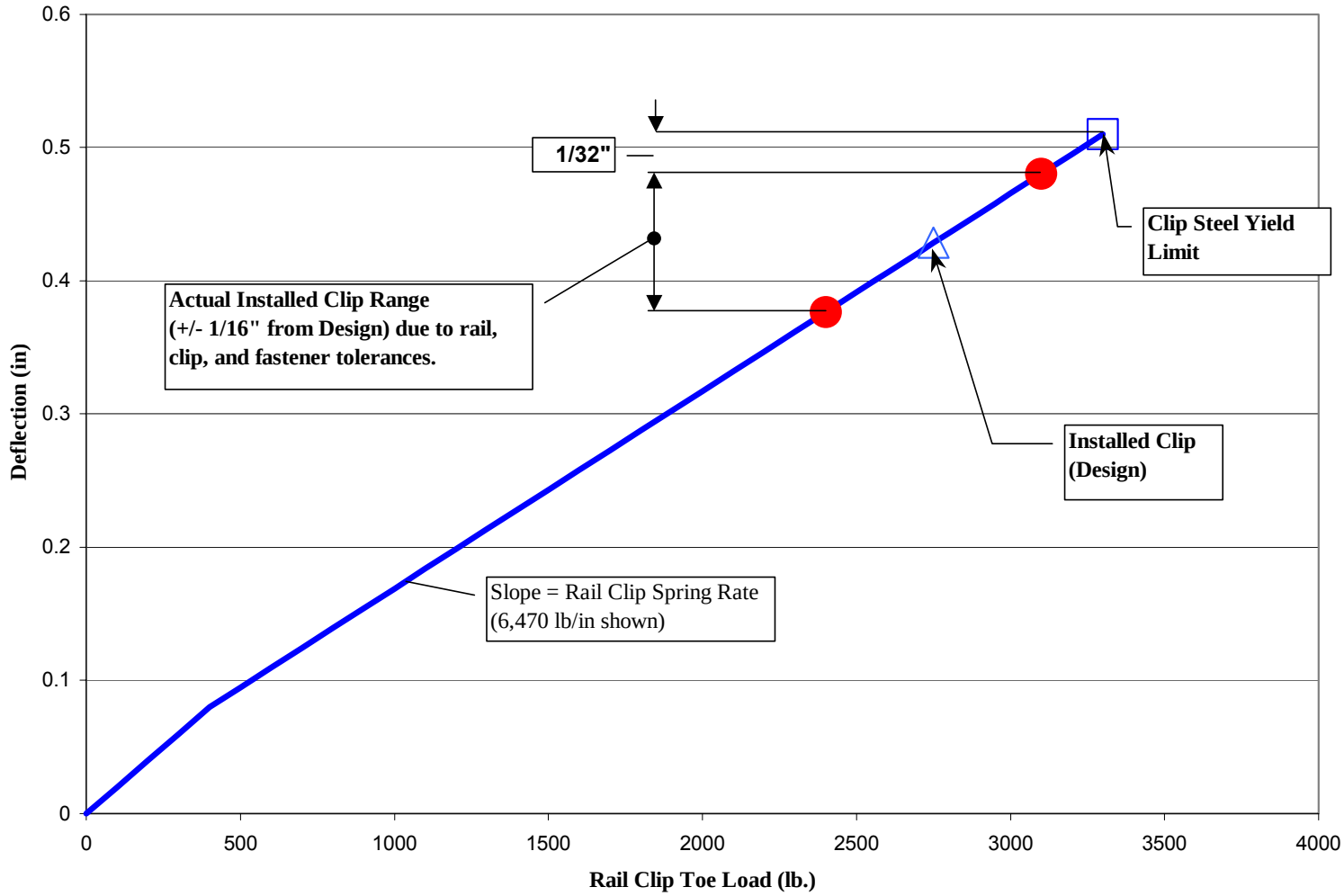


Figure 48. Installed Rail Clip Characteristics

Attachment 1A.
Relationships Between Fastener Stiffness, Track Stiffness and Track Modulus

Track Modulus and Fastener Stiffness	$K_{TrackMod} = \frac{k_f}{a}$
Track Stiffness	$K_{TrackStiffness} = \sqrt[4]{K_{TrackMod}{}^3 (64EI)} = \sqrt[4]{\left(\frac{k_f}{a}\right)^3 (64EI)}$
Load from a wheel directly over a fastener[59,60]	$F = \frac{P}{2}\sqrt[4]{\frac{K_{TrackMod} a^4}{4EI}} = \frac{P}{2}\sqrt[4]{\frac{k_f a^3}{4EI}}$ $F = \frac{P}{2}\sqrt[3]{\frac{K_{TrackStiffness} a^3}{8EI}}$

where

$K_{TrackMod}$	=	Track modulus, lb/in/in (N/m/m)
$K_{TrackStiffness}$	=	Track stiffness, lb/in (N/m)
k_f	=	Fastener stiffness, lb/in (N/m)
a	=	Fastener spacing, in (m)
P	=	Wheel load, lb (kN)
F	=	Load on an individual fastener, lb (kN)
E	=	Young's modulus for rail steel, psi (Pa)
I	=	Rail moment of inertia, in^4 (mm^4)

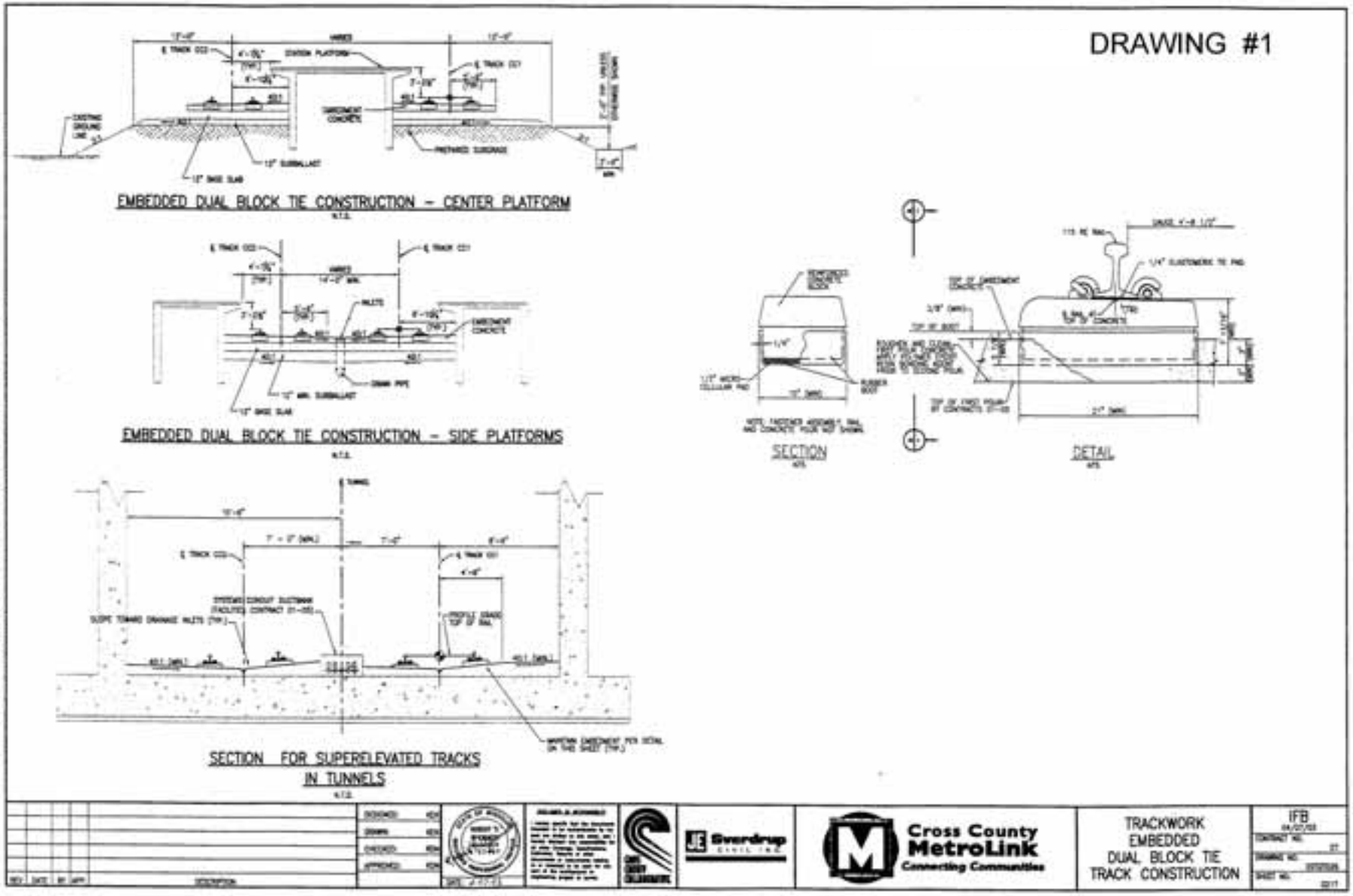
[59] To add the load from an adjacent axle, add $F_{adjacent}$ from $F_{adjacent} = \frac{k_f P \beta}{2K_{TrackMod}} e^{-\beta x}(\cos \beta x + \sin \beta x)$, where x is the distance between axles, and $\beta = \sqrt[4]{\frac{K_{TrackMod}}{4EI}}$

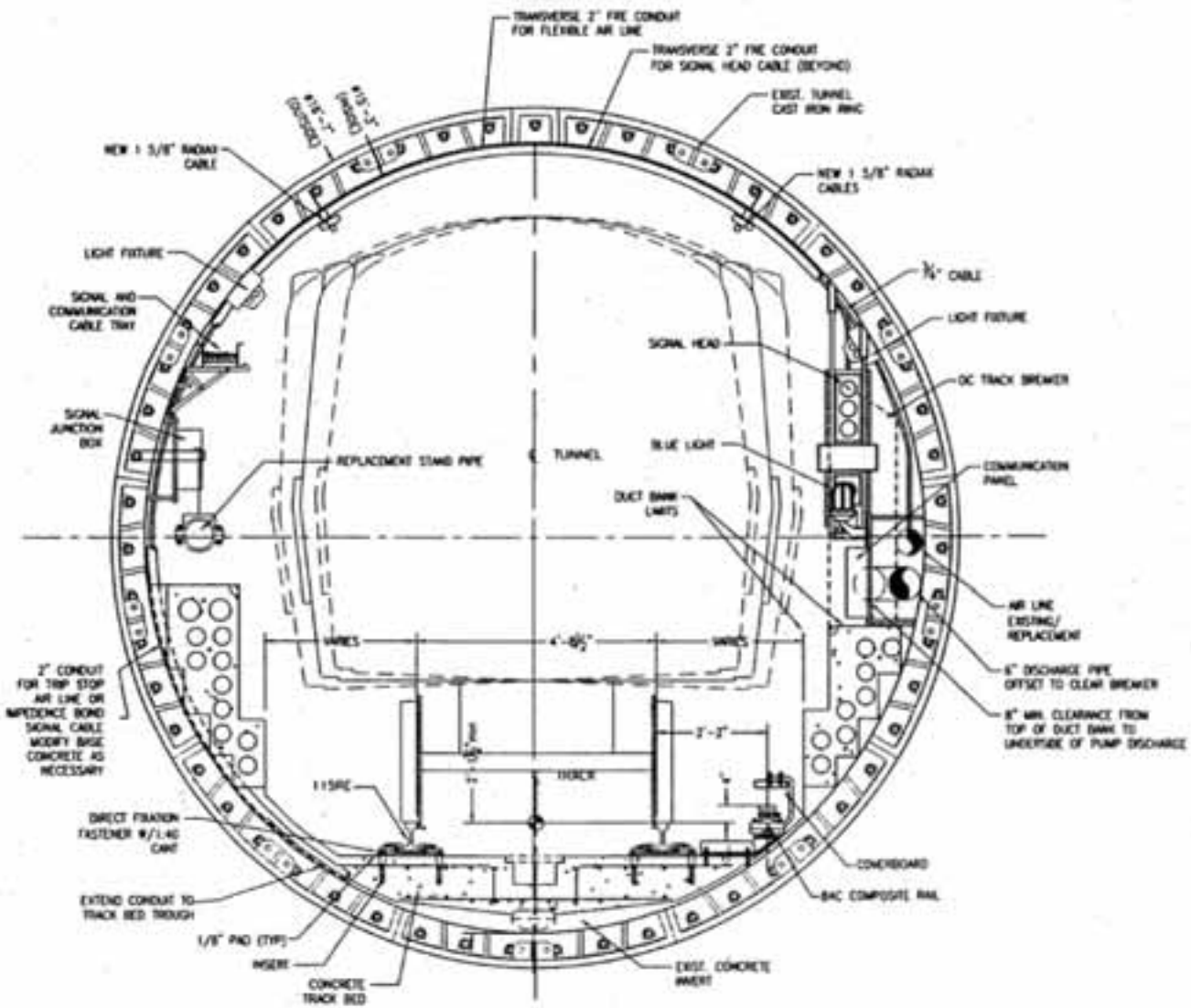
[60] Relationships are derived from: S. Timoshenko, B.F. Langer, *Stresses in Railroad Track*, The Proceedings of The American Society of Mechanical Engineers, paper APM-54-26, pp. 277 – 302, Nov. 30, 1931.

Implications from these relationships are (for a given rail weight):

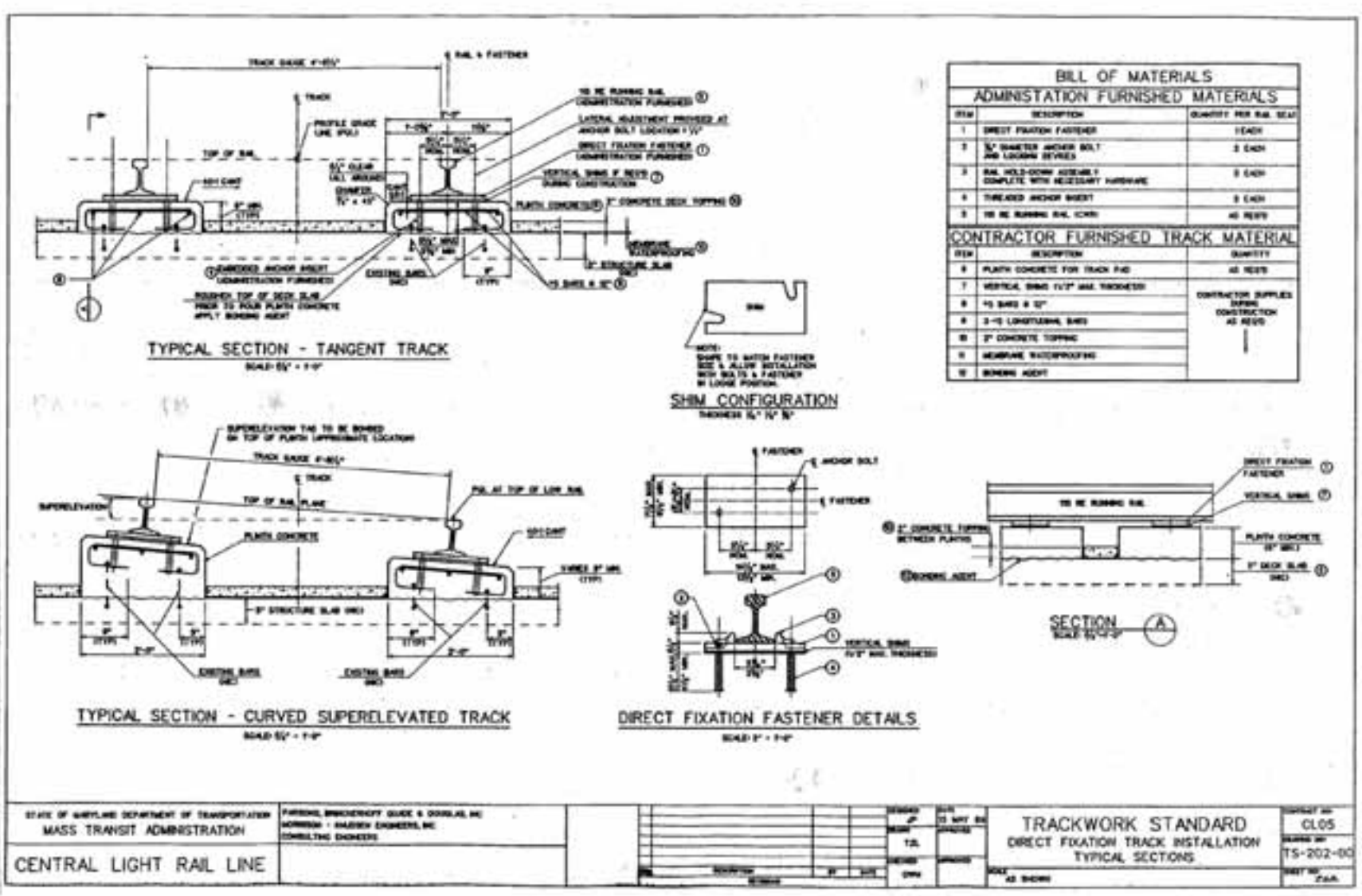
- Lower fastener stiffness reduces the load to individual fasteners.
- Lower fastener stiffness reduces the rate of loading on fasteners because the deflection wave is longer with a flatter (longer duration) approach shape.
- Lower fastener stiffness can allow waveforms from adjacent wheels to overlap (from the longer deflection wave).
- The track stiffness can be modified by changing either the Direct Fixation fastener stiffness or the fastener spacing.

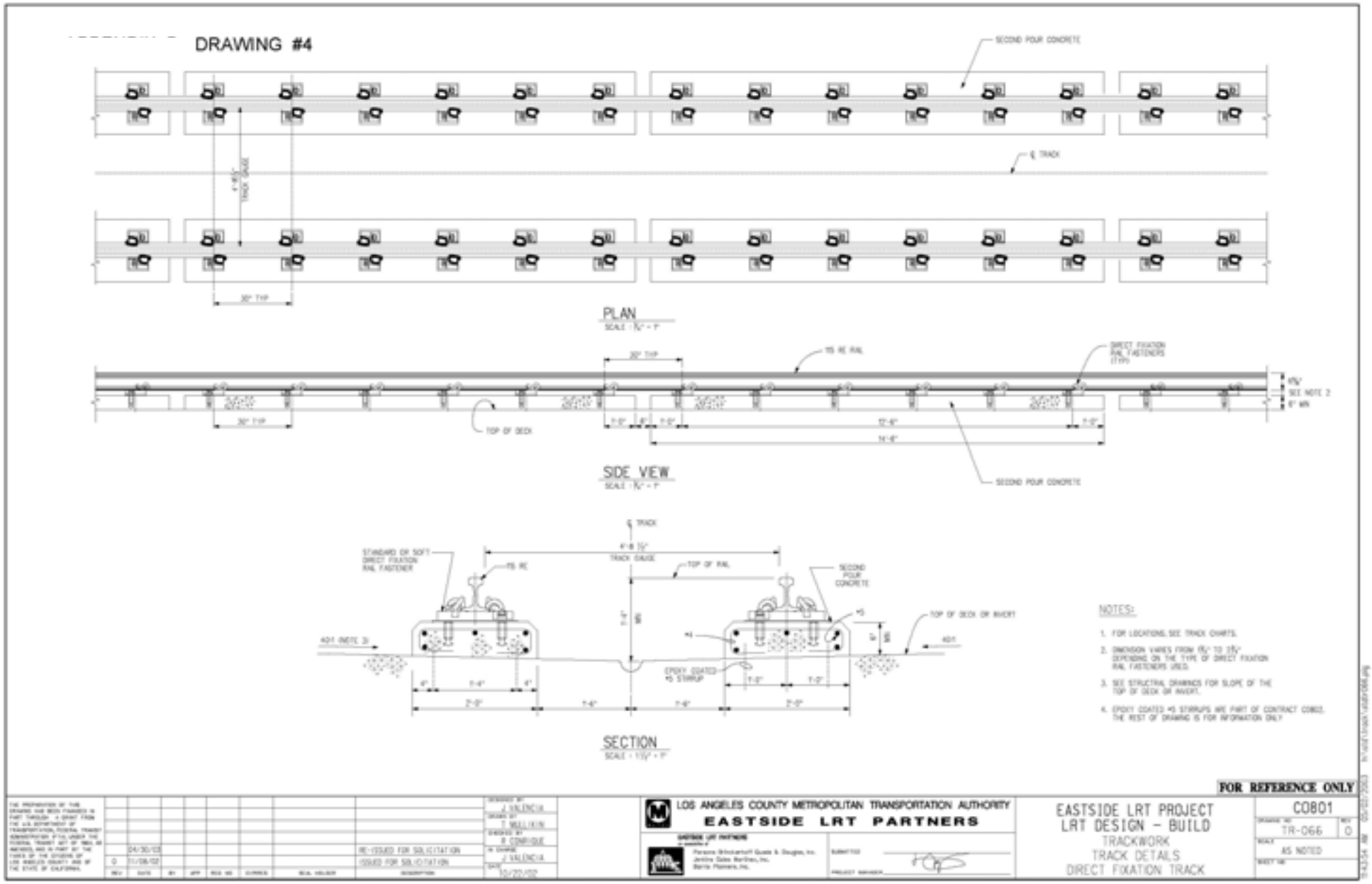
Attachment 1B.
Direct Fixation Track Examples

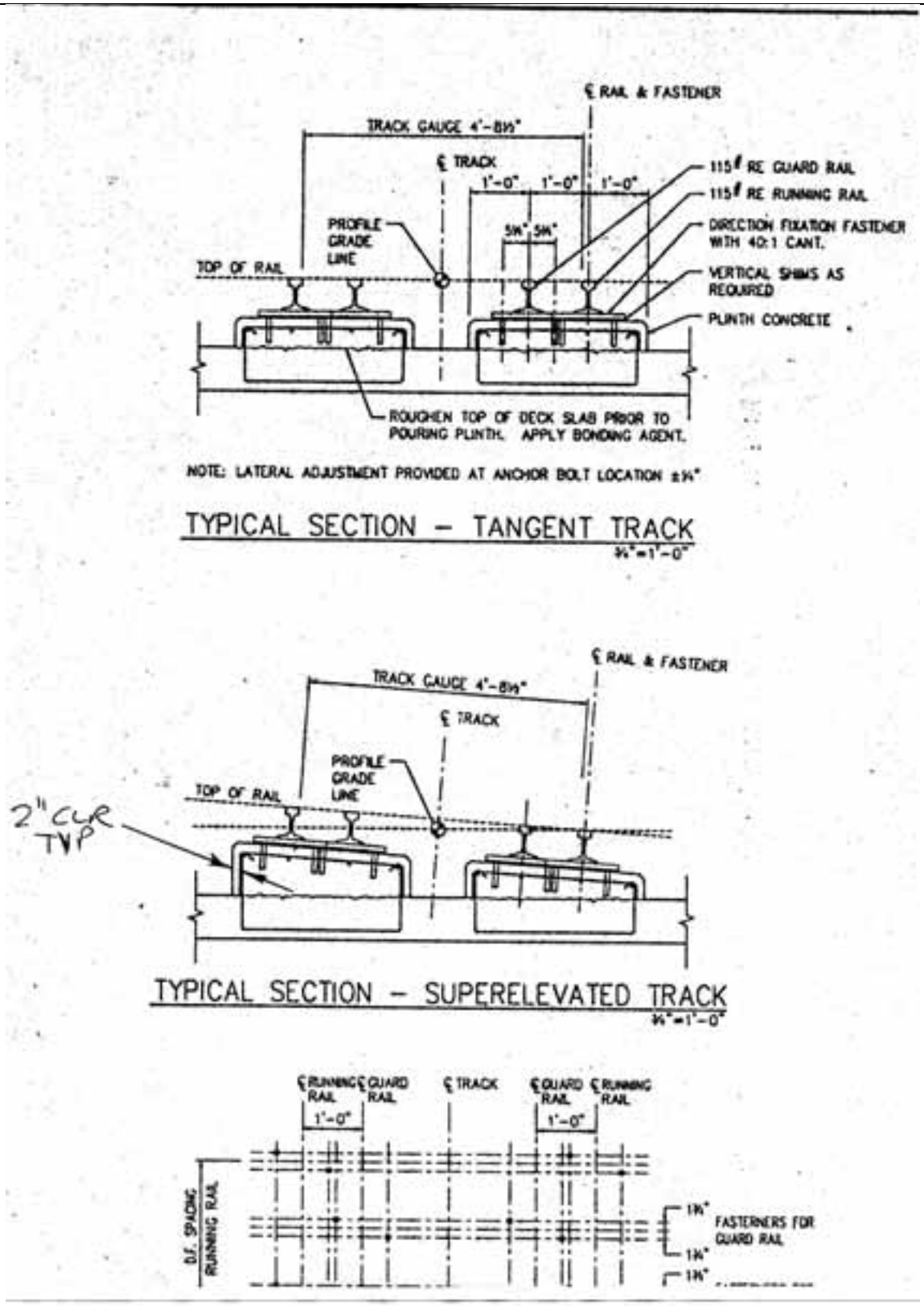

DRAWING #1
EMBEDDED DUAL BLOCK TIE CONSTRUCTION – CENTER PLATFORM
EMBEDDED DUAL BLOCK TIE CONSTRUCTION – SIDE PLATFORMS
SECTION FOR SUPERELEVATED TRACKS IN TUNNELS
SECTION
DETAIL
Cross County MetroLink
Connecting Communities
Sverdrup
TRACKWORK EMBEDDED DUAL BLOCK TIE TRACK CONSTRUCTION
IFB


TRANSVERSE 2" FIRE CONDUIT FOR FLEXIBLE AIR LINE
TRANSVERSE 2" FIRE CONDUIT FOR SIGNAL HEAD CABLE (BEYOND)
EXIST. TUNNEL CAST IRON RING
NEW 1 5/8" RADIAX CABLE
NEW 1 5/8" RADIAX CABLES
LIGHT FIXTURE
SIGNAL AND COMMUNICATION CABLE TRAY
SIGNAL JUNCTION BOX
REPLACEMENT STAND PIPE
TUNNEL
SIGNAL HEAD
BLUE LIGHT
DUCT BANK LIMITS
LIGHT FIXTURE
DC TRACK BREAKER
COMMUNICATION PANEL
AIR LINE EXISTING/ REPLACEMENT
6" DISCHARGE PIPE OFFSET TO CLEAR BREAKER
8" MIN. CLEARANCE FROM TOP OF DUCT BANK TO UNDERSIDE OF PUMP DISCHARGE
VARIES
VARIES
2" CONDUIT FOR TRIP STOP AIR LINE OR IMPEDENCE BOND SIGNAL CABLE MODIFY BASE CONCRETE AS NECESSARY
DECK
DIRECT FIXATION FASTENER W/LAG CAMT
EXTEND CONDUIT TO TRACK BED TROUGH
1/8" PAD (TYP)
INSERT
CONCRETE TRACK BED
EXIST. CONCRETE INVERT
CONDEBOARD
BAC COMPOSITE RAIL
SECTION A
SCALE 3/4"=1'
DRAWING #2

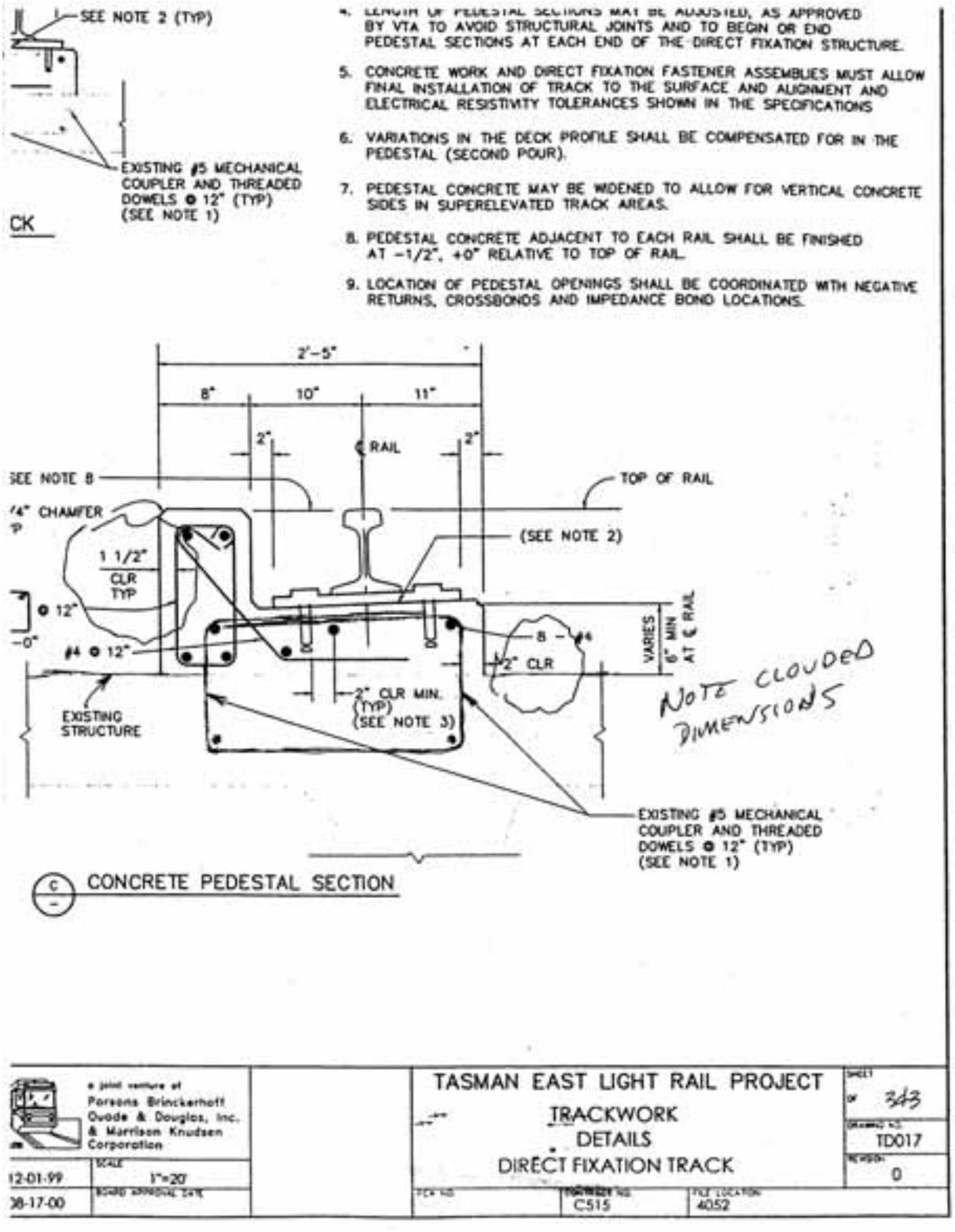
DRAWING #3


BILL OF MATERIALS
ADMINISTATION FURNISHED MATERIALS
CONTRACTOR FURNISHED TRACK MATERIAL
TYPICAL SECTION - TANGENT TRACK
SHIM CONFIGURATION
TYPICAL SECTION - CURVED SUPERELEVATED TRACK
DIRECT FIXATION FASTENER DETAILS
SECTION A
MASS TRANSIT ADMINISTRATION
CENTRAL LIGHT RAIL LINE
TRACKWORK STANDARD
DIRECT FIXATION TRACK INSTALLATION
TYPICAL SECTIONS
CL05
TS-202-00


DRAWING #4
SECOND POUR CONCRETE
℄ TRACK
TRACK GAUGE
30" TYP
PLAN
SCALE : 1/2" = 1'
115 RE RAIL
DIRECT FIXATION RAIL FASTENERS (TYP)
SEE NOTE 2
8" MIN
TOP OF DECK
SIDE VIEW
SCALE : 1/2" = 1'
STANDARD OR SOFT DIRECT FIXATION RAIL FASTENER
TOP OF RAIL
TOP OF DECK OR INVERT
401 (NOTE 3)
EPOXY COATED #5 STIRRUP
SECTION
SCALE : 1 1/2" = 1'
NOTES:
1. FOR LOCATIONS, SEE TRACK CHARTS.
2. DIMENSION VARIES FROM 6 1/2" TO 18 1/2" DEPENDING ON THE TYPE OF DIRECT FIXATION RAIL FASTENERS USED.
3. SEE STRUCTRAL DRAWINGS FOR SLOPE OF THE TOP OF DECK OR INVERT.
4. EPOXY COATED #5 STIRRUPS ARE PART OF CONTRACT C0802, THE REST OF DRAWING IS FOR INFORMATION ONLY.
FOR REFERENCE ONLY
LOS ANGELES COUNTY METROPOLITAN TRANSPORTATION AUTHORITY
EASTSIDE LRT PARTNERS
EASTSIDE LRT PROJECT
LRT DESIGN - BUILD
TRACKWORK
TRACK DETAILS
DIRECT FIXATION TRACK
C0801
TR-066
AS NOTED
04/30/03
11/08/02
RE-ISSUED FOR SOLICITATION
ISSUED FOR SOLICITATION
10/22/02



Drawing #5, MTDB Fletcher Park



Drawing #6, VTA Direct Fixation Track with Upstand (to the left of the rail)

Attachment 1C. Lateral Thermal Rail Load on a Fastener

Lateral rail force is generated on a fastener in curves from rail thermal forces. Representation of the forces is shown in Figure 49.

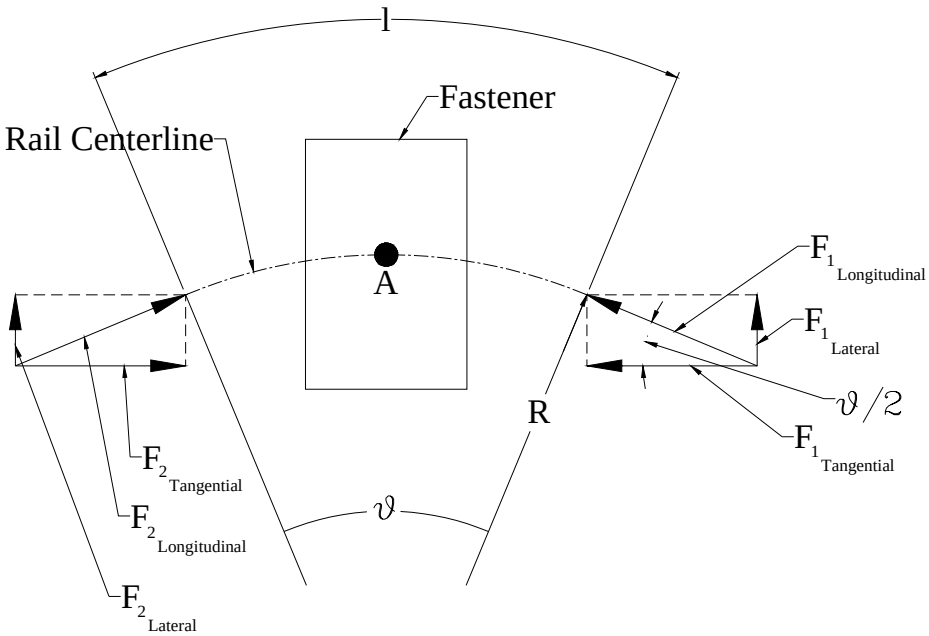


Figure 49. Thermal Rail Force Diagram for a Fastener in a Curve

Consider rail thermal forces F_1 and F_2 (subscript "Longitudinal"), and their lateral and tangential components acting at the mid-points between adjacent fasteners. The rail length, $\boldsymbol{l}$, is then the fastener spacing over arc length $\boldsymbol{q}$ for a curve radius of $\boldsymbol{R}$.

These forces may be moved to act at point A in Figure 49 by adding moments about A from each longitudinal force as shown in Figure 50. The moments from the two longitudinal forces are equal but in opposite direction, thereby canceling one another. The moments are not shown in Figure 50 for clarity.

The sum of moments as just stated are zero.

From Figure 50, the sum of tangential components of F_1 and F_2 are also equal and in opposite direction, equaling zero net force on the fastener.

The lateral components of F_1 and F_2 are in the same direction and add to create the lateral thermal rail force on the fastener. That is, if $F_{Lateral}$ represents the lateral force from either longitudinal force F_1 or F_2, then the lateral force on the fastener is

(32) $$F_{fastener_{Lateral}} = 2F_{Lateral}$$

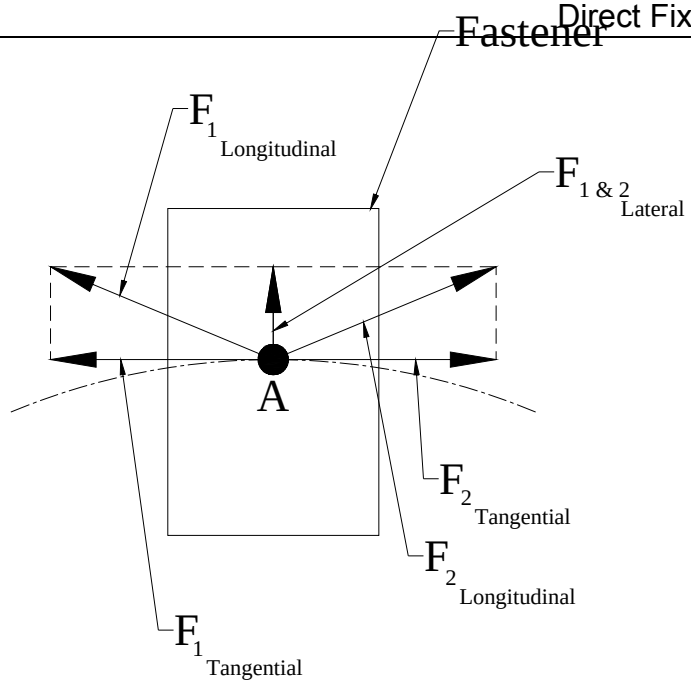


Figure 50. Free Body Diagram of Longitudinal Forces Acting on a Fastener (moments not shown)

The longitudinal forces F_1 and F_2 are equal and calculated by $\boldsymbol{F}$ in the following relationship:

(33) $$F_{1or2_{Longitudinal}} = EA\alpha\Delta T$$

Where

$\boldsymbol{F}$	=	Longitudinal Rail Force, F_1 or F_2, lb (N)
$\boldsymbol{E}$	=	Young's Modulus of Elasticity for Steel, lb/in^2 (Pa)
$\boldsymbol{A}$	=	Rail cross sectional area, in^2 (mm^2)
$\boldsymbol{\alpha}$	=	Coefficient of rail expansion, in/in/^{o}F (mm/mm/^{o}C)
$\boldsymbol{\Delta T}$	=	Rail temperature difference between the temperature under consideration and the temperature at which there is zero longitudinal force in the rail, ^{o}F (^{o}C).

The angle, $\boldsymbol{\theta/2}$, that the longitudinal rail force is applied to the fastener relative to a tangent to the curve is

(34) $$\frac{\theta}{2} = \frac{l}{2R}$$

Where

$\boldsymbol{\theta}$	=	The angle subtended by the arc length, $\boldsymbol{l}$, radians
$\boldsymbol{l}$	=	Fastener spacing (arc length), inches (mm)
$\boldsymbol{R}$	=	Curve radius, inches (mm)

The lateral component of either of the longitudinal forces F_1 or F_2, represented by $\boldsymbol{F}$ above, is

$$F_{Lateral} = F \sin\left(\frac{\theta}{2}\right) \tag{35}$$

The lateral force on a fastener in a curve from rail thermal forces is then

$$F_{fastener_{Lateral}} = 2F_{Lateral} = 2F \sin\theta = 2EA\alpha\Delta T \sin\left(\frac{l}{2R}\right) \tag{36}$$

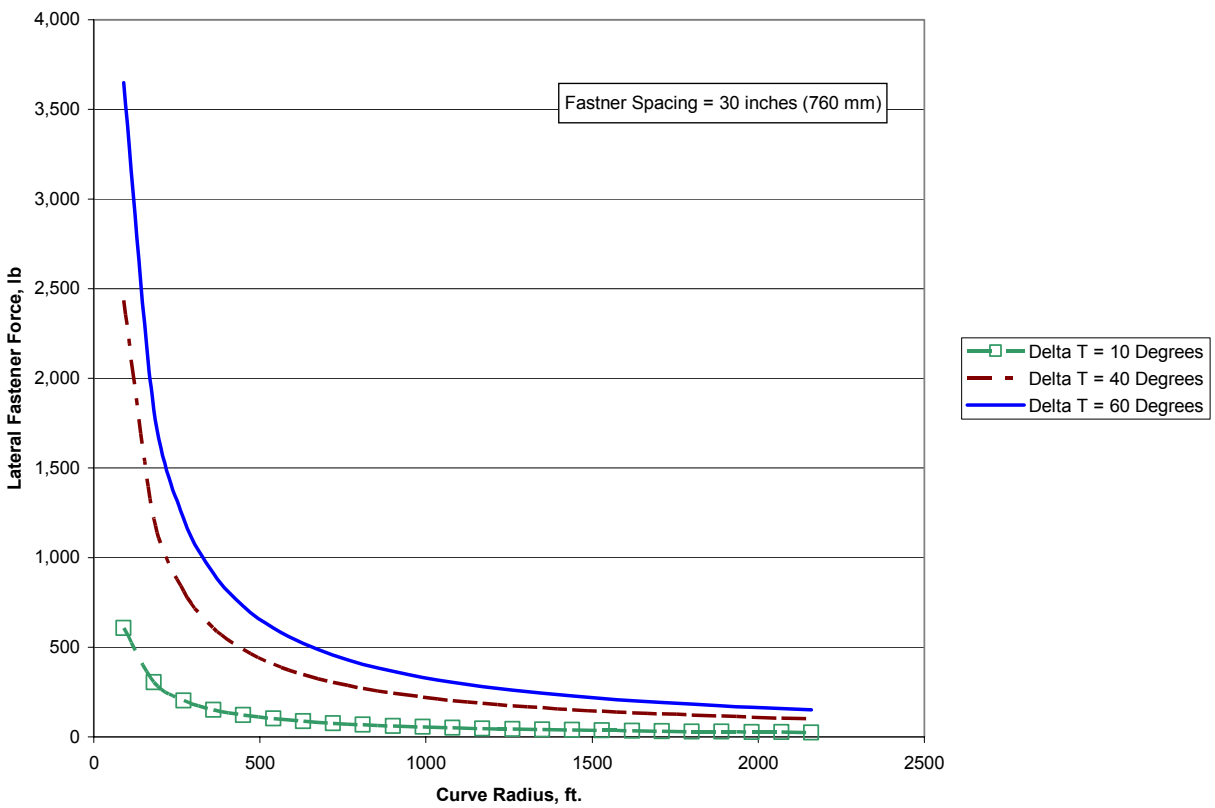


Figure 51. Lateral Fastener Force from Thermal Rail Force (115 RE rail).

Attachment 1D.
Broken Rail Gap Derivation

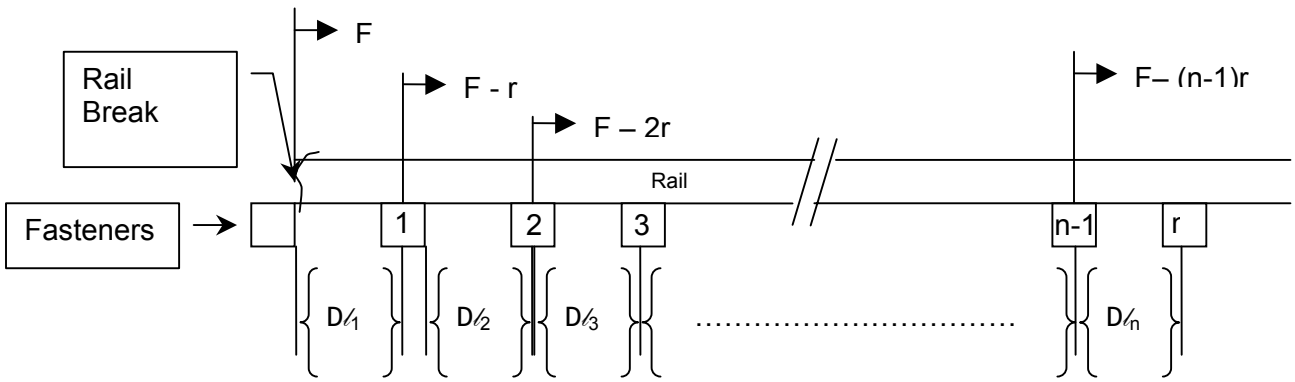


Figure 52. Constrained Rail Break Gap Nomenclature

Referring to Figure 52, a rail breaks at the left side of the figure, releasing a force, F, which is $\boldsymbol{P_{Longitudinal}}$).

The movement of the broken rail end attributable to the rail length to the adjacent fastener (fastener 1 in *Figure 52*) is Δl_1.

(37) $$\Delta l_1 = Spcg * \alpha * \Delta T$$

Using the relation for $\boldsymbol{P_{Longitudinal}}$, (see main text)

$$\alpha \Delta T = \frac{P_{Longitudinal}}{EA}$$

Substituting,

(38) $$\Delta l_1 = Spcg \frac{P_{Longitudinal}}{EA}$$

Fastener 1 in Figure 52 reduces the rail break force by the fastener resistance, $\boldsymbol{r}$. The broken rail end movement from the rail between the first and second fastener is then

$$\Delta l_2 = Spcg\left(\frac{P_{Longitudinal} - r}{EA}\right)$$

Similarly, the rail end movement from the rail between the second and third fastener from the broken rail end is

$$\Delta l_3 = Spcg\left(\frac{P_{Longitudinal} - 2r}{EA}\right)$$

And so on until the broken rail force is fully constrained by fastener ***n***, where the length of rail between fastener ***n*** and ***n***-1 allows the following broken rail end movement:

$$\Delta l_{n-1} = Spcg\left(\frac{P_{Longitudinal} - (n-1)r}{EA}\right)$$

The broken rail end movement is the sum of the movement from the individual rail lengths between fasteners:

$$\Delta l = \sum_{0}^{n-1} \Delta l_n = \int_0^{n-1} Spcg\left(\frac{P_{Longitudinal} - nr}{EA}\right) dn$$

$$\Delta l = \frac{1}{EA}\left(2SpcgP_{Longitudinal} - \frac{(n-1)^2 r}{2}\right)$$

The broken rail gap will be twice $\Delta \boldsymbol{l}$ because the rail on both sides of the break will contract $\Delta \boldsymbol{l}$**.**

(39) $$Gap = 2\Delta l = \frac{2}{EA}\left(2SpcgP_{Longitudinal} - \frac{(n-1)^2 r}{2}\right)$$

Attachment 1E.
Derivation of Dynamic Fastener Characteristics

Assume a cyclical load is applied to a mass supported by a spring and a damper.

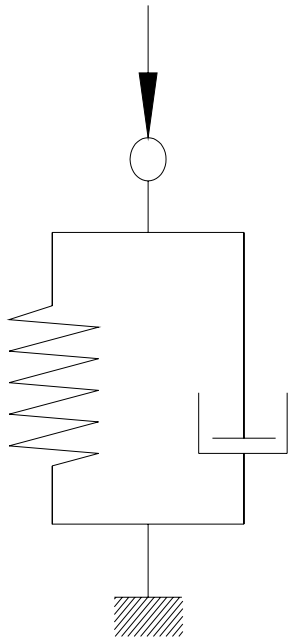


Figure 53. Spring-Damper Idealization for Fastener

The equation of motion with viscous damping and where the force is applied at a frequency much different from the fastener's resonance frequency is described by:

(40) $$m\left(\frac{d^2x}{dx^2}\right)+c\left(\frac{dx}{dt}\right)+kx=F_0\sin(\omega t)$$

Where:

x	=	deflection
m	=	mass
c	=	damping coefficient
k	=	dynamic stiffness
F_o	=	amplitude of the cyclic load
ω	=	cyclic frequency (radians/sec)
t	=	time

Assume a solution of the form

(41) $$x(t)=a\cos(\omega t)+b\sin(\omega t)$$

where *a* and *b* are constants to be determined.

The derivatives of (41) are

$$\frac{dx}{dt} = -a\omega \sin \omega t + b\omega \cos \omega t$$

$$\frac{d^2x}{dt^2} = -a\omega^2 \cos \omega t - b\omega^2 \sin \omega t$$

Inserting (41), and the foregoing derivatives into (40) and algebraically rearranging, results in the following relation:

(42) $$\cos \omega t\left(-ma\omega^2 + cb\omega + ka\right) + \sin \omega t\left(-mb\omega^2 - ca\omega + kb\right) = F_o \sin \omega t$$

This solution can be true only if

$$-ma\omega^2 + cb\omega + ka = 0$$

and

$$-mb\omega^2 - ca\omega + kb = F_o$$

Solving these simultaneous equations results in

$$a = \frac{c\omega F_o}{(c\omega)^2 + \left(k - m\omega^2\right)^2}$$

and

$$b = \frac{F_o\left(k - m\omega^2\right)}{\left(k - m\omega^2\right) + (c\omega)^2}$$

For the steady state response

(43) $$x = A\sin(\omega t - \psi)$$

where

A	=	the response amplitude
Ψ	=	the phase angle

In terms of *a* and *b*, above, the response amplitude is

(44) $$A = \sqrt{a^2 + b^2}$$ [61]

Substituting *a* and *b* into (44), and rearranging, produces the response amplitude which we will call x_0:

(45) $$x_0 = A = \frac{F_0}{\sqrt{(c\omega)^2 + (k - m\omega^2)^2}}$$ [62]

The full response for any time, t, for a given oscillating load frequency, ω, is, from (43)

(46) $$x = \frac{F_0 \sin(\omega t - \psi)}{\left[(k - m\omega^2)^2 + (c\omega)^2\right]^{1/2}}$$

The phase angle, ψ, in terms of a and b is

$$\psi = \arctan\left(\frac{a}{b}\right)$$

Inserting a and b into the foregoing relationship results in:

(47) $$\psi = \arctan\left(\frac{c\omega}{k - m\omega^2}\right) \qquad \text{or} \qquad \tan\psi = \frac{c\omega}{k - m\omega^2}$$

The dynamic stiffness, k, can now be found using the definition of the phase lag, ψ, from (47) and extracting k-$m\omega^2$ from the denominator:

$$x_0 = \frac{F_0}{(k - m\omega^2)\left[1 + \tan^2\psi\right]^{1/2}}$$

Rearranging:

(48) $$k = \frac{F_0}{x_0\left[1 + \tan^2\psi\right]^{1/2}} + m\omega^2$$

The dynamic stiffness, k, is dependent on the amplitude of the forcing function, F_0, and the angular frequency, ω.

---

[61] S.Timoshenko, D.H. Young, W. Weaver, *Vibration Problems in Engineering*, Fourth Edition, John Wiley & Sons, 1974, pg. 74.

[62] *Engineering with Rubber*, Ed. A. Gent, Hansen Publishers, 1992, pg. 78, eq. 4.22.

With the dynamic stiffness known, the damping coefficient can be calculated by rearranging (47):

(49) $$c = \frac{k - m\omega^2}{\omega} \tan\psi$$

This can be expressed in terms of the measured quantities as:

(50) $$c = \frac{F_0}{x_0 \omega} \frac{\tan\psi}{\left[1 + \tan^2\psi\right]^{1/2}}$$

Resonance

The dynamic response in (46) will vary significantly when the angular frequency, ω, of the applied force is near the resonance frequency of the fastener, and depending on whether the damping coefficient is below, near or greater than the value of damping called *critical damping*.

Critical damping is the level of damping where the motion first loses it vibratory character. For the model used here, forced vibrations with viscous damping, the critical damping value is:

(51) $$c_{cr} = 2\sqrt{km}$$

where

c_{cr} = critical damping value
k and m are as before.

The critical damping value is dependent on dynamic stiffness and effective mass, which will be fairly uniform for a specific fastener over practical ranges of applied loads and angular frequencies. In contrast, as seen previously, the damping coefficient, *c*, is dependent on applied load and frequency of the load application, both which vary considerably. The effect is that the value of the damping coefficient can be very different from the critical damping coefficient, eliciting different responses, for the same fastener depending on the applied loads and applied frequency of those loads.

The ratio of the damping coefficient to the critical damping value is a fastener characteristic that indicates the nature of the response for a particular load/frequency combination.

(52) $$\gamma = \frac{c}{c_{cr}}$$

where

γ = damping ratio

The resonance frequency is of particular interest because it determines which vibrations the fastener will filter. If the vibration frequency is well below the resonance frequency, the vibrations will not be significantly attenuated, passing directly through the fastener to the support. If the vibration frequency is well above the resonance frequency, the vibrations will be significantly attenuated or isolated from the support. In either case, the damping coefficient and damping ratio have little influence on fastener response.

When the vibration frequency is near the resonance frequency, the fastener response becomes sensitive to the damping ratio. In this case, the vibration amplitude will be amplified when the damping ratio is less than 1. The vibration amplitude at resonance is not amplified when the damping ratio is 1 or greater.

The resonance frequency is determined differently for an underdamped (γ<1), critically damped (γ=1), and overdamped (γ>1) conditions.

($a_{resonance}$) For $\gamma < 1$: $$\omega_r = \sqrt{\frac{k}{m} - \frac{c^2}{2m^2}}$$ [63]

When $\omega = \omega_r$, the response is a resonance response, with the deflections amplified. The maximum deflection will be

$$x_0(\max) = \frac{F_0}{\sqrt{(\omega_r c)^2 + \left(\frac{c^2}{2m}\right)^2}}$$ [64]

($b_{resonance}$) For $\gamma = 1$: $$\omega_r = \sqrt{\frac{k}{m}}$$ [65]

When $\omega = \omega_{cr}$ there is no amplification of deflections.

($c_{resonance}$) For $\gamma > 1$: $$\omega_r = \frac{c}{2m} - \sqrt{\left(\frac{c}{2m}\right)^2 - \frac{k}{m}}$$ [66]

---

[63] *Engineering with Rubber*, Ed. A.N. Gent, Hanser Publishers, 1992, pp. 78, 79.

[64] Gent, pg. 79, eq. 4.24.

[65] S. Timoshenko, D.H. Young, W. Weaver, *Vibration Problems in Engineering*, Fourth Edition, John Wiley & Sons, 1974, pg. 69.

[66] Timoshenko, pg 69 & 71.

So when $\omega > \omega_{cr}$ the deflections will be diminished below the static deflections.

Repeating an earlier comment, any fasteners may exhibit several or all of these behaviors depending on the load and the frequency of the force. The dynamic test regimen must be designed to create conditions that will elicit responses to loads and vibration frequencies expected in service.

Loss Factor or, Tangent Loss

Thus far, the modeling considered the case of a fastener system where the elastomer is a spring and damper supporting a mass (a section of rail, the fastener's top plate and rail clip hardware, and presumably the unsprung mass of the wheel set).

Turning the attention to the elastomer only, the elastomer absorbs and dissipates mechanical energy during cyclic loading which is termed mechanical loss factor or tangent . A summary of a complete explanation[67] is provided here.

The ratio of stress to strain, the elastomer's dynamic modulus, is

(53) $$\frac{\sigma}{\varepsilon} = E + i\omega\eta$$

where

σ	=	Stress
ε	=	Strain
E	=	the real part of the complex dynamic modulus
i	=	$\sqrt{-1}$
η	=	tensile viscosity of the elastomer

Restating the foregoing relation,

(54) $$\frac{\sigma}{\varepsilon} = E_1 + iE_2$$

where

E_1	=	The real part of the dynamic modulus (stated as E in the previous equation).
E_2	=	The imaginary part of the dynamic modulus.

[67] Gent, pp. 76-78, with relevant application comments on pp 84-88.

The following are alternative definitions for the real and imaginary components of the complex modulus:

$$E_1 = \frac{\text{Component of stress in phase with strain}}{\text{Strain}}$$

$$E_2 = \frac{\text{Component of stress } 90^{\circ} \text{ out of phase with strain}}{\text{Strain}}$$

The loss tangent is the ratio of these two components:

(55) $$\tan\delta = \frac{E_2}{E_1}$$

In terms of damping, c, and dynamic stiffness, k, the loss tangent is

(56) $$\tan\delta = \frac{\omega c}{k}.$$

Repeating equation (47) for phase angle:

$$\tan\psi = \frac{c\omega}{k - m\omega^2}.$$

On inspection of equation (56) and (47), the loss tangent and the tangent of the phase angle are equivalent when k is much larger than $m\omega^2$ at low frequencies. At high frequencies (and/or with significantly greater mass), the mass term becomes dominant and $\tan\psi = -\frac{c}{m\omega}$.

In Battelle testing, the loss tangent and the tangent of the phase angle are equivalent using the tested mass (rail and fastener top plate).

Laboratory testing uses only a rail and the fastener. The effective weight of these components for mass determination is on the order of 100 pounds (more for multiple fastener tests, but the same effect per fastener).

In service, the effective mass also includes the unsprung mass of the truck. The unsprung mass is at least one half-axle and a wheel, a mass about 15 times the mass used in current testing.

Further research is required to determine the representative mass for fastener dynamic testing. The mass in current and proposed testing may be indicative of the fastener characteristic, with the calculated in-service mass inserted in the calculations for predicted response.

Comparison of Past Dynamic Stiffness Test Results to Results from the Foregoing Analysis Method

Past practice defined the dynamic stiffness, k_{dyn}, as the dynamic force divided by the dynamic deflection:

$$k_{dyn} = \frac{F_0}{x_0} \tag{57}$$

Substituting and rearranging:

$$k_{dyn} = \frac{F_0}{x_0} = \left(k - m\omega^2\right)\left[1 + \tan^2 \psi\right]^{1/2} \tag{58}$$

Then, k_{dyn} is related to k, the dynamic stiffness defined by (48) as:

$$\frac{k_{dyn}}{k} = \left[1 + \tan^2 \psi\right]^{1/2}\left(1 - \frac{m\omega^2}{k}\right) \tag{59}$$

For practical cases, $k \cong k_{dyn}$ and the foregoing ratio will be very near 1 for practical purposes.

However, the past practice makes no attempt to determine all the fastener dynamic characteristics, particularly the fastener resonance frequency, and therefore provides no information required by designers and vibration specialists to evaluate or validate the transit's design.

Also, the past test practice is performed at a singular load and disturbing frequency. That disallows understanding fastener response over a range of service conditions (loads and vibration frequencies).

The current practice relies on a "dynamic to static stiffness ratio" as a measure of fastener design quality. Lower ratios are preferred by the acceptance criteria.

The basis of the dynamic-to-static-stiffness ratio presumably arises from the idea that a goal in fastener design is to provide the qualities of a spring (i.e. no damping), resulting in a linear stiffness, and a low loss factor. The result would be a dynamic to static stiffness ratio as close to 1 as possible.[68]

Basing the acceptance criteria on the spring-like characteristics of a fastener ignores that a fastener is different from a spring and therefore must be treated differently. The

[68] A spring without damping will have the same dynamic and static stiffness, as long as the spring does not bottom out.

example specifications replace the current Dynamic to Static Stiffness Ratio test procedure with a Dynamic Characterization Test. The procedures are nearly identical, with the Dynamic Characterization Test adding only testing at several different frequencies and including the analysis provided in this Attachment.

SECTION 2

Direct Fixation Fastener Example Procurement Specification and Commentary

For

TCRP Project D-07/Task 11

Development of Direct-Fixation Fastener Specifications and Related Material

by

Laurence E. Daniels
Railroad Consulting Engineer

May 2005

SECTION 2

Direct Fixation Fastener Example Procurement Specification and Commentary

This example specification is for the procurement of direct fixation fasteners. The example assumes that a Transit Agency is issuing a stand-alone contract for fasteners, independent of any other parallel contracts that may be active or planned for a project. The contractor may be a distributor, but the specification is written around the assumption that the contract will be directly with a fastener manufacturer. In this context, the Engineer is an employee of the Agency or a consultant to the Agency, the contractor is the manufacturer, and suppliers are firms providing materials (such as elastomer material, rail clips, and bolts) and services (such as machining) to the manufacturer.

The purpose of this Section is to provide a framework for discussing the intention of stipulations, for identifying technical and procedural issues, and for suggesting available alternative approaches. The purpose is not to promote a standard specification.

The example specification language is in normal *text. Commentary follows each statement in italics. Where no commentary is offered, the specification paragraph is considered self-explanatory or no discussion is warranted.*

The example specification usefully addresses the major points of a proper procurement specification but intentionally contains common misunderstandings or misstatements for discussion.

This example is for bonded plate-type direct fixation fasteners, a common type of direct fixation fastener. The specification with noted amendments also applies to non-bonded fasteners and framed fasteners.

Portions of the example specification are not suitable for the parallel category of embedded block products, although the underlying track design principles do apply. Separate specifications are encouraged for each category of ballastless track.

Qualification testing, normally integrated into a direct fixation procurement specification, is separated into Section 3 of this volume for added clarity and closer compliance with standard CSI specification format.

This example specification includes Fastener Prequalification Waiver requirements not normally included in direct fixation procurement specifications. The waiver requirements apply to products that have service experience and have previously passed qualification tests.

Broader track technical issues that influence a direct fixation specification are presented in Section 1, Direct Fixation Track Design.

SECTION 2

Direct Fixation Fastener Example Procurement Specification and Commentary

Table of Contents

DIVISION 1 - DIRECT FIXATION RAIL FASTENER GENERAL REQUIREMENTS AND PRODUCTS

PART 1 - GENERAL

1.01. DESCRIPTION

This section includes specifications for the manufacture and supply of direct fixation fastener assemblies including fastener bodies, rail clips, anchor bolts and any other components required for full assembly.

1.02. SCOPE

A. This section applies to direct fixation assemblies that fasten rail, restraining rail, guardrail, and turnout components (switches and stock rail, frogs, closure rail and frog guardrail) directly to structural support such as concrete decks using anchor bolts.

The scope must be tailored to clearly enunciate exactly the types of products the specification will cover, and the circumstances of the application. The example specification is stating that the specification applies to a rather complete range of applications from line track to turnouts.

It is appropriate to use the scope to state the environment of the application, such as train speed, maximum curvature and grades, rail size, fastener life expectation and other factors that define in general the level of service demand.

B. Similar track forms such as resilient ties (mono-block, dual block) and embedded track are not included in this section.

1.03. PREQUALIFICATION

This specification provides a procedure for a fastener design to receive a waiver from some or all of the qualification testing. The fastener must meet minimum prior service requirements and must have documentation showing it passed qualification tests.

The Engineer has full discretion whether a fastener design will be granted Pre-Qualification status. The Engineer may reject a submittal for Pre-qualification, require any additional tests within the specification, or grant a waiver of qualification testing.

It is anticipated that an agency may wish different rail clips or other change to a fastener that was previously tested. Similarly, a supplier may have to make a change in the materials or design for a number of reasons (vendors no longer available, etc.).

It is also anticipated that a prior fastener acceptance may include a waiver for a requirement that the fastener did not pass.

For any of these eventualities, the Engineer has the discretion to require additional testing for any reason he deems appropriate. The Engineer should require repetition of one or more of the required tests for the following reasons:

1. *The proposed fastener has different subcomponents from those tested.*
2. *The fastener or subcomponents are made of different materials, different compounding, or different grade than previously tested.*
3. *The manufacturing process for the proposed fastener is different from processes used in the tested fastener manufacturing.*
4. *The fastener previously failed to pass any requirement.*

For example, if the rail clip is a different design than that tested, the Engineer should require testing of the fastener longitudinal restraint, vertical uplift and rail lateral restraint.

Also, it is the intent of this paragraph that the Engineer may only call for tests within the battery of tests that comprise the direct fixation Qualification Tests.

A. Any direct fixation fastener assembly that has previously been tested and qualified in accordance with this specification or a specification with similar tests and test parameters and has a minimum 2-year full service in a rail operation equal to or more severe than the service environment for this procurement may receive prequalification certification.

B. The vendor shall submit the following to the Engineer.

1. Certification that the fastener design, manufacturing, and materials are identical to those previously tested.
2. The prior specification(s) under which the fastener design previously qualified.
3. The complete independent laboratory's report of the fastener tests, including test data and the laboratory's certification of pass/fail for every requirement.

4. Formal reports, letters or other documents that exist on the fastener system performance.

5. A list of prior installations of the fastener system stating the date, fastener quantity, rail clip type, and current contact at the transit or railway familiar with their track fastener installations.

C. The Engineer will issue one of the following notices as a result of consideration of the submittals.

1. Prequalification approval. The Engineer approves the fastener as pre-qualified, waiving the qualification testing requirements.

2. Conditional prequalification approval. The Engineer will direct additional qualification testing. The additional required tests may be repetition of previously conducted tests, similar tests or additional tests to attain qualification under these specifications. The Engineer will not direct additional testing that is not contained in this specification.

   The Contractor shall submit the results of the required testing to the Engineer for approval. The Engineer may then require further prequalification testing, deny prequalification certification, or grant prequalification approval. Fastener production shall not commence until the supplier has received prequalification approval from the Engineer, or, in the case of prequalification denial, completed full prequalification testing, submitted the test report(s) and received approval of the reports from the Engineer.

3. Prequalification certification denied. The Engineer denies the request for prequalification certification. The fastener shall be tested to, and successfully pass, these specifications.

D. Any fastener that has qualified under a specification significantly different from this specification prior to January 1, 2005 and has 5 years service in equal or more severe service will be given equal consideration for prequalification. The contractor or vendor shall make the same requests and submittals as above.

E. Where this specification varies from those generally accepted direct fixation industry practices, test procedures or test parameters that existed prior to 2004, the Engineer will accept the stipulations, procedures, test parameters, and acceptance criteria in the submitted specification governing the original test regimen provided:

1. The Engineer establishes the fastener's service record is exceptional and any occurrences of distress in the fastener where not attributable to the fastener design (derailments, extraordinary local corrosion conditions, incorrect installation or maintenance, etc.).

2. The fastener passed all tests to the original criteria (prior waivers that accepted non-conforming results will not be recognized).

In the event either of these provisions are not satisfied, the Engineer will direct appropriate tests as stipulated in this specification and to this specification's criteria.

F. All fasteners shall be subject to the production testing and quality control specifications herein.

1.04. REFERENCES

The reference list is a complete list of standards and guidelines cited or implied in the remainder of the specification. Subordinate standards referenced by a cited standard and applicable to this specification must be included in the reference list.

A. American Society of Mechanical Engineers (ASME):

ASME B1.1	Unified Inch Screw Threads (UN and UNR Thread Form)
ASME B1.3	Screw Thread Gaging Systems for Dimensional Acceptability
ASME B18.2.1	Square and Hex Bolts and Screws (Inch Series)
ASME B18.21.1	Lock Washers (Inch Series)
ASME B18.22.1	Plain Washers

B. American Society for Testing and Materials (ASTM):

ASTM A36/A36M	Standard Specification for Carbon Structural Steel
ASTM A153/A153M	Standard Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware
ASTM A325	Standard Specification for Structural Bolts, Steel, Heat Treated, 120/105 ksi Minimum Tensile Strength
ASTM A536	Standard Specification for Ductile Iron Castings
ASTM A615/A615M	Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement
ASTM A775/A775M	Standard Specification for Epoxy-Coated Reinforcing Steel Bars

ASTM B117	Standard Practice for Operating Salt Spray (Fog) Apparatus
ASTM B695	Standard Specification for Coatings of Zinc Mechanically Deposited on Iron and Steel
ASTM C39/C39M	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
ASTM D257	Standard Test Methods for DC Resistance or Conductance of Insulating Materials
ASTM D297	Standard Test Methods for Rubber Products-Chemical Analysis
ASTM D395	Standard Test Methods for Rubber Property-Compression Set
ASTM D412	Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers-Tension
ASTM D429	Standard Test Methods for Rubber Property-Adhesion to Rigid Substrates
ASTM D471	Standard Test Method for Rubber Property-Effect of Liquids
ASTM D518	Standard Test Method for Rubber Deterioration-Surface Cracking
ASTM D573	Standard Test Method for Rubber-Deterioration in an Air Oven
ASTM D624	Standard Test Method for Tear Strength of Conventional Vulcanized Rubber and Thermoplastic Elastomers
ASTM D1149	Standard Test Method for Rubber Deterioration-Surface Ozone Cracking in a Chamber
ASTM D1193	Standard Specification for Reagent Water
ASTM D1229	Standard Test Method for Rubber Property-Compression Set at Low Temperatures
ASTM D1248	Standard Specification for Polyethylene Plastics Extrusion Materials For Wire and Cable
ASTM D1566	Standard Terminology Relating to Rubber

ASTM D2084	Standard Test Method for Rubber Property-Vulcanization Using Oscillating Disk Cure Meter
ASTM D2240	Standard Test Method for Rubber Property-Durometer Hardness
ASTM E10	Standard Test Method for Brinell Hardness of Metallic Materials
ASTM E23	Standard Test Methods for Notched Bar Impact Testing of Metallic Materials
ASTM E162	Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source
ASTM E662	Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials
ASTM F436	Standard Specification for Hardened Steel Washers

C. National Association of Corrosion Engineers (NACE):

NACE RP0188	Discontinuity (Holiday) Testing of New Protective Coatings on Conductive Substrates

D. Society of Automotive Engineers (SAE):

SAE J429	Mechanical and Material Requirements for Externally Threaded Fasteners
SAE J434	Automotive Ductile (Nodular) Iron Castings

E. Steel Structures Painting Council (SSPC):

SSPC SP1	Solvent Cleaning
SSPC VIS 1	Visual Standard for Abrasive Blast Cleaned Steel (Standard Reference Photographs)

F. Rubber Manufacturers Association, Inc. (RMA):

RMA Publication Rubbers Handbook

1.05. SUBMITTALS

A. Submit design drawings, material specifications, laboratory test results, and fabrication procedures in sufficient detail to demonstrate conformance or equivalence with the Contract requirements herein.

B. Provide additional submittals as required herein.

C. Provide submittals in compliance with the general conditions for this contract.

D. DESIGN SUBMITTALS

1. Separate submittals are required for DF and SPECIAL TRACKWORK fasteners.

2. Prior to manufacture of fasteners for qualification testing submit the following for review and approval.

   a. Shop Drawings of each of the various fasteners, standard rail clip, special rail clip, anchorage assembly and shims, which detail each fastener component separately before assembly and the completely assembled fastener assembly. Drawings shall include all necessary dimensions, manufacturing tolerances and material descriptions for manufacturing the components as well as a table listing all components shown by name and by part number. Part numbers shall be assigned to fastener components and to finished assemblies. All parts identified by the same part number shall have the same physical dimensions, material composition, performance characteristics and durability.

   b. Method for identifying each lot and fastener as detailed herein.

   c. Installation and replacement procedures as detailed herein.

   d. Manufacturing plan as detailed herein.

3. All submittals shall be made in accordance with the approved schedule to allow sufficient time for review and approval of resubmittals, if required, prior to manufacture of fasteners for qualification testing.

   a. Preliminary Shop Drawings shall be submitted. Final Shop Drawings shall be submitted 30 days prior to commencing qualification testing.

   b. Lot and Fastener Numbering System.

   c. Installation Procedure.

   d. Manufacturing Plan.

4. Quality Program Plans.

   a. Quality assurance/control plan as specified herein.

   b. Test program plan as specified herein.

5. Qualification Test Results.

   Submit the following for review and approval prior to commencing fastener manufacture.

   a. Certification of the elastomer samples used in qualification testing as detailed herein.

   b. Elastomer qualification test results for each test specified herein.

   c. Anchorage assemblies qualification test results for each test specified herein.

   d. Fastener body metal qualification test results for each test specified herein.

   e. Fastener assemblies qualification test results for each test specified herein.

6. Submit qualification test results within 14 days after completion of testing.

   Submit elastomer certification with the elastomer qualification test results.

E. Production Submittals.

1. Submit the following for review and approval prior to shipping each fastener production lot.

   a. Certification of the elastomer samples used in the production testing of each production lot as detailed herein.

   b. Elastomer production test results for each test specified herein.

   c. Anchorage assemblies production test results for each test specified herein.

   d. Fastener production test results for each test specified herein.

2. Submit production test results within fourteen days after completion of testing. Submit elastomer certification with the elastomer production test results.

3. Submit the method of packaging, loading, shipping and handling the fasteners, rail clips and anchorage assemblies for review and approval prior to the initial shipment. Submit the methods no later than 60 days prior to the initial shipment.

4. Submit record drawings, which incorporate all Engineer-approved changes into the fastener Shop Drawings, for review and approval within 15 days of the final fastener delivery and prior to acceptance of the last product.

5. Submit sample fasteners for DF and Special Trackwork of each type and anchorage assemblies, complete with associated hardware and shims five days prior to commencing qualification testing. Submit direct fixation fasteners and anchorage assemblies, and shims in the quantities indicated herein.

   In practice, only several of the special trackwork fasteners are provided to fulfill this requirement.

F. QUALITY CONTROL

1. The Contractor shall submit establish, implement and maintain a detailed Quality Plan in conformance with applicable requirements of Section _____, Quality Assurance, and Section _____, Quality Control.

2. In addition to the other requirements herein, the plan shall include the following.

   a. Material specifications; certificates of compliance for all components.

   b. Process control.

   c. Quality control testing procedures and frequency.

   d. Vendor (sub-supplier) quality plan.

   e. Corrective action and disposition of defective components.

   f. Delivery protection and handling.

   g. Identification.

   h. Acceptable quality levels and sampling plans.

3. Tolerances.

   a. Manufacturing tolerances for the fastener shall be as shown in Table A.

These tolerances are allowable deviations from shop drawing dimensions. This table assumes the anchor bolt will use a ribbed washer (generally called "serrated washer") to mate with serrations cast or machined into a fastener plate.

If cant in the top plate is required, a tolerance for cant should be added.

The suggested values are more generous than in most specifications.

Table A. Direct Fixation Fastener Manufacturing Tolerances

DIMENSION	TOLERANCE
Length and width	± 1/16 inch.
Height	± 1/32 inch.
Squareness	All angles shall be within ± 0.5degree.
Centering of holes	± 1/32 inch.
Diameter of holes	± 1/32 inch.
Durometer Shore A	± 5.
Serration depth	± 1/32 inch.
Serration spacing	± 1/32 inch.
Width between shoulders at rail base	± 1/32 inch.
Rail seat area flatness measured from a straight edge placed across the rail seat area	Less than 0.050 inch.

b. Forming tolerances for the concrete test block used for fastener tests shall be as follows.

(1) The concrete surface flatness shall have a maximum 1/16 inch gap between a 16 inch straight-edge and the concrete surface all around.

(2) The elevation of top face of anchorage insert embedded in concrete shall be 0 inch above or 1/16 inch below top surface of concrete.

(3) No void in bearing surface of concrete shall be greater than 1/2 inch and total area of voids shall be less than 10 percent of total fastener bearing area.

The fastener bearing area is the foot print of the fastener on the supporting concrete.

4. Approval of the fastener design will be dependent upon successful completion of the qualification testing program specified herein.

5. All fastener testing and inspection shall be performed by a qualified, independent testing laboratory approved by the Engineer. The selected laboratory shall use the proper equipment and qualified testing personnel for the testing and inspection described in these Specifications. Fastener testing and inspection equipment and personnel shall be subject to approval by the Engineer. The Engineer, or an independent witness designated by the Engineer, will monitor the operations at the testing laboratory to ensure that the inspections and tests are being performed in accordance with approved procedures and in compliance with these Specifications.

   The stipulation for independent laboratory testing is a common requirement for objectivity. Vendors have occasionally negotiated self-testing and self-certifications on their own products, resulting in significant savings to both the vendor and procuring agency.

6. Personnel performing tests and inspections shall be qualified for such work by virtue of prior experience or training.

7. Testing equipment shall be in good operating condition, of adequate capacity and range, and accurately calibrated. Testing equipment calibration shall be certified and traceable to recognized national standards such as the National Institute of Standards and Technology. Testing equipment shall be calibrated in accordance with the schedule in the approved Quality Plan specified in Section _____, Quality Control.

G. Test Program Plan.

1. A test program plan shall be prepared describing the approach for accomplishing each of the specified fastener inspections and tests. A detailed narrative shall be prepared for each test and inspection specified herein, describing the test set-up; equipment, and instrumentation that will be used; procedure to be implemented; and the anticipated, as well as acceptable test results. Drawings detailing test equipment and test set-up of fastener or fastener component that will be tested shall be included.

2. Drawings shall show the relationship of the fastener or fastener component and all significant components of the testing equipment, including the test block. Pertinent testing drawings included in industry standard specifications herein may be referenced in lieu of actual drawings. The test program plan shall include the test sequencing.

3. Equipment specifications and calibration methods for all testing equipment used to perform fastener testing and inspection shall be included in the test program plan. The plan shall indicate the calibration certificates that will be submitted with the test reports.

4. Identity and qualifications of personnel who will perform fastener testing and inspection shall be included in the test program plan. Also include certification records for personnel who will perform nondestructive testing.

5. The test plan shall include the name and location of the testing facility, qualifications of the testing facility, a description of the testing facilities, and a layout of the test equipment that will permit efficient performance of the testing.

6. The plan shall include the proposed format for reporting test data.

7. The projected schedule for test procedure submittals, test execution, and test result reports submittals shall be included in the test program plan.

8. The test program plan shall address qualification testing and production testing separately. Elastomer, anchorage assemblies, fastener body metal, and fastener assemblies shall also be addressed separately.

9. After approval of the test program plan, any proposed changes shall be approved by the Engineer prior to implementing the change.

H. Test Report.

1. A report of test results of each test shall be submitted which includes test name, identity of test sample, original data calculations, test procedure references, test equipment identification, test personnel, time and date of test, specified requirements, actual test results, nonconformance if any, and interpretation of the results. The format for the test report shall be arranged so that the data is presented in an orderly manner.

2. Accompanying the written test reports shall be a photographic record of the tests. The photographic record shall contain photographs of sufficient clarity to distinguish relevant details as described or referenced in the respective written report.

3. Copies of calibration certificates shall be submitted with the initial test results. If test equipment is recalibrated while work is being performed on this Contract, calibration certificates shall be submitted for the recalibrated test equipment with the test reports of the first tests performed after recalibration.

4. The Engineer shall be notified in writing not less than seven days in advance of dates scheduled for any tests or inspections. The Engineer retains the right to witness the tests.

I. Manufacturing Plan

The specification requirement for a manufacturing plan provides one means of validating that processes follow accepted industry practices where there may not be guidelines or standards. The manufacturing plan submittal should not reveal proprietary information or industrial secrets.

For suppliers seeking pre-qualification (waiver from qualification testing), this narrative must state what if any materials, suppliers, subcontractors, or processes are different for the proposed procurement from the fasteners previously manufactured and tested.

The Contractor shall prepare a manufacturing plan including:

1. An activity network delineating each step of production that will produce the fastener configuration shown on the approved Shop Drawings and made of the approved materials.

2. A narrative shall be included describing each activity. Special attention shall be given to key procedures such as curing temperature, curing time, molding pressure and heat-treating.

3. A list of all company names and locations of any plant or subcontractors plant where work will be performed on any fastener or component part of any fastener. This list shall show what type or work function each company shall perform. Off the shelf, standard products such as bolts and nuts, need not show manufacturing location, but must show the company name and address from which it is proposed to be purchased.

PART 2 - PRODUCTS

2.01. PRODUCTS AND MATERIALS

A. General

1. All fastener components shall comply with the minimum standards set forth herein.

2. All surfaces of materials shall be free of gaps, burrs, sharp edges, wrinkles, waves, blemishes, or other unsightly or unsafe defects that potentially detract from the functionality, durability and neat appearance of the finished product.

Some specifications include ambient conditions under the General requirements. These include temperature range, relative humidity, rainfall, snow, maximum wind speeds, and air quality (including typical pollutant content).

B. The same brand, type and style of fasteners shall be used throughout.

The intent is that fasteners are uniform in a project. Ideally the fasteners on any Agency are uniform to allow interchangeability, avoiding confusion by field maintenance personnel, and minimize stocking costs of spare components.

The ideal seems to be difficult to achieve. Procurement regulations, changing consultants and viewpoints, and specialist consultants recommending different fasteners purportedly for ground borne vibration mitigation, conspire to defeat standards within an Agency much less fastener uniformity within a project.

These realities notwithstanding, this requirement imposes the responsibility for uniformity on the Designer. If the project will have different fasteners, there must be a different specification for each fastener.

C. Fastener Dimensions

The dimensions in this example specification must be reviewed prior to use in an actual specification. The example is typical but excludes some direct fixation fastener designs and is not appropriate for products used in other categories of ballastless track. The criteria for specification dimensions are:

- *The dimensions are stated as a maximum envelope reflecting policies and practices of a particular agency. Critical clearances, maintenance equipment constraints, reduced fastener exposure to derailment, and plinth dimensional constraints are among reasons for fastener envelope dimensional constraint.*

- *Agencies with existing direct fixation fasteners usually wish new fasteners to be interchangeable with the existing fasteners. This limits inventory stocking expense. It also eliminates incorrect installation of replacement components or fasteners (most track maintenance on transit agencies is performed at night with poor lighting).*

The maximum anchor bolt insert depth, not included in the example specification, must be added if the plinth depth is restricted.

Dimensions for other ballastless track products will be framed in a manner similar to the example, but with different limits for the desired configuration. For embedded block systems, the maximum depth of the block embedment must be stated for the same reason as stating a maximum anchor bolt insert depth.

The referenced Figure 2 in this example specification must be replaced with a correct figure with the stated dimensions.

1. When completely assembled with clips and anchors all parts of the fastener above the concrete trackbed shall stay within a design envelope 14-1/2 inches long minimum and 16 inches long maximum, measured horizontally perpendicular to the rail; and 7 inches wide minimum and 8 inches wide maximum, measured horizontally parallel to the rail.

2. The height of the fastener body in the installed position measured vertically from the base of the fastener body to the base of rail at the rail centerline and excluding shims shall be no greater than 2 inches.

3. No portion of the completely assembled fastener, including rail clips and anchor bolts, shall extend any higher than 4 inches measured vertically from the base of rail at the rail centerline.

4. The normal-to-rail offset from centerline of anchor bolt to centerline of fastener shall be 5-1/4 inches. The parallel-to-rail offset from centerline of anchor bolt to centerline of fastener shall be 1-3/4 inches. In addition, the centerline of anchor bolt shall be no closer than 1-1/2 inches from any side.

5. When installed, no part of the anchorage insert shall extend into the track concrete deeper than 5-1/2 inches from the concrete trackbed surface.

6. The diameter of the fastener body and anchorage assembly component holes through which the anchor bolt passes shall not be less than 0.895 inch nor more than 0.938 inch.

7. With the rail clips removed from the otherwise assembled fastener, no portion of the fastener shall extend any higher than 1-1/2 inches above the base of rail, as measured vertically from the base of rail at the rail centerline.

8. These and other dimensional requirements are shown graphically in Figure 2.

The following subparagraphs D through Q are the fastener design criteria. The example specification is for a bonded plate-type fastener without cant using an elastic rail clip.

D. Specific Fastener Requirements

1. The fasteners shall be for use with *[insert rail size]* continuously welded running rail, jointed rail, within special trackwork and insulated rail joints.

2. The fastener shall consist of as few components as economically and technically feasible for ease of assembly, disassembly and maintenance in the field.

3. The anchor bolt shall be capable of being removed and installed using a socket wrench or vertical bolting machine, without removing the rail clip.

4. When installed in track it shall not be necessary to raise the rail more than 1-1/2 inches to remove or install the fastener.

This requirement prohibits the use of studs as anchor bolts and prohibits rail encasement designs that require a number of fasteners to be partially disassembled to remove a single fastener.

5. Welding shall not be used in the fabrication or assembly of the fastener nor any fastener component.

This requirement intends to limit metal plate warping from weld heat and avoid possible fatigue in the rail lateral retention feature of the fastener. If elastic rail clips (boltless rail clips) are preferred, this requirement will probably eliminate any design that does not have a casting for the top plate.

6. Except for fasteners used under switch points and stock rails, there shall be no specific field or gauge side to the fastener.

This requirement is only possible if the plate has no cant. The advantage of the requirement is the symmetry prevents installation error (remember, most transit maintenance replacements will be done at night under adverse lighting conditions). The requirement will be deleted if an agency desires cant in a fastener.

7. Longitudinal restraint properties of the fastener shall be identical in both longitudinal directions. Lateral restraint properties of the fastener shall be identical in both lateral directions.

The longitudinal restraint symmetry may be assumed without this stipulation. The requirement is optional.

The requirement for uniform lateral restraint in both directions is not appropriate for fasteners with cant, or designs intentionally designed with field and gage sides.

8. Rail fastener shall provide a means of adjusting the rail laterally within a range of plus or minus 1 inch in increments of 1/8-inch or less. The lateral fastener adjustment shall be integral with the fastener anchorage assembly.

Most specifications require ½" lateral adjustment with 1/8" increments. The accumulation of construction tolerances and the need for future adjustments for rail wear, as an example, should be carefully considered in stating the amount of adjustment required. The adjustment requirement

becomes critical during construction when construction errors require use of the adjustment, disallowing future maintenance adjustment without moving anchor bolt inserts.

The requirement for adjustment "integral with the fastener anchorage assembly" requires that the entire fastener body is adjusted rather than having adjustment using the rail clip. The designs that best fit this requirement have the anchor bolt through the bottom fastener plate only (or through a frame element of frame-style fasteners), in contrast to designs where the anchor bolt goes through both the top and bottom plates. The bottom plate anchor configuration has the advantages of simplifying the insulation of the bolt from the rail and eliminating potential elastomer compression from over-torquing the anchor bolt.

Fastener designs that do not have a bottom plate or frame are prohibited by this and other stipulations in the example specification. To allow designs without bottom plates or frames, these requirements must be amended or eliminated from the specification.

The 1/8" adjustment increment is essentially requiring a ribbed washer plate for the anchor bolt. The washer's ribs fit into machined serrations in the plate's surface providing mechanical interlocking against lateral movement of the fastener.

9. Lateral or longitudinal stability of the rail shall not be reduced in any adjustment position. All requirements of these specifications shall be satisfied for all increments of adjustment of the fastener. Friction alone shall not be used as a means of adjustment. Lateral adjustment shall be by a method that does not require removal, substitution or addition of any fastener components.

This requirement prohibits fastener designs that use top plate adjustment (rail is moved laterally relative to the top plate).

The restriction from using friction as a means of adjustment prohibits systems without serrations (mechanical interlocking) in the lateral adjustment feature.

The restriction may also prohibit cam-style adjustment designs. Cam-style adjustment allows infinitely small adjustments without serrations or special washers.

The last sentence prohibits designs that require changing a serrated washer, insulator or rail clip to adjust the fastener. It also prohibits designs that require addition or removal of shims or spacers to make an adjustment.

10. If serrations are used for lateral rail adjustment, not less than three interlocking serrations shall be engaged in any position of lateral adjustment. The bottom plate serrations shall be an integral part of the bottom plate.

This and the previous stipulations essentially require serrations and ribbed washers for lateral adjustment without directly stating the intention. This stipulation simply assures that the foregoing requirements are implemented with minimum serration engagement within the adjustment range. The example specification is calling for a design where the anchor bolt only penetrates the bottom plate and the adjustment will be at the anchor bolt/bottom plate interface.

The requirement for bottom plate serrations is not appropriate if the specification intends to allow fastener designs with adjustment at the rail clip, fasteners with anchor bolts through top and bottom plates and fasteners with no bottom plates.

11. A lot and fastener numbering system shall be developed for marking each fastener. A lot number, daily production identification number, and manufacturer's name or trademark shall be permanently and clearly stamped or molded on the top of each fastener. The marking shall be readily visible in the installed position. The location and method of marking of identification data shall be shown on the Shop Drawings.

E. Fastener Body Requirements

1. The rail fastener body shall consist of an elastomeric pad bonded between metal top and base elements. Bonding shall use the vulcanization process.

The example specification is for a bonded fastener. This and the following requirements would be amended to remove the bonding requirement or to specifically include both bonded and non-bonded fastener designs. The benefits of different fastener designs is presented in Section 1, Direct Fixation Track Design, paragraph VI.A.

The example specification requirement for a bottom plate prohibits any design without a bottom plate ("base element") which may exclude some fastener designs. The wording should be amended if the procurement intends to include fasteners without bottom plates.

The requirement for bonding by vulcanization prohibits gluing elastomer pads to the plates. This may be an unnecessary requirement for modern materials and processes. While vulcanization bonding is proven for this application, fastener designers may find beneficial manufacturing

efficiencies or improved fastener configurations by using other bonding methods without loss of long-term performance.

2. The metal top and base elements shall be designed with sufficient material strength, thickness and shape to withstand the loading requirements of the specifications and the transit system.

3. The metal top element shall have a flat rail-bearing surface in the center of the fastener that supports the rail directly without intermediate pads or shims beneath the rail. The rail seat area shall be flat to provide a uniform bearing surface within the tolerances of Table 1.

4. Shoulders which position and secure the rail against lateral movement, both with and without the rail clips installed, shall be integral with the metal top element along the entire rail bearing surface and shall be set parallel on both sides of the rail base. Width between shoulders at the rail base shall be 5-9/16 inches.

   The requirement calls for fixed rail seat shoulders, consistent with the requirement that all lateral adjustment will be performed by moving the entire fastener.

   The width between shoulders is for 112 to 119 RE rail. The dimension must be changed to the appropriate width of other rail base widths, adding 1/16" to the nominal rail base width.

5. The bottom of the fastener shall be parallel to the rail seat so as to provide no cant to the rail.

   If cant is desired, this requirement will be replaced with a stated cant value.

6. The bottom of the fastener shall be flat and without any downward projections.

7. The fastener's metal top and base elements shall have full bearing on the elastomer pad in all positions of lateral fastener adjustment.

   The stipulation, taken rigorously, limits introduction of voids and shapes in the elastomer to generate desirable mechanical properties. The internal shape of the fastener's elastomer is purview of the fastener designer. The requirement constrains the design unnecessarily.

   This and the following requirements may be better combined and replaced with a similar statement such as "Adjoining surfaces of the metal top and base elements with the elastomer pad shall be fully bonded."

On the other hand, stray current specialists discount voids within the elastomer as insulated space, fearing moisture and dust will accumulate in any open space. A specification may mitigate this concern by adding a requirement that insulating coating shall be applied to the full plate surfaces facing the elastomer where design shapes of the elastomer would not contact the plates.

The requirement will affect bonded fasteners somewhat differently than non-bonded fasteners. Bonded fasteners typically mold the elastomer into shapes (voids, cells, etc.). Non-bonded fasteners typically have a uniform pad and would meet this stipulation.

8. The fastener design shall be such that the elastomer is fully bonded to all parts except for the detachable components.

   To allow non-bonded fastener designs, this stipulation would be amended, such as "If the fastener design is a bonded fastener, the elastomer shall be fully bonded to …"

9. Bonding of any part of the fastener to the rail or track concrete is prohibited.

   This requirement is unnecessary for bonded fasteners. The bonding process, called vulcanization, is performed at the time of molding the elastomer into its final shape. The top and bottom plates are coated with an adhesive on faces mating with the elastomer. The mold with the plates is heated to an elevated temperature and elastomer inserted into the mold. This process would not take place in the field.

10. All metal surfaces of the fastener body's top and bottom elements that are not covered with elastomer shall be coated with the adhesive used to form the bond of elastomer to metal.

    During the vulcanization process, this requirement will turn the adhesive into an insulating material. The material protects the plate material from corrosion.

11. The bottom of the base element shall be free of elastomer except that minimal flashing of bonded elastomer, not exceeding 1/32 inch in thickness, will be acceptable providing it does not interfere with retention of proper anchor bolt tension nor otherwise interfere with the performance of the fastener.

    Whether there is a protective coating or an elastomeric coating on the bottom of the bottom plate is a fastener designer prerogative.

    The fastener designer has a number of options to minimize corrosion that are prohibited by the example specification. The bottom of the plate may

be coated by bonding elastomer or other durable material, such as in this example specification. The plate may be made of corrosion resistant material. The designer may choose not to employ a bottom plate, having the elastomer bear directly on the support.

While this commentary encourages implementation of local choices, it also encourages a balance of those choices with specification flexibility where warranted. This issue is one where the example specification should be more flexible.

12. The rail seat area of the top element shall be free of elastomer except that minimal flashing of bonded elastomer, not exceeding 1/32 inch in thickness, will be acceptable providing it does not interfere with the performance of the fastener, and it allows full contact of the rail with the rail seat.

13. Except within the rail seat area and on the fastener bottom, loose, unbonded flash not extending out greater than 1/4 inch from a bonded surface will be allowed.

14. The elastomer pad shall not be thinner than 5/8 inch.

    This and the following requirement are not recommended fastener criteria language because they intrude too deeply into fastener designer prerogatives.

    The fastener dimensional constraints are covered previously and in Figure 2. If there is a construction or operational reason for limiting the elastomer thickness, those constrained dimensions should be presented in Figure 2 and the associated text.

    A better approach to the underlying technical issues for this and the following requirement is to state the desired fastener stiffness and the load at that stiffness along with a maximum strain rate. Suggested language for the requirements of the example agency is: "The fully assembled fastener shall have a vertical stiffness of 150,000 lb/in ± 10% at a load of 15,000 lb with the maximum strain at any point within the elastomer no greater than 15%."

15. The load deflection on fasteners of the elastomer shall not exceed 25 percent of its uncompressed thickness for a load of 15,000 pounds applied vertically to the rail in a fully assembled rail fastener. Precompression of elastomer in rail fasteners in the installed position shall be included in determining the total compressive strain.

    See the comments for item 14, above.

16. No mechanical metal distortion during the molding process is allowed.

F. Fastener Anchorage Assembly Requirements

[This section is for plate-type fasteners and is inappropriate for embedded block type systems.]

1. DF fastener bodies shall be secured to the track concrete with a minimum of two anchorage assemblies, with an equal number on each side of the rail. The anchorage assemblies shall be located as shown in Figure 2. Each anchorage assembly shall consist of an anchor bolt, anchorage insert, lock washers, washers and other components required for lateral adjustment of the fastener.

2. Special trackwork fastener bodies shall be secured to the track concrete with four anchorage assemblies, two on each side of the fastener. Each anchorage assembly shall consist of an anchor bolt, anchorage insert, lock washers, and washers. Other components required for lateral adjustment of the fastener shall be provided. Lateral adjustment feature of the fastener shall be a part of the fastener anchorage assembly.

   Track load capacity and safety will be met with two anchor bolts. The additional bolts in this example may unnecessarily limit fastener designer prerogatives. A preferred statement is: the fastener design shall have a minimum of two anchorage assemblies.

   The requirement to have the lateral adjustment by the anchorage assembly may not be a good practice for turnout fasteners because a single fastener supports two rails or a rail and a switch point. A good design will allow relative lateral adjustment between the two rails. It is not clear whether that is possible using the language in the example.

3. The anchorage assembly shall anchor the metal base element to the track concrete, with a 7/8 inch diameter anchor bolt. The anchor bolt shall be threaded into a female-type anchorage insert embedded in the track concrete perpendicular to the fastener base. Anchor bolts shall not penetrate the metal top element.

   This requirement precludes fastener designs with anchor bolts through the top and bottom plate. If a desire is to include a wider range of fasteners, or if the desire is to replicate existing fasteners with anchor bolts through the top plate, this requirement should be amended.

   The benefits of bottom plate only anchorage are noted previously.

   The requirement stipulates the anchor bolt assembly will include a female insert embedded in the support concrete. This prohibits use of bolts or studs concreted into the support with the thread up to secure the fastener with a nut. Stud arrangements have too little concrete

engagement to reliably withstand the torque requirements. Studs are also objectionable because the rail and fastener have to be lifted free of the stud to change the fastener or repair the stud, requiring substantial more effort and track time compared to repairs with female inserts.

This example does not make an exception for special trackwork where fastener designers must incorporate adjustment of multiple rail on the same fastener. There should be a provision here and other effected stipulations that allows lateral adjustment of either rail (including a switch point) by methods other than adjusting the anchor bolt. Alternatively, the stipulation should be amended to exclude special trackwork fasteners from the requirement in the last sentence.

4. The anchorage assembly shall not permit more than 1/8 inch total lateral movement of the fastener relative to the concrete track bed when the anchor bolts are finger tight.

   The requirement simplifies track alignment by allowing the rail and fastener to be positioned along a track section without having to torque each bolt in order to secure the rail in proper position. Once the rail and fastener are in the correct position throughout the section, all the anchor bolts are then torqued to the correct value.

   The requirement is again stipulating mating serrations at the adjustment feature. If a fastener design does not have serrations at the adjustment feature, the rail and fastener will move during the alignment process if the bolt is not substantially torqued as each fastener is positioned. In this case, the alignment process can become iterative, and inefficient, with repeated passes required to achieve correct alignment.

5. Each anchorage assembly shall require a lock washer.

   Lock washers are common in Direct Fixation configurations. The inclusion of lock washers should be a fastener designer's prerogative. Please see Section 1, Direct Fixation Track Design, paragraph VI.E.6. for bolt loosening prevention.

G. Electrical Insulation Requirements

1. The fastener design shall provide a 3/4 inch minimum electrical leakage distance under all load and adjustment conditions. The electrical leakage distance shall be measured from any grounded portion of the fastener to any charged portion of the fastener by the most direct path that does not pass through insulating material. The leakage distance path shall exclude recesses and other geometric configurations that are susceptible to collecting and holding moisture, dust, and other electrically conductive materials.

The leakage distance or leakage path is generally the distance between the top and bottom fastener plates, the elastomer thickness in non-bonded plates. The leakage path may be increased by coating the sides of the top and bottom plates (item 4, below).

The language in this requirement discounts shapes (voids) within the elastomer as insulation because those spaces may be water and dust collectors. While the concern is noteworthy, it may conflict with a fastener designer's ability to create shapes within the elastomer to obtain beneficial mechanical properties.

The resistance and impedance measurements in the following subparagraphs 5 and 6 take precedence over the statement excluding recesses in considering the leakage distance.

2. Recesses or notches which penetrate the metal top element and expose the elastomer shall be free draining at all values of track superelevation from 0 to 8-1/4 inches if draining in a direction perpendicular to the rail and at all values of track profile grade from 0 to 4 percent if draining in a direction parallel to the rail.

   The maximum superelevation and grade must be changed to those in an agency's design criteria.

   This requirement prevents a fastener design that does not have drained top surface pockets. Preferably, the top surface will not have any feature that will allow water to collect on the surface or allow water to enter the fastener.

   Related sections on water accumulation on, in or under fasteners are:

   - *The example construction specification includes a requirement that the concrete adjacent to a fastener will not be above the bottom of the fastener to disallow water accumulation under a fastener.*

   - *Section 1, Direct Fixation Track Design, paragraph VI.A, that track designs with the cant in the concrete surface aids drainage away from the fastener.*

3. Fastener surfaces shall be resistant to conductive oil and dirt buildup and facilitate effective periodic cleaning by track maintenance equipment and personnel.

   While the concern here is for electrical properties, the fastener should tolerate all oils. Rubber in its native state is highly susceptible to degradation when exposed to most oils. Additives in the elastomer chemistry prevent degradation when exposed to oil.

4. Exposed metal surfaces on the sides of the fastener shall be covered by at least a 1/16 inch of the same elastomer as used in the fastener body. The elastomer covering shall be securely bonded to the metal surfaces during the same vulcanization process as the rest of the elastomer.

   This requirement intends to increase the insulated path between the rail and the support. Some fastener designers use the principle that the issue is properly satisfied when elastomer is terminated beyond the active elastomer surfaces – surfaces that do not bulge and are not strained.

5. The minimum resistance for 500 V dc shall be 10 MΩ when dry and 1 MΩ when wet.

6. The minimum impedance for frequencies between 20 Hz and 10 kHz with 50 V ac shall be 10 kΩ when wet.

   Refer to Section 1, Direct Fixation Design, paragraph VI.B.3 for discussion of fastener resistance and impedance requirements.

H. Vibration Isolation Requirements

1. The rail fastener shall be designed to attenuate vibration forces transmitted to the concrete track bed by vehicle operation on the rail.

   Some specifications insert performance values in place of this general statement. A performance value would be a static fastener stiffness value at a stated load, for example.

2. The elastomer used to attenuate vibration forces shall be fully bonded to both the metal top element and the metal base element. Separate resilient pads placed between rail base and the fastener rail seat is prohibited. The fastener static and dynamic stiffness requirements shall be met without supplemental resilient pads.

   The stipulation will be modified if the specification intended to allow non-bonded fastener designs.

   Many direct fixation specifications use this and similar language in the attempt to have a fully integrated, fully compliant system to reduce the complexity of installation and maintenance.

   Rail pads are prohibited because elastic rail clips would unload during a wheel pass reducing the available longitudinal restraint.

   The requirement intends that fastener design meet the mechanical requirements and performance requirements using only the main

elastomer and plate(s). That is not a prohibition against installing resilient pads under the fastener.

Some specifications also prohibit elastomeric washers in bolted assemblies. That practice is questionable because spring washer elements should be included in a proper bolt design to maintain bolt tension during vibration.

3. The vibration isolation performance of the fastener shall not be compromised in any position of lateral adjustment.

4. Dimensions affecting the shape of the elastomer in the fastener shall be determined by the manufacturer so that the complete rail fastener conforms to the physical requirements and acceptance criteria for all fastener tests.

I. Fastener Installation

The installation requirements in this section are for the test bed construction, only.

1. The anchor bolt shall be capable of being removed and installed, using a socket wrench or vertical bolting machine without removing the rail or rail clips. Special tools developed to perform a unique function related to the fastener or not available from commercial sources shall not be permitted.

2. For height adjustment during installation, one or two shims of variable thickness shall be placed by the installer between the fastener base and the concrete trackbed to provide for vertical adjustment to compensate for construction tolerances and variations. The nominal design thickness of the shim shall be 3/8 inch. The Contractor may vary the shim thickness from a minimum of 1/8 inch to a maximum of 1/2 inch in 1/16 inch increments. The shims shall be high-density polyethylene conforming to the specifications herein. The Contractor shall provide all shims, including those shims required for fastener testing.

   The example specification departs from most specification by incorporating a shim pad in the design that is 3/8" thick. That is, the standard installation is the fastener and a 3/8" shim. This allows downward vertical fastener adjustment without grinding the concrete support, as well as upward shimming.

   Since the maximum allowable shim height is ½" in the example specification, a better choice for this shim may be ¼" thick rather than 3/8".

3. The Contractor shall place the fasteners upon a 1:40 canted reinforced concrete trackbed. The concrete will have a 28 day compressive strength

of 4,000 pounds per square inch. The female-type anchorage inserts will be cast into the concrete during the pour spaced beforehand to match the anchor design of each fastener and fastener spacing along each rail. They will be set perpendicular to the top of the track concrete so that the top face of the insert is flush with the top surface of the concrete. The Contractor shall ensure that the top surface of the concrete is flat and free of cavities and voids. Concrete forming tolerances will match those required of the concrete test block for the fastener tests. Bonding agents for application to base of fastener, to shims, or to concrete surface during installation shall not be permitted.

4. A relative installation tolerance between adjacent top of shim bearing surfaces of 1/16 inch will be allowed.

   It is more practical to specify that the rail seats of adjacent fasteners are within 1/16", because that is where the difference is most important. This tolerance must be complied with rigorously.

   Note that the bearing area tolerance (Direct Fixation Construction Specification, Part A, Section 4, paragraph 3.09.B.7.e) may supersede this requirement. That section requires 90% full bearing of the rail on the fastener, fastener on the shim and shim on the concrete support within the rail footprint.

   This requirement would not meet the bearing area requirement if the rail seat of a fastener is 1/16" below the two adjacent fasteners.

5. The Contractor shall submit a set of instructions, approved by the manufacturer, for installation and replacement of the fasteners in-track. The instructions shall describe the proper method of assembly and installation that shall be followed by the installer to ensure optimum performance and longevity of service. The component assembly and installation specifications and instructions provided in the installation requirements shall be in total agreement with the approved fastener as-built drawings and the installation conditions used for the fastener assembly qualification testing on the concrete test block. As a minimum, the installation instructions shall include the following.

   a. Installation procedures

   b. Installation drawings

   c. Anchorage insert care and installation

   d. Shim thickness and placement restrictions

   e. Lateral adjustment method

f. Anchor bolt torquing requirements

g. Allowable tolerances

h. Installation tools required

i. Installation requirements at bonded insulated joints

j. Installation requirements at rail joints

J. Metal Components

1. The metal top and base elements shall each be one-piece rolled, forged or cast steel or ductile iron.

2. The rail seat and clip mating surfaces of the top element shall be smooth, free from injurious warp and other imperfections in surface and projecting fins of metal caused during forming.

3. Ductile iron castings shall be minimally Grade 65-45-12 in accordance with ASTM A536. The chemical composition shall meet the acceptable level per SAE J434. The Brinell hardness in accordance with ASTM E10 shall be within the limits set by SAE J434. The microstructure shall be within the limits set by SAE J434. The fracture energy at 21.1 degrees C in accordance with ASTM E23 shall be equal to or greater than 3 foot-pounds.

   Ductile iron is also known as nodular iron or spherical iron. ASTM ductile iron grades are based on mechanical properties. The iron in the example, commonly used in this application, has a tensile strength of 65,000 psi, a yield strength of 45,000 psi and elongation of 12% for a 2 inch long specimen. The material will have a hardness between 156 and 217 Brinell Hardness from SAE J434 and the following chemical composition (also from the SAE standard):

Carbon	*3.20 – 4.10%*
Silicon	*1.80 – 3.00%*
Manganese	*0.10 – 1.00%*
Phosphorus	*0.050% max.*
Sulfur	*0.035% max.*
Magnesium	*0.025 – 0.060%*

   The microstructure for this grade of steel in SAE J434 must comply with Figure 1.

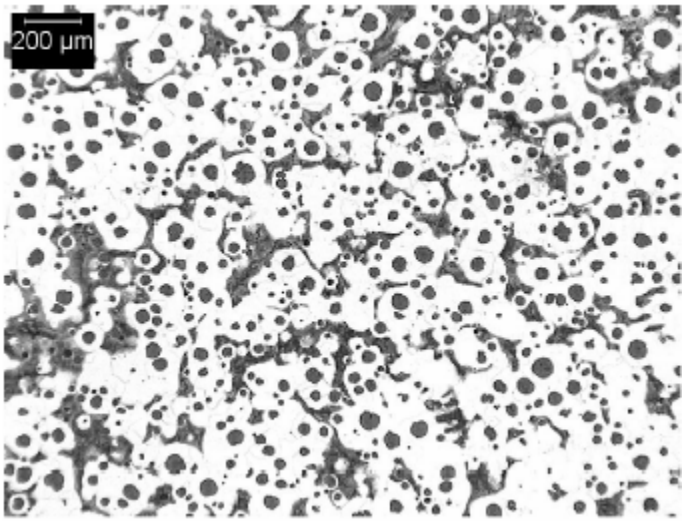


Figure 1. Required Microstructure for Grade 65-45-12 Ductile Iron

The specification should state that the specimen for ASTM E23 testing is per Figure 3 in the standard, and the specimen tested using the Izod Impact method. The expected results should be at least 12 ft-lb on average.

4. Rolled steel plate shall be minimally ASTM A36/A36M steel. The fracture energy at 21.1 degrees C in accordance with ASTM E23 shall be greater than 15 foot-pounds.

The required chemistry according to ASTM A36 is:

Carbon, max, %	*0.25*
Manganese, %	*No reqmt.*
Phosphorus, max, %	*0.04*
Sulfur, max, %	*0.05*
Silicon, %	*0.40 max*
Copper, min, % when copper steel is specified	*0.20*

The minimum mechanical properties for plates less than ¾" thick are:

Tensile strength, ksi [MPa]	*58–80 [400–550]*
Yield point, min, ksi [MPa]	*36 [250]*
Elongation in 2 in. [50 mm], min,	*23%*

ASTM requires a tensile test for plates more than ½ inch thick.

The specification should state the impact test specimen for the ASTM E23 is Type A.

The expected fracture energy from this material should average about 44 ft-lb.

5. Direct fixation fasteners shall have provisions for installing two resilient rail clips, one on each side of each rail, for securing the running rail to the metal top element of the fastener body. The clip holder shall be a permanent and integral part of the metal top element.

   With this requirement in combination of several others, the example specification is stating the top plate should be a plate formed or machined from a single steel or iron piece. Elsewhere, the specification disallows welding to attach the clip holder. Resilient clips are often called elastic clips.

   This specification is prohibiting rigid rail clips and any configuration that requires bolts to retain the rail clips. If such configurations will be permitted, the example requirements must be amended.

6. The rail clips shall be held by a clip holder that does not allow lateral rail adjustment on the metal top element.

   This and other requirements require lateral adjustment to be at the anchor bolt, and not the rail clip. This requirement must be deleted if rail adjustment using adjustable rail clips or adjustable shoulders are permitted.

K. Elastomer

1. The elastomer shall be natural rubber based as defined in ASTM D1566 or polychloroprene (neoprene). A blend shall have more than 50 percent of natural rubber or neoprene. The manufacturer shall formulate the elastomer based on successful long-term case histories in service conditions similar to those at the Engineer.

   Please see Section 1, Direct Fixation Track Design, paragraph V.A., for descriptions of elastomer materials and discussion of issues for direct fixation fastener design.

2. Except as required to meet the requirements for identification markings, exposed elastomer surfaces of the finished fastener shall be smooth with a finish and appearance equal to or better than an F-3 designation in accordance with RMA Rubbers Handbook.

   The cited finish is third of four finish designations. Termed a "Commercial Finish", the standard requires "Surfaces of the mold [to]

conform to good machine shop practice…" No surface roughness is stated for the F3 designation.

3. The Durometer A hardness shall be between 40 and 70 as measured in accordance with ASTM D2240.

While it is common to have a elastomer hardness value in a direct fixation specification, and while the range provided is fairly generous[1], the stipulation is not necessarily useful if it limits fastener designer prerogatives.

Elastomer hardness is one of several parameters the fastener designer may use to meet specification criteria. Elastomer geometry or "shape factors" created by cavities within the elastomer are a second means for imparting desirable mechanical properties. Various methods of forming the plates and frames for fasteners allow vertical and lateral mechanical property control, a third part of the approach to fastener design.

The requirements the fastener designer is attempting to satisfy are the mechanical properties (static and dynamic stiffness, primarily), strength (plate bending, elastomer strain), and electrical properties.

These criteria may be satisfied by softer or harder elastomers depending on the designer's choices. For example, the designer may prefer a harder material to provide durability and higher electrical insulating properties, which is shaped to a desired stiffness value.

Another design approach is to use an elastomer with lower hardness that allows higher elastomer strain rates, with more of the stiffness value imparted by the material itself (less dependence on shape factors). Frames or upturned bottom plates have been incorporated to control shear strain.

Some fasteners are designed to have dual stiffness values. These fasteners have a low stiffness value at lower loads and significantly higher stiffness at high loads. These properties are achieved by shapes in the fastener, elastomer material selection and reinforcement by the plate system.

L. Anchor Bolts

[1] Examples of Shore A hardness values: *tire tread is 60, an inner tube material is 50, and a rubber band is about 35.*

Direct fixation fastener anchor bolts are uniform in North American transit direct fixation applications. Please see Section 1, Direct Fixation Track Design, paragraph VI.E. for discussion of anchor bolt design issues.

1. The anchor bolts shall be 7/8-9 UNC heavy hex structural bolts of the following material in accordance with ASME B18.2.1, except with 2 ½" clean thread length.

   a. ASTM A325, Type 1, zinc coated, or

   b. SAE J429, Grade 5, zinc coated.

   These bolt standards have 1 ½" thread length. To meet the requirements of following subparagraph 3, the clean thread length must be 2 ½".

   Properties of the specified bolt materials are:

Designation	*Material*	*Proof Load (lb)*	*Yield Strength (psi)*	*Tensile Strength (psi)*
ASTM A325, Type 1	*Medium Carbon*	*74,000 through 85,000*	*81,000 through 92,000*	*105,000 through 120,000*
SAE J429	*Medium Carbon*	*74,000 through 85,000*	*81,000 through 92,000*	*105,000 through 120,000*

2. The threads shall be the Unified Coarse Thread Series with a Class 2A tolerance in accordance with ASME B1.1 and ANSI B1.3.

3. The length shall be sufficient to provide at least 1-1/2 inch thread engagement with the anchorage insert threads when the fastener is installed at the maximum vertical adjustment, using 1 inch of shims.

   The example specification earlier establishes ½" maximum shim height. The stipulations here require the bolt length to be compatible with 1" shim height. While this requirement does not supersede the maximum shim height of ½", it prudently recognizes that construction realities may force the agency to resolve a problem by allowing additional shim height.

   An overriding concern is that all the bolts on a project or on an agency will be identical, particularly in length, and within the minimum thread engagement.

   See paragraph 2.01.I in this Section for additional comments on shim height and anchor bolts.

M. Washers.

The washers shall be for 7/8 inch diameter bolt of the following material.

1. Hardened steel washers in accordance with ASTM F436. Carbon steel washers shall be zinc coated. Weathering steel washers shall be supplied for use with ASTM A325, Type 3 bolts.

   Type 3 bolts are made with weathering steel. The specification is requiring the washer steel to match the steel in the bolt. However, paragraph L.1, above does not allow weathering steels. The second sentence should be deleted.

2. Plain washers in accordance with ASME B18.22.1, Type B, regular, zinc coated.

3. Lock washers in accordance with ASME B18.21.1, helical spring, extra duty, zinc coated.

The washers in this example should not be construed as a preference. There are many arrangements of washers and a variety of washer types. The critical nature of the anchor bolts suggests the anchor bolt design should be a fastener designer's prerogative. The only justification for the specificity in this example is to constrain the components to be compatible with existing Direct Fixation components at an agency.

N. Serrated Washer or Block

1. The serrated washer or block shall be for a 7/8 inch diameter bolt.

2. Serrated washer or block shall be ductile iron castings minimally Grade 65-45-12 in accordance with ASTM A536. The chemical composition shall meet the acceptable level per SAE J434.

Typical fastener lateral adjustment arrangements use a block with bottom serrations (ribs) that engage machined serrations (grooves) in the fastener top or bottom plate. The example specification is for a washer-like block with a centered hole for the anchor bolt. Designs that adjust the rail position using a rail clip may have a serrated block or the clip bottom surface may have serrations. In the latter case, this stipulation is for the rail clip.

The specification is requiring ductile iron, implying that the part will be cast. If the part is to be machined from steel, ASTM A36 is the proper material specification.

O. Anchorage Inserts

1. Anchorage inserts shall be non-welded, female type, and shaped as required to prevent rotation and pullout. The total length shall not exceed 5-1/2 inches. The insert shall remain within the envelope indicated on Figure 2 in all positions of adjustment.

   The features important for direct fixation anchor bolt inserts are

   - *The body must have external "keys" or ribs to engage the embedment concert to create torque resistance.*
   - *The external bottom shape should have some protrusion to generate pullout resistance.*

   The insert pullout resistance is developed by an inverse cone of concrete, thus the resistance depends on the depth of embedment. The depth of the insert should be coordinated with other criteria such as the minimum plinth depth.

   The depth in the example specification is suitable for all inserts designed for this purpose. If other criteria demand a shorter insert than stated in the example, the pullout capacity of the insert must be tested or certified as having the required capacity (see Section 3, Direct Fixation Tests).

2. The inserts shall be threaded to receive the anchor bolts using 7/8-9UNC-2B threads in accordance with ASME B1.1. For anchorage inserts to receive zinc coated bolts, the pitch diameter shall be increased to account for the zinc coating thickness. The allowance for the pitch diameter shall be six times the minimum zinc coating thickness specified. The threads shall be coated with a rust inhibitive to prevent rust formation during pre-installation storage yet will not hinder the threading on and tightening to proper torque of the anchor bolts during installation in track. The rust inhibitive shall be indicated and specified on Shop Drawings for approval by the Engineer.

   If the bolt is hot-dipped galvanized, the Engineer must have the bolt and insert checked for thread compatibility.

   Please see Section 1, Direct Fixation Track Design, paragraph VI.E for discussion of thread coatings, torque and insert pullout resistance.

3. The top of the insert in the installed position shall have a smooth and flat bearing surface. The bearing surface shall have a minimum area of one square inch.

4. A nylon or plastic pull-away type plug capable of sealing the insert threads against concrete seepage that is easily removable shall be provided with each insert.

5. The insert shall be made of one of the following materials.

   a. SAE J429, Grade 5 steel.

   b. Carbon steel with 0.50 percent maximum carbon and hardness in the range of 248-352 BHN (or 24-38 HRC).

   c. Ductile cast iron, Grade 65-45-12, in accordance with ASTM A536.

   These materials are typical citations for inserts. The reference specifications' material properties and chemistry are the same as included in the above commentary for plates.

   The following statement requires an insulating coating to minimize corrosion of the insert and stray current development. However, those coatings have not been fully successful. Thread corrosion and frozen bolts are a primary cause of failure in direct fixation installations. Construction invariably nicks the insert coating, allowing corrosion from stray current.

   Inserts are also made from high density plastics for this purpose and are gaining acceptance in direct fixation applications because the products eliminate corrosion and generally have a smaller envelope. In designs using reinforcement bar in the plinth, insert clearance from reinforcement is a universal difficulty.

6. All inserts shall be coated with a fusion-bonded epoxy.

   In most direct fixation specifications, this paragraph cites several epoxy coating products by name. Federal Acquisition Regulations discourage naming specific products, so the products are noted by their absence.

   Please refer to the comments in preceding item 5 regarding the effectiveness of insert coatings.

7. The fusion-bonded epoxy coating shall be applied to all surfaces of the insert, except for the threaded hole, which shall remain uncoated. The coating shall be applied in accordance with ASTM A775/A775M, except for the following modifications.

   a. The coating shall be applied by either the electrostatic spray method or the fluidized bed method, as recommended by the epoxy manufacturer.

b. Prior to surface preparation, oil and grease shall be removed by solvent cleaning, vapor degreasing, or steam cleaning in accordance with SSPC SP1.

c. The fusion-bonded epoxy coating shall be applied in accordance with the coating manufacturer's latest published instructions.

d. The dry film thickness shall be 12 mils minimum to 30 mils maximum. The thickness shall be measured with a magnetic thickness gage.

e. The coating shall be uniform and free of runs, sags, or chips. The coating shall meet the discontinuity (holiday) test requirements herein.

f. The bend test specified in ASTM A775/A775M is not required.

P. Shims

1. Polyethylene Pads

a. Polyethylene shims shall conform to ASTM D1248, Type III, Class C, Grade W8 for high-density polyethylene plastic with a durometer hardness of 60 to 65D. The hardness shall be stable between + 140 degrees F and – 40 degrees F.

b. The nominal thickness of the pad shall be 3/8 inch. The Contractor may vary pad thickness from a minimum of 1/8 inch to a maximum of 1/2 inch in 1/16inch increments. Test shims shall be 3/8 inch thick.

Track designed with a prescribed shim thickness is recommended to allow for upward and downward fastener adjustment (see subparagraph I.2, above, for further discussion). The track designer should evaluate the accumulation of track material tolerances and construction tolerances to determine the design shim thickness.

c. The shims shall provide a ½ inch projection beyond the sides of the fastener perpendicular to the rail and a one-inch projection beyond the sides of the fastener parallel to the rail. Anchor bolt holes in the shim shall be located at each bolt location. The hole shall be one inch in diameter.

The ½ inch projection is another measure to reduce stray current.

d. The shims shall be used for qualification and production quality control tests and delivered to the Engineer after the testing is complete.

2. Galvanized Vertical Steel Shims

Steel shims are not expected to be needed for the laboratory test bed. This section may be removed. It will be repeated in the direct fixation construction specification.

a. Shims shall be used only where approved. Shims shall be galvanized steel shims in general conformance with shape, size, and configuration of the direct fixation fastener, and as designed by the direct fixation fastener Supplier.

b. Material shall be ASTM A 1011 steel sheet for shims 1/8" and over in thickness, galvanized in accordance with ASTM A 653, Grade G 165. Material shall be ASTM A 591, commercial quality, coating class C for shims less than 1/8" thickness.

c. Shims shall conform to the following:

(1) Shim configuration same as direct fixation fastener.

(2) Deviation from flatness on both surfaces not to exceed 0.020" at the mid-ordinate of the shim surface.

(3) Sheared edges painted with galvanize repair paint conforming to DOD-P-21035.

(4) Smoothly finished, free of warps, projecting fins and other imperfections caused by shearing, drilling or punching.

(5) Shims shall be slotted for anchor bolts in a manner that permits shim insertion without removal of the fastener, but prevents shim movement if the bolts are loosened.

d. The following tests shall be performed prior to delivery to the site:

(1) Test at least 2 percent of total for conformance to requirements specified in Subparagraph c above.

(2) Test at least one per 200 shims for conformance to coating thickness specified in Subparagraph b above.

(3) Submit certified test reports substantiating conformance to the specified requirements.

Q. Metal Protective Coatings

1. The following coating shall be used for metal components when specified.

   a. Hot dip galvanizing in accordance with ASTM A153.

   b. Mechanical zinc galvanizing in accordance with ASTM B695, Class 55-110.

R. RAIL FASTENERS

1. The rail fastener system includes rail clips and rail clip fasteners.

2. The rail fastener system shall be compatible with the existing rail fastener deployed on the railway. Alternative systems shall be subject to the Engineer's review and approval.

   The compatibility with an existing direct fixation fastener stated in the example requires that the anchor bolt spacing, the rail seat cant (or lack of cant), and the thickness of the fastener at the middle of the rail seat is identical to the existing fastener, as a minimum. A more rigorous interpretation requires interchangeable rail clips, anchor bolts and all washers. The compatibility issue may cause difficulty in public procurements where rigorous interpretations may be construed as sole sourcing the procurement to the manufacturer of the existing fastener.

3. Boltless, resilient rail clip systems are preferred.

   a. Clips shall be forged from alloy steel and quenched to achieve a minimum longitudinal restraint of 2,400 pounds per rail seat.

   b. The same rail clip shall be used in all positions of adjustment.

The foregoing parts of the example specification cannot be met without boltless, resilient clips. The stated "preference" is language that may be more comfortable for procurement officers, but no federal regulations would be broached by stating the requirement directly.

Resilient or elastic rail clips must be a high strength steel to achieve the performance criteria of this stipulation. Alloyed, quenched steel is necessary.

The requirement for the same clip intends to mean only one clip design will be provided for all purposes, except for the circumstances in the following paragraph.

4. Special Rail Clips at Rail Joints

   a. Special rail clips shall be used for rail joints and insulated rail joints, and in special trackwork.

   b. At insulated rail joints, the rail clips shall not come in contact with any portion of the rail joint, thus helping ensure the integrity of the insulation capability of the joint.

   c. Contractor altered rail clips shall not be accepted

The following stipulations 5 through 7 eliminate all but one clip design. The argument in favor is an agency will have standardized components, highly desirable for track maintenance efficiency. The argument against the practice is prejudices creep into the procurement processes based on perhaps as little as one person's perspectives. That individual many times is a consultant with no long-term obligation for the consequences of a specification. The dilemma between track maintenance efficiency and open processes will undoubtedly persist. The process of formulating a specification must be based on clear understandings of the maintenance difficulties and the procurement regulations.

5. The rail clips shall be designed to be easily installed and removed by one person with standard, readily available hand tools, but not able to vibrate loose under load. Clip installation and removal shall not damage the fastener body, clip holder, clip, or rail. The rail clip shall not notch nor otherwise damage the rail base during installation or removal.

6. The rail clips shall be held to the metal top direct fixation element by shoulder aligned with the rail base.

   This stipulation limits the number of clips to one design that is available from multiple manufacturers.

7. Neither the rail clip nor the clip shoulder shall make point contact with the rail. The rail clip contact area with the rail shall not be shorter than one inch measured along the rail and not smaller than 5/32 square inch in area.

   This and the following requirement eliminate clip designs that have edges or shapes that are perceived to create damage. The statements are sufficiently vague that any design other than that favored by item 6 may be dismissed by judgment of the Engineer.

8. The clip action in track shall be such that longitudinal rail slippage can occur without denting, carving, or scoring the rail flange and without permanently stressing, bending, twisting, or otherwise damaging the clips, or clip shoulders.

9. The fasteners shall have either stops or visible permanent marks to indicate the proper position to which the spring clips are to be inserted.

   Spring clips are the same as resilient clips and elastic clips.

10. The fastener shall permit removal of the rail clips so that the rail may be removed by lifting it vertically until it is completely free of the fastener without disturbing the horizontal and vertical alignment of the fastener.

    The intent is a design that allows rail changes or repairs can be made without disturbing the fastener body.

11. The modal frequencies of the spring clip and the metal top element shall be different by such a factor that the spring clip will not vibrate loose from the metal top element.

    This requirement may be deleted without consequence. The hypothesis underlying the requirement arises from inexplicable ground vibration frequencies. Research has not validated the hypothesis.

12. The rail clip assembly shall not include any elastomeric components.

    This requirement eliminates rail insulators, insulators in clip holders or other components, resulting in a design where all fastener mechanical and electrical properties must be integrated with the fastener's body unit.

    The requirement reduces the number of components of a fastener, which lowers maintenance effort and part stocking costs.

13. Special Trackwork Direct Fixation Fasteners

    a. Rail clip assemblies for special trackwork rail fasteners may vary from as many as one rail clip assembly on each side of the rail base, or a rail clip assembly opposite an adjustable rail brace, or two opposing adjustable rail braces.

    b. Where rails converge and there is insufficient space between rails for a clip assembly, a bolted clip may be used. Where there is insufficient space for a rail clip assembly, a rail stop may be used. In any case there shall be no more than two consecutive fasteners without a rail clip assembly or rail clip.

2.02. QUALIFICATION TESTING

This subsection establishes the test regimen for qualifying the fastener design. The regimen is different from production testing, although some tests are performed as part of the production quality control.

There are two general approaches to the test regimen that are explained in detail in Section 3, Direct Fixation Qualification Testing. The different approaches attempt to resolve the difficulty of representing service loads in the laboratory.

The details of these two approaches are discussed in the Qualification Test Commentary.

One test approach loads the rail head with a short rail section supported by one or two fasteners. The arrangement will not allow field level vertical and lateral load combinations (L/V load ratios) because the rail will roll over sufficiently to damage clips at field L/V loads. Tests involving rail rotation are limited. We call this the Quasi-static Vertical Load approach because the vertical load is a slow (static) application during stiffness characterization tests, and the vertical load is maintained at uniform a uniform value during varying lateral load in the repeated load test.

The second approach loads the rail nearer the rail base with the rail supported by up to four fasteners spaced 1 inch apart. This arrangement allows field level forces with the complexity near that which will occur in service, but the forces to individual fasteners are not a representative test. We call this the Synchronized Vertical and Lateral Load approach, because the vertical and lateral load vary in a prescribed synchronized manner during the repeated load test.

The following example specification represents the Quasi-static Vertical Load approach, although the differences between approaches for this portion of the specification are minimal. The significant differences become evident in the test setup and execution, presented in Section 3.

The tests are those included in most direct fixation procurement specifications. Some have little or no value and are optional. Please see Section 3 for comments on individual tests.

A. General: All qualification tests shall be successfully completed to the satisfaction of the Engineer prior to commencing any production of fasteners or fastener components.

B. The test procedures are in Section 3, Direct Fixation Qualification Tests.

C. Testing of Elastomer: All elastomer qualification tests shall be successfully completed and approved by the Engineer prior to commencing qualification testing of fastener assemblies.

1. Hardness Test.

2. Tensile Strength Test.

3. Ultimate Elongation Test.

4. High Temperature Compression Set Test.

5. Low Temperature Compression Set Test.

6. Accelerated Aging Test.

7. Resistance to Ozone Cracking Test.

8. Oil Absorption Test.

9. Adhesion to Metal Test.

10. Flame Spread and Smoke Generation Test.

11. Electrical Resistivity Test.

12. Water Absorption Test.

13. Rheology (Cure and Strength Indicator) Test

14. Specific Gravity Test

D. Testing of Anchor Assemblies: All anchor assemblies that are tested shall have successfully met the test requirements and been approved by the Engineer prior to commencing qualification testing of fastener assemblies.

1. Restrained Pullout Test.

2. Unrestrained Pullout Test.

3. Torsion Test.

E. Testing of Fastener Body Metal: Each metal specimen shall have met the minimum impact requirements and be approved by the Engineer before fastener assembly qualification testing proceeds.

1. Charpy Impact Test.

F. Testing of Fastener Assemblies:

1. Following review and approval of the Shop Drawings, and the review and approval of the foregoing qualification test report(s) of the elastomer, anchor assemblies, anchor inserts, and fastener body metal by the Engineer, the fastener assembly tests shall commence.

2. Four complete fastener assemblies shall be manufactured and identified as A, B, C and D. Fastener assemblies shall be installed in accordance with paragraph 2.01.l, and tested according to the sequence in Table B.

3. Testing and qualification of restraining rail, guard rail or special trackwork type fastener assemblies shall be conducted by the same methods. For special trackwork fasteners, the Supplier shall submit a test sequence, within one month after notice of award that includes all tests in Table A on a representative sample of special trackwork fasteners reflecting the various fastener designs within the special trackwork unit.

Table B. Fastener Group Tests and Test Sequence

	Fastener Groups To Be Tested		
Test	Preliminary Tests	Intermediate Tests	Final Tests
Vertical Load Test.	A, B, C, D		A, B, C, D
Vertical Uplift Test.	A, B, C, D		A, B, C, D
Lateral Load Test.	A, B, C, D		A, B, C, D
Lateral Restraint Test.	A, B, C, D		A, B, C, D
Longitudinal Restraint Test.	A, B, C, D		A, B, C, D
Voltage Withstand Test.	A, B, C, D		A, B, C, D
Electrical Resistance Test.	A, B, C, D		A, B, C, D
Electrical Impedance Test.	A, B, C, D		A, B, C, D
Corrosion Test (744 hours).		C	
Vertical and Lateral Repeated Load Test (3,000,000 cycles).		A	
Repeated Load Test with One Anchor Bolt Loosened (15,000 cycles).		A	
Uplift Repeated Load Test (1,500,000 cycles).		C	
Push-Pull Test (2,000 cycles and 1,000,000 cycles).		D	
Dynamic to Static Stiffness Ratio Test (1,000 cycles).		B	
Heat Aging Test (336 hours).		B	

G. Test Failure: Should any fastener assembly fail a test, the entire sequence of tests shall be performed on a new fastener assembly. If the fastener assembly must be modified to pass any test, Shop Drawings of the new design shall be approved by the Engineer before performance testing is

continued. A lot of new fastener assemblies shall be produced and all tests performed on the new fastener design. The revision, approval and test cycle shall continue until fastener assemblies are approved, but no longer than twelve weeks after acceptance of the new design. The cost of all such additional designing, manufacturing, and testing caused by failure of any component that does not comply with these Specifications, including expenses for witnessing tests, shall be at no additional expense to the Engineer. After the Engineer has approved the fastener assembly design, changes in the design, materials, and manufacturing process shall not be made without written approval by the Engineer. Should the Contractor propose a change, the Engineer may require retesting of the fastener as altered. All such testing shall be performed in the same laboratory on the same equipment, and insofar as possible, by the same laboratory personnel as the qualification test.

PART 3 - EXECUTION

3.01. GENERAL PRODUCTIONS

A. Production of direct fixation fasteners or components prior to the Engineer's review and approval is prohibited.

B. Manufacture all direct fixation fasteners using the same methods used to produce qualification test pieces.

3.02. SOURCE QUALITY CONTROL

A. Production quality control inspection and testing shall be as specified herein.

B. Production Testing

1. Production quality control tests shall be performed during fastener manufacture to verify that the fasteners meet the requirements of these Specifications.

2. Perform all inspections and tests in accordance with the approved test program plan.

C. Elastomer Production Testing

1. The Contractor shall require the manufacturer to perform all inspections and tests specified herein on each of two samples certified to have been taken from the first production size batch of elastomer used in the manufacture of the initial fastener production lot of 50 or more fasteners and having an equivalent degree of cure to the fastener elastomer. Use

a separate pair of samples for each test. The elastomer batch shall meet the acceptance criteria for all the elastomer tests as specified herein.

There is confusion in the example specification between Contractor, Manufacturer and Agency (or Engineer). This specification is written with the assumption that an Agency is procuring fasteners from a Contractor who will actually make the fasteners. The Contractor is obtaining the elastomeric compound from a supplier (usually a chemical company) who is called the Manufacturer in this specification.

2. After the first production size batch, the manufacturer shall perform the inspections and tests specified below on each of two samples certified to have been taken from the elastomer batch used in the manufacture of each fastener production lot and having an equivalent degree of cure to the fastener elastomer. Use a separate pair of samples for each test. The elastomer batch shall meet the acceptance criteria for the following tests as specified herein.

   a. Hardness Test

   b. Tensile Strength and Ultimate Elongation Tests

   c. Tear Resistance Test

   d. Rheology (Cure and Strength Indicator) Test

   e. Specific Gravity Test

3. Should any elastomer sample fail to meet the test requirements, the entire elastomer batch shall be rejected and the entire fastener production lot manufactured from the rejected elastomer batch shall also be rejected.

4. Should an elastomer batch be rejected, the manufacturer shall perform all tests and inspections specified herein on each of two samples certified to have been taken from the next production size batch of elastomer used in the manufacture of fasteners and having an equivalent degree of cure to the fastener elastomer. Use a separate pair of samples for each test. The elastomer batch shall meet the acceptance criteria for all the elastomer tests as specified herein.

D. Anchorage Assemblies Production Testing

1. Test Method

   a. A discontinuity (holiday) test shall be performed on each anchorage insert produced, in accordance with NACE RP0188, at the fusion-bonded epoxy applicator's plant using a high

voltage holiday detector at 2 kV. The test shall be performed with a brass brush on the stem.

b. As an alternative a discontinuity (holiday) test shall be performed on each anchorage insert produced using a low voltage holiday detector at 9 V to 100 V DC. The test shall be performed using an electrolyte solution.

This specification requires 100% testing of all the inserts. There is a perennial question whether testing a statistical sample is more practical to determine that there is no systematic flaw in the process. By the time inserts are mounted for the final concrete installation, a significant number of inserts will require coating touch-up to repair scrapes and dings in the coating. Thus the inserts should receive 100% inspection in the final field inspection before the final concrete pour.

2. Any piece having holidays shall be rejected, however, repair of one minor holiday per insert shall be permitted. Repaired inserts shall be retested as specified above, and the repaired insert shall be free of holidays upon repair. Any repaired inserts that fail the retest shall be rejected. An insert shall be repaired and retested only once. Any repaired inserts that fail the retest may be stripped of all coating, recoated as specified herein and retested as specified herein. The repair method shall conform to ASTM A775/A775M. The Contractor shall submit the proposed repair method with the test procedure for approval by the Engineer.

E. Fastener Production Testing

1. Production quality control testing of fasteners shall be performed on two fasteners from the first 50 fasteners produced and on two fasteners from each production lot. A production lot is defined as a quantity of manufactured and completed fasteners produced in a continuous run, but not to exceed 5,000 units. Fasteners shall be selected for testing by the Engineer.

2. All production quality control tests for each particular production lot shall be successfully completed and the test reports for the tests approved by the Engineer before that production lot will be accepted. Should either of the sample fasteners from a production lot fail any test, a second pair of fasteners from the same lot shall be subjected to the complete set of production quality control tests. If either of the second pair of tested fasteners fails to meet the test requirements, the entire production lot shall be rejected or tested and only those fasteners that successfully pass the production quality control tests will be accepted. The cost of all such additional testing, including costs for the Engineer or a representative of the Engineer to witness the tests, of any fastener or

fastener component that does not comply with these Specifications shall be at the Contractor's expense.

3. Fasteners used for production testing and meeting all test requirements shall be permanently marked as production test fasteners and shall be delivered separately to the Engineer.

4. Production quality control testing of fastener assemblies shall include the following tests as specified herein.

   a. Vertical Load Test

   b. Lateral Restraint Test

   c. Longitudinal Restraint Test

   d. Voltage Withstand Test, Electrical Resistance and Impedance Test

5. Contractor shall certify that all fasteners were manufactured in the same manner as the fasteners subjected to the Qualification Testing. Upon submittal of certification, the entire lot of fasteners will be released by the Engineer for shipment.

3.03. PACKAGING, LOADING, SHIPPING AND HANDLING

A. General:

1. The Contractor shall replace all fasteners damaged during packaging, shipping, and unloading with new units at no additional cost to the Engineer.

2. Fasteners used in qualification testing shall be delivered separately to the Engineer and shall not be included in the final delivered quantity.

3. All containers shall be clearly marked with the identification of item contained, Supplier's name, shipping date, number of pieces, destination, and gross weight.

B. Packaging:

1. Pack fastener bodies, rail clips, anchor bolts and anchor assemblies separately in units convenient for handling. The fastener bodies shall be in weatherproof containers, banded on pallets for forklift handling. Anchor bolts, and anchor assemblies shall be packed in sealed, waterproof, steel or heavy-duty plastic barrels, or other approved weatherproof container. All containers and/or pallets containing non-metallic parts shall specifically protect the components from damage by ultraviolet light and

shall be capable of withstanding outdoor storage without additional cover for at least one year.

2. All fastener shipments shall be adequately prepared to preclude damage during shipment.

3. Package and label spare parts and replacement materials in moisture-proof containers suitable for shipment and storage. Attach copies of shipping list within moisture-proof and see-through envelopes in the package so that the list is readable from the exterior of the package.

C. Shipping: All fasteners and spare parts shall be shipped to the location(s) designated by the Engineer.

D. Handling, Unloading, and Stacking: Fastener bodies and associated hardware shall be unloaded and stacked by a method that will prevent damage to or loss of products. The Contractor shall furnish all equipment, labor, rigging, dunnage, and other materials necessary to perform the work.

E. Spare Parts

1. Unloading: Unload the spare parts and materials in a manner that will prevent damage to the packages and the contents. The Engineer will open the packages and inspect spare parts and materials for damage. Damaged parts and materials will be returned to the Contractor to be replaced with undamaged parts and materials, at no additional expense to the Engineer. Damage to any moisture-proof containers for the spare parts and replacement materials shall be repaired at no additional expense to the Engineer.

2. Delivery: Deliver spare parts and materials not later than the date of Final Acceptance at a location specified by the Engineer.

PART 4 - MEASUREMENT AND PAYMENT

4.01. GENERAL

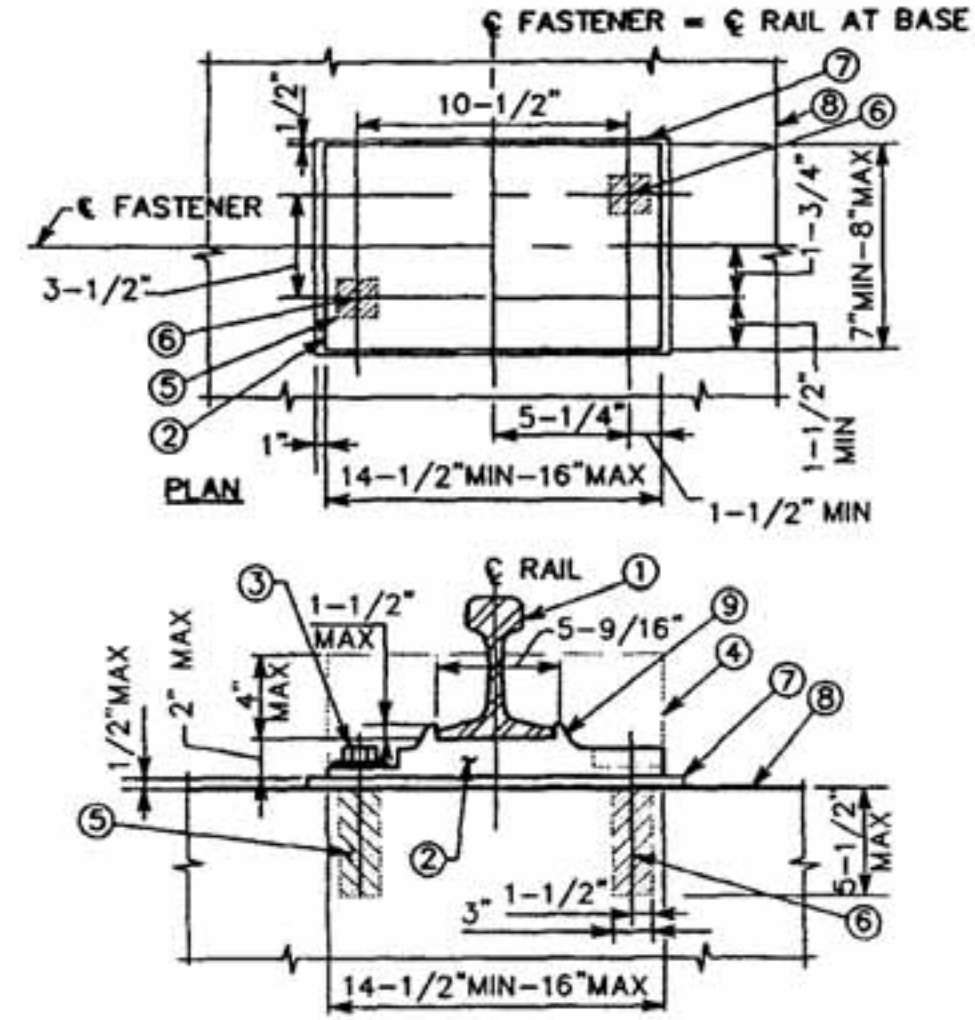
The contract terms for each project should be inserted in place of the following example terms.

A. The design and qualification testing for direct fixation fasteners will not be measured and paid for separately and all costs associated therewith shall be included in the items of work to which they apply. Submittals for design and qualification testing program shall also be included in the items of work to which they apply and no additional compensation will be allowed therefore.

B. Direct Fixation Rail Fasteners will be measured and paid for at the contract unit price as shown in the Schedule of Quantities and Prices for each complete direct fixation fastener delivered, including fastener body, rail clips, anchor bolts with silica sand epoxy grout or cast-in-place threaded anchor inserts, washers, production quality control tests, inspection, shipping, unloading, and stacking.

C. The fabrication and delivery of spare parts for direct fixation fasteners as specified herein will not be measured and paid for separately. Quantities of spare parts required for each bid item are shown in the table at the end of this Section and are included in each respective bid item for payment.

D. Shim plates and polyethylene pads will not be measured and paid for separately and all costs associated therewith shall be included in the items of work to which they apply.



1. 119 RE RAIL
2. FASTENER BODY
3. 7/8 ANCHOR BOLT
4. FASTENER ENVELOPE
5. ANCHORAGE ENVELOPE
6. CENTER LINE - ANCHOR BOLT
7. SHIM
8. CONCRETE TRACK BED
9. SHOULDER

Figure 2. Example Clearance Envelope.

Modify this Figure for local criteria.

SECTION 3

Direct Fixation Fastener Example Qualification and Production Test Specification and Commentary

For

TCRP Project D-07/Task 11

Development of Direct-Fixation Fastener Specifications and Related Material

by

Laurence E. Daniels
Railroad Consulting Engineer

May 2005

Section 3

Direct Fixation Fastener Example Qualification and Production Test Specification and Commentary

This example specification is a framework for explaining the purpose and methods of tests commonly required for direct fixation fasteners.

The example specification is in normal *text with commentary following each specification paragraph in italics.*

Specification paragraphs without commentary are considered self-explanatory or comment is not warranted.

The test setup and sequence of testing is provided in Section 2, Direct Fixation Fastener Example Procurement Specification & Commentary.

The requirements for restraining rail and turnout fasteners are a bit vague in this portion of the specification. For example, some suppliers have a variety of Direct Fixation fasteners for a single turnout. The specification does not state whether all the different fasteners require qualification. In practice, it is generally prudent to subject several of the different fasteners to qualification testing but not all. Specification language to reflect an agency's preferences on testing these fasteners should be included. The depicted test beds are not compatible in detail with restraining rail and turnout fasteners. The control of deflections at switch points has different requirements than in the example specification. The example specification provides a basic framework that requires additional consideration at the specification planning and implementation stage.

Broader technical issues that establish the underlying reasons for these test requirements are discussed in Section 1, Direct Fixation Track Design.

Section 3

Direct Fixation Fastener Example Qualification and Production Test Specification and Commentary

TABLE OF CONTENTS

Section 3

Direct Fixation Fastener Example Qualification and Production Test Specification and Commentary

List of Figures

Direct Fixation Fastener Example Qualification and Production Test Specification and Commentary

1. TESTING OF ELASTOMER

Much of the commentary on elastomers is paraphrased from Sommer and Yeoh[1], with other specific sources footnoted as appropriate.

1.01. PREPARATION OF TEST SPECIMENS

Elastomer tests shall be performed on each of two specimens that are identical in all respects to the elastomer proposed for use in fasteners. Use a separate pair of specimens for each test. Use specimens taken from a batch of compound used for making the elastomeric component of the fastener and having a cure equivalent to the cure of the elastomeric component. Before testing, condition specimens for at least seven days at 23°C and 50 percent +/- 5% relative humidity.

The requirement for elastomer test specimens from the fastener compound batch precludes the use of laboratory-mixed compounds where dispersion of fillers is better than large factory mixers that will produce the fastener's elastomer. The language allows curing of the compound in the laboratory.

The paragraph also states a time to condition the specimen. Rubber formation process creates molecular crosslinks that give rubber its properties. Crosslinking, which is the vulcanization process, does not stop precisely at the time the rubber is taken from the mold. It is a standard practice not to test rubber within 16 hours of vulcanization. The fastener assembly tests should have a longer time between vulcanization and testing because the fasteners have greater elastomer bulk.

1.02. ELASTOMER MATERIAL

Test specimen shall correspond to the rubber content specified in Section 2, Direct Fixation Fastener Example Procurement Specification & Commentary, paragraph 2.01.J.1.

[1] *Engineering With Rubber*, Ed. Alan N. Gent, Hanser Publishers, copyright 1992 by Carl Hanser Verlag, Chapter 10.

Direct Fixation fastener specifications have gravitated to natural rubber as the primary component of the elastomer material. Early bonded Direct Fixation fasteners (~1975) and successors used neoprene (polychloroprene) blends. There is no evidence that compounds with either material has an advantage in the long-term performance of the fasteners.

Please see Section 1, Direct Fixation Track Design, paragraph V.A., for discussion of elastomer materials.

1.03. ELASTOMER TESTS

A. Hardness Test:

1. Test Method: ASTM D2240.

2. Acceptance Criteria: 40 to 75 Durometer, Shore A.

While it is among the most widely used tests in the rubber industry, rubber or elastomer hardness has less fundamental meaning and correlation to material properties than Brinell Hardness measurements for steel. Rubber technologists use hardness as a convenient means of classifying rubber materials.

The range of allowable rubber hardness for Direct Fixation fasteners is fairly wide. For comparison, the Shore A hardness of a golf ball cover is 98, faucet washer is about 90, tire tread is 60, an inner tube material is 50, and a rubber band is about 35.[2]

An acceptable alternative measurement method is ASTM D1415, Standard Test Method for Rubber Property: International Hardness. This test purports to have a predictable relation to the Young's modulus of the elastomer.

B. Tensile Strength Test:

1. Test Method: ASTM D412.

2. Acceptance Criteria: 1,500 pounds per square inch, minimum.

See the commentary for item C, following, for tensile test comments.

C. Ultimate Elongation Test:

1. Test Method: ASTM D412:

[2] Harold Belofsky, *Plastics: Product Design and Process Engineering*, Hanser Publications, copyright 1995 by Carl Hanser Verlag, pg 146.

2. Acceptance Criteria: 350 percent, minimum.

The tensile strength test and ultimate elongation test are obtained in a single, simple test procedure.

While a Direct Fixation fastener has relatively light tensile loads, the tensile test is a general measure of the material's quality. Fillers used in rubber to reduce material costs usually decrease tensile strength. Tensile properties are sensitive to inadequate dispersion of fillers during mixing. The tensile test is particularly useful for checking rubber vulcanization for adequate cure.

The tensile properties are related to material fatigue.[3]

The test procedure requires a dumbbell-shaped specimen (Figure 1) to be stretched (Figure 2) until the material yields (which is the "tensile strength" for the purposes of this specification) and ultimately breaks (ultimate elongation).

Figure 1. Dumbbell Test Specimen

[3] G.J. Lake and A.G. Thomas, *Engineering With Rubber*, Ed. Alan N. Gent, Hanser Publishers, copyright 1992 by Carl Hanser Verlag, pg. 117

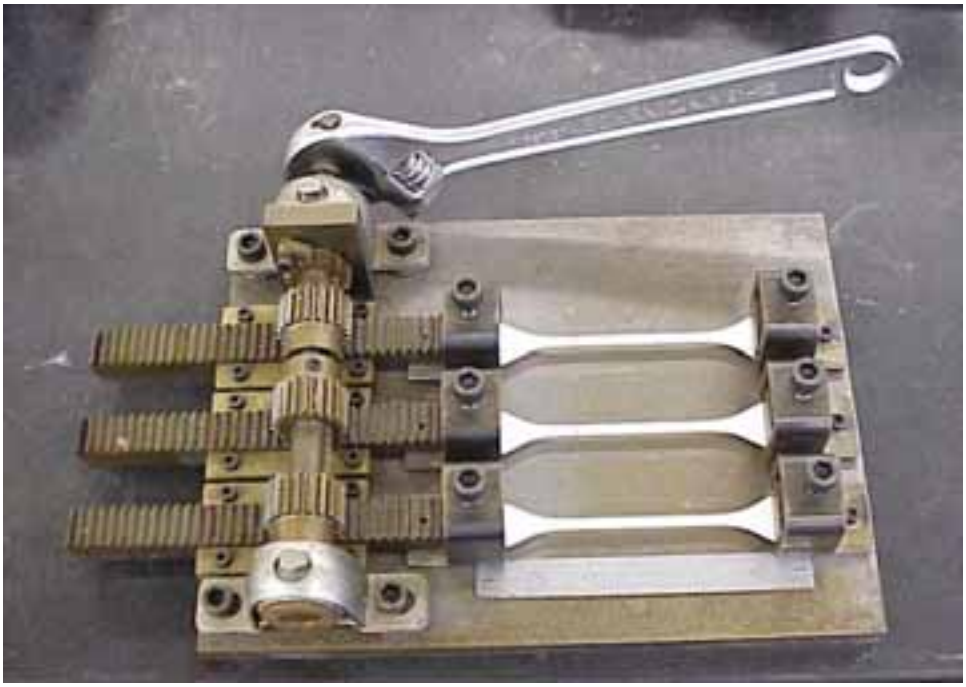


Figure 2. Tensile Strength and Ultimate Elongation Test of Dumbbells.

The specification's parameter values for compliance are chosen to assure that the material has sufficient strength (reflecting the absence of the foregoing detrimental factors of fillers, mixing and curing) while having suitable flexibility.

The percent ultimate elongation means that the specimen must elongate 350% of its original gauge length before failing.

D. High Temperature Compression Set Test:

1. Test Method: Test for 22 hours in accordance with ASTM D395, Method B. The test shall be conducted at a temperature of 70°C.

2. Acceptance Criteria: The set shall not exceed 25 percent.

See the commentary for the following item E. for comments on High Temperature Compression Set Test.

E. Low Temperature Compression Set Test:

1. Test Method: Using ASTM D1229, test for 70 hours at a temperature of minus 10°C.

2. Acceptance Criteria: The compression set at 30 minutes after release (plus 30 reading) shall not exceed 65 percent.

Compression set testing is used to determine the ability of elastomeric materials to maintain elastic properties after prolonged compressive stress. The test measures the permanent deformation of the specimen after it has been exposed to compressive stress for a set time period.

These simple tests represent the fastener material under the clamping force of anchor bolts (for many Direct Fixation fastener designs) over a representative range of temperatures from –10°C (14°F) to 70°C (158°F).

Method B means the measurement is taken under constant deflection (Figure 3 & Figure 4) rather than constant force (Method A)

The tests are less representative of the compression and rebound of the fastener material under rail loads.

If the anchor bolt passes through the top plate, the tests will have relevance because the bolt may impart compression load on the elastomer in some fastener designs. The test will have less relevance in fastener designs where the anchor bolt only passes through the bottom plate or through a frame.

The procedure is rather imprecise and irreproducible, attributed to the nature of elastomers inconsistent recovery from large deformations with time, and the inability to accurately measure the deformation (the specimen deforms out of plane and the outer portions of the specimen recover at different rates than the interior portion).

The compression set of the elastomer is tested more appropriately in the vertical load test (q.v.), where the fully assembled fastener is tested with the elastomer in its design configuration.

For these reasons, these tests are considered optional for all fastener designs.

Figure 3. Compression Set Apparatus with Cylindrical Specimen

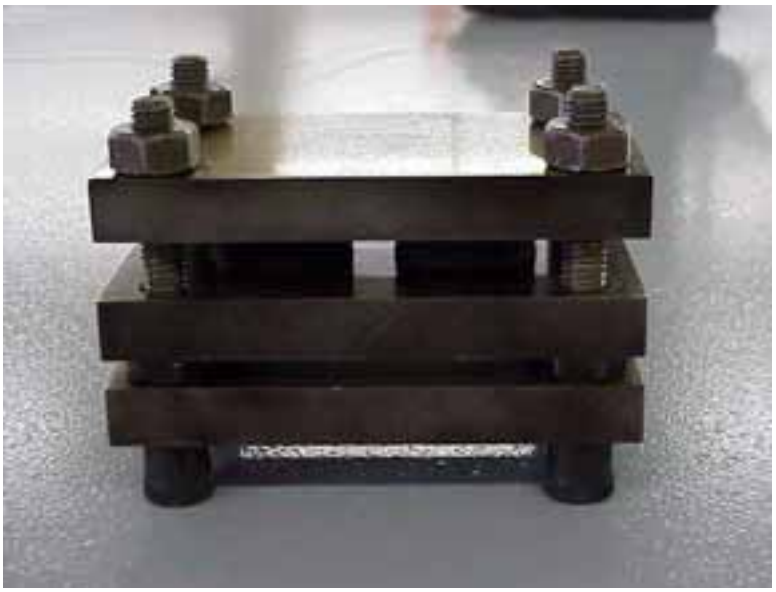


Figure 4. Compression Set Apparatus During Load Application

F. Accelerated Aging Test:

1. Test Method: Using ASTM D573, age the elastomer for 70 hours at a temperature of 70°C. Measure and record the change in hardness, tensile strength and ultimate elongation.

2. Acceptance Criteria: The tensile strength shall exceed 1,125 pounds per square inch, the ultimate elongation shall exceed 310 percent, and the change in hardness, measured on the Durometer A scale, shall not exceed 10 points.

This test, along with the following two tests (Ozone Cracking, Oil Absorption), is an effort to study how the properties of rubber vulcanizates change during service, especially in a hostile environment.

This standard test evaluates the deterioration of an elastomer from the combined effects of oxidative and thermal aging.

The specimen is oven heated for the prescribed time at the prescribed temperature. The test time and temperature in the specification are commonly used values for this test in the rubber industry.

After oven heating, the specimen is tested according to the foregoing hardness, tensile strength and ultimate elongation tests.

While the results of this test may be indicative of a good compound, there are significant difficulties in predicting service life from accelerated oven aging tests. With this inability to assess whether a result is harmful (or beneficial), it is inappropriate for an agency to make a design competency judgment based on this test.

This test is considered optional.

G. Resistance to Ozone Cracking Test:

1. Test Method: Prepare test specimens in accordance with Procedure A of ASTM D518. Test the specimens in accordance with ASTM D1149 at a temperature of 40°C and ozone concentration of 50 pphm.

2. Acceptance Criteria: The elastomer shall not exhibit cracking at the end of a 100-hour exposure.

Unsaturated rubbery polymers, such as natural rubber and neoprene (polychloroprene), are susceptible to ozone attack. When vulcanizates are held stretched in the presence of ozone, cracks can develop on the surface. They grow at right angles to the direction of principal strain. This phenomenon occurs in air even though the concentration of ozone is only of the order of a few parts per hundred million.

The test exposes three test strips to an ozone rich environment. Different strain (tensile stress) is applied to each strip (to 20% elongation) during the ozone exposure, thereby providing results on the effects of different strain levels.

Ozone cracking occurs only in rubber subjected to tensile stresses. Rubber components used in compression will crack only in the regions of the surface where tensile stresses are induced. These cracks are unable to penetrate very far because they soon encounter compressive rather than tensile stresses. Thus, ozone cracking is not a serious problem for components used in compression. Nevertheless ozone cracks are unsightly and may initiate fatigue crack growth, which leads ultimately to

failure; thus it is a good practice to avoid ozone cracking by the use of protective waxes and antiozonants in the rubber compound.[4]

The bulk of the Direct Fixation fastener elastomer precludes ozone cracks to penetrate the material, and therefore cannot alter the life expectancy of the fastener nor change the properties of the fastener.

As a result, this requirement is considered optional.

H. Oil Absorption Test:

1. Test Method: Determine the volume change of the elastomer using ASTM D471. Conduct one test with ASTM IRM 903 oil at a temperature of 23°C for 70 hours and conduct the other test using a different sample with ASTM IRM 902 oil at a temperature of 23°C for 70 hours.

2. Acceptance Criteria: The volume change for the IRM 902 oil shall not exceed minus ten or plus 20 percent; and for the IRM 903 oil, the volume change shall not exceed 100 percent.

ASTM Oil IRM 903 tends to swell most rubbers to a high degree.[5]

Natural rubber degrades when exposed to oil. Additives prevent oil absorption. The rate at which oil is absorbed determines whether a component will fail prematurely. Components with large volumes compared to their surface area are likely to have less significant swelling. Natural rubber engine mounts are well known to operate successfully in an oily environment for long time periods. The reason for this is that depth of penetration of the oil depends roughly on the square root of time. For example, an SAE 40 oil will penetrate 1 mm in 4 weeks, but it will take 100 years to penetrate 40 mm. Hence, thick components such as engine mounts are effectively protected by their bulk.

Direct fixation fasteners are viewed as having sufficient bulk to exhibit behavior parallel to engine mounts.

Swelling causes loss in mechanical strength in rubber as well as the obvious volume and dimensional changes.[6]

---

[4] Ibid, *Engineering with Rubber*, pg. 296.

[5] Ibid, *Engineering with Rubber*, pg. 321.

[6] Ibid, *Engineering with Rubber*, pp. 297-298.

Because of fastener elastomer bulk, this test is considered optional.

I. Adhesion to Metal Test:

1. Test Method: Test the elastomer's adhesion to the metal top and base elements as per ASTM D429, Method B. Use the same metal, metal preparation, elastomer, and adhesives in preparing the test specimen as are used in the production of the fastener body.

2. Acceptance Criteria: The failure shall be a Type R, in which the elastomer tears before the elastomer bond to the metal parts.

This test is intended for determining the adhesive strength of rubber-to-metal bonding agents. The test pulls a ¼ inch thick, 1 inch wide, 5 inches long vulcanized elastomer that is bonded only for 1 inch of its length to a metal strip that is 1/16 inch thick, 1 inch wide and 2.36 inches long. An unbonded end of the elastomer is pulled by grips at an angle of 90° from the metal strip with an increasing force away from the metal strip. The force at separation of the bonded segment from the metal is measured and recorded.

The materials and bonding process are to be the same as used in the fastener vulcanization process.

Type R failure is failure of the elastomer's bond to metal. The other failure types in ASTM D429 are:

- *RC indicates the failure is at the rubber-cover cement interface.*
- *CP indicates the failure is at the cover cement-prime cement interface,*
- *M indicates the failure is at the metal-prime cement interface.*

ASTM has not performed testing to establish the precision and bias for this test.

The acceptance criterion implies a proper elastomer design has higher bond to metal strength than the tensile strength of the elastomer (the elastomer fails before the bond to the metal plate). The results of this test must be considered in light of results from the tensile tests and elongation tests to judge whether the bond strength may be reduced or the elastomer strength increased.

This test is not required for non-bonded fastener designs.

J. Flame Spread and Smoke Generation Test:

3. Test Method: Test the elastomer in accordance with the ASTM E162 to determine the flame propagation index. Test the elastomer in accordance with NFPA 258 in both the flaming and non-flaming modes to determine the smoke generation specific optical index.

4. Acceptance Criteria: The elastomer shall not exhibit flaming drippings when tested. No acceptance criteria are specified for the flame propagation index and the smoke generation specific optical index. Report these indices to the Engineer for information only.

This fire-test-response test measures the surface flammability of materials. Surface flammability is a measure of the speed that flames develop across a test material's surface. ASTM E162 test methods measure surface flammability by applying a radiant heat source of 1238°F aimed at a slanted 12" by 18" by 1" thick (max) elastomer specimen mounted on a panel. The top of the mounting panel is closest to the heat source, angling away from the heat source at 30° from vertical. The specimen will catch fire at the top of the panel first. The fire will progress down the specimen. The rate of flame progress is measured by score marks made in the material every three inches from top to bottom. The technician records the time flames reach each three inch score mark. The test is conducted until the surface flame reaches the bottom of the specimen or 15 minutes of testing, whichever occurs first.

An index is then calculated from the rate of flame spread and the measured heat (based on exhaust stack temperatures).

The specification only requires that the calculated index be reported and that the elastomer does not exhibit dripping (complete melting).

The second test, NFPA 258, measures the density of smoke produced by heating a 3" by 3" by 1" thick elastomer specimen. The test produces an index indicating the smoke obscuration from the material. The smoke density is measured by a photo cell on the opposite side of the emission stack from a light source. The test places 2.2 Btu/sec/ft^2 radiant heat on a chamber containing the specimen. The chamber containing the specimen has one edge exposed for applying a direct flame, a propane flame applied directly to the exposed edge.

The specification calls for the test to be conducted with the propane flame and radiant heater, and a second test with the radiant heater only. The standard requires three specimens to be tested by each procedure.

The specification requires reporting an index calculated by the maximum smoke obscuration, the time to reach that level, and the pressure that develops in the chamber from the process.

These standards specifically state that they are for research and not for determining ratings for building codes or other regulatory purposes.

The elastomer will pass if no dripping (melting) occurs in any of the specimen tested under ASTM E162.

K. Electrical Resistivity Test:

1. Test Method: ASTM D257. For testing under wet conditions, the elastomer shall be immersed for 24 hours in potable water with a resistivity of 1,000 to 1,500 ohm-cm. Resistivity of potable water shall be adjusted to the required range by the addition of sodium chloride.

2. Acceptance Criteria: The elastomer shall have a minimum volume resistivity of 10^{12} ohm-centimeters under dry conditions and a minimum of 10^{11} ohm-centimeters after 24 hours immersion in water.

   A purported measure of elastomer material to mitigate stray current is electrical resistivity.

   Electrical resistivity (also known as specific electrical resistance*) is a measure indicating how strongly a material opposes the flow of electric current. A low resistivity indicates a material that readily allows the movement of electrons.*

   The resistivity of a material is usually denoted by the lower-case Greek letter rho (ρ) and is given by $\rho = \frac{RS}{l}$ *, where* $\mathbf{R}$ *is the resistance of a uniform specimen of the material having a length* $\mathbf{l}$ *and a cross-section area* $\mathbf{S}$*. The units of ρ are ohm-centimeters.. Its reciprocal quantity is electrical conductivity.*

   Typical values of dry rubber electrical resistivity are 10^{13} to 10^{16} ohm-meter[7] *or 10^{12} to 10^{15} ohm-centimeter. Increasing carbon black content of rubber mixes decreases the materials electrical resistivity (Figure 5).*

[7] http://www.ac.wwu.edu/~vawter/PhysicsNet/Topics/DC-Current/IntrinsicResist.html

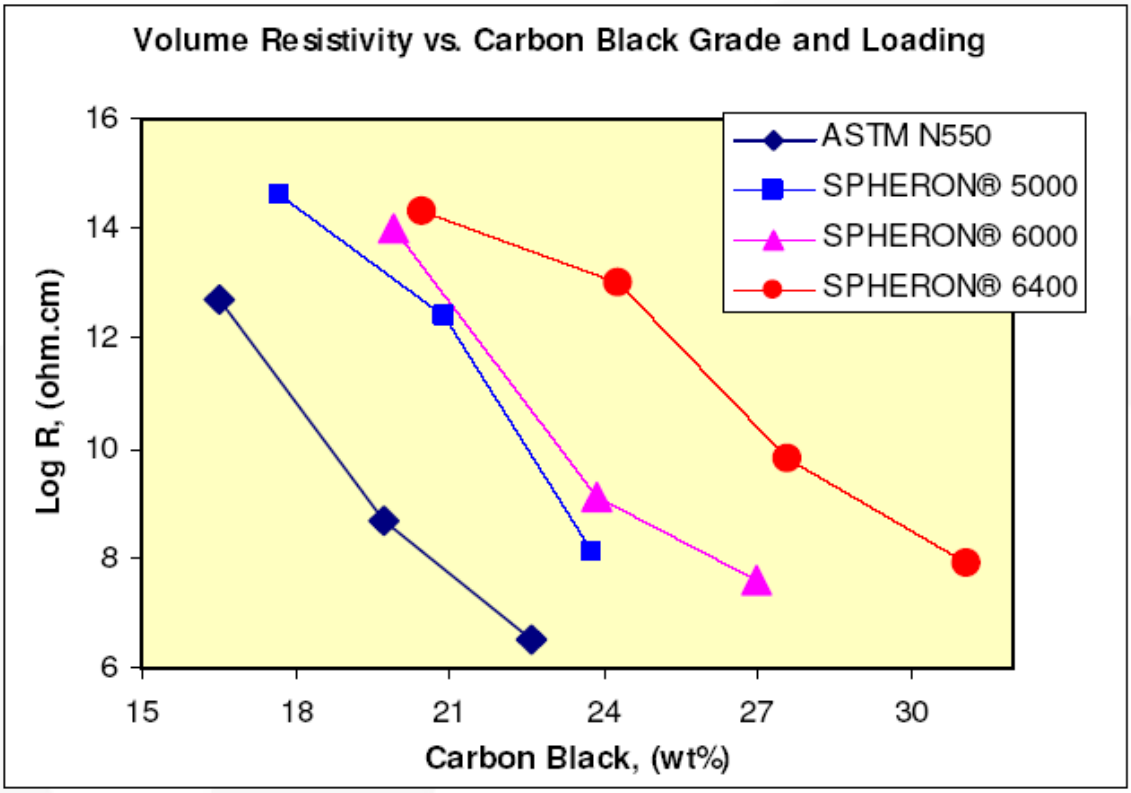


Figure 5. Carbon Black vs. Electrical Resistivity[8]

The wet test procedure has a waiting period after removal from the immersion bath, so that the specimen is damp, not wet. The test requires resistivity measures using a specific water resistivity, derived probably from statistics on rainwater impurities. The wet test is largely measuring the specified resistivity of the laboratory-constructed water more than that of the fastener. The correlation of the prescribed acceptance criteria to wet conditions in service is without supporting research, which if improbably done would find a range of water resistivity that, when mixed with normal track dust, grease and debris, could leave the measurements with prescribed water resistivity values as academic and meaningless.

The value from the dry test has a relationship with the finished fastener's resistance and impedance, but that relationship is dependent on the fastener's design. The wet test is hardly a test of the elastomer's electrical resistivity.

[8]Cabot Corporation, http://www.cabot-corp.com/cws/businesses.nsf/8969ddd26dc8427385256c2c004dad01/1587559b85f19a6785256e820031d5b2/$FILE/SPH6400HighElectralResistivity.pdf

The test arguably produces data that is important for stray current protection. The dry test on only the elastomer material has no value without the geometry of the assembly. If the dry test is considered of some value, the wet test is absolutely without use.

The true measure of the fastener's capacity to control stray currents is in the full assembly tests (Voltage Withstand Test, Electrical Resistance Test).

This requirement may be deleted in its entirety without concern that any parameter is overlooked.

L. Water Absorption Test:

1. Test Method: Determine the change in weight of the elastomer due to absorption of water using ASTM D570. Immerse the specimens in distilled water for 24 hours at a temperature of 23°C .

2. Acceptance Criteria: The elastomer shall have a maximum increase in weight of 1.0 percent.

Water absorption is used to determine the amount of water absorbed under specified conditions. Factors affecting water absorption include: type of plastic, additives used, temperature and length of exposure. The data sheds light on the performance of the materials in water or humid environments.

Test procedure:

For the water absorption test, the specimens are dried in an oven for a specified time and temperature and then placed in a desiccator to cool. Immediately upon cooling, the specimens are weighed. The material is then immersed in water at agreed upon conditions, often 23°C for 24 hours or until temperature equilibrium is achieved. Specimens are removed, patted dry with a lint free cloth, and weighed.

Specimen size: *Two inch diameter disks, 0.125" or 0.250" thick.*

Figure 6. Water Absorption Apparatus[9]

Data: *Water absorption is expressed as increase in weight percent. Percent Water Absorption = [(Wet weight - Dry weight)/ Dry weight] x 100.*

Excessive water absorption will cause swelling which can reduce elastomer strength and contribute to fatigue.

Water absorption in detrimental quantities is not expected with rubber or neoprene materials.

This specification requirement is optional if the material blends specified are mixes with natural rubber or neoprene as the predominant material.

M. Rheology (Cure and Strength Indicator) Test:

1. Test the elastomer in accordance with ASTM D2084.

2. During qualification testing a cure curve shall be developed based on the rheology test results for approval by the Engineer. Specification limits shall be established at several points along the curve for approval by the Engineer.

[9] Plastics Technology Laboratories, http://www.ptli.com/testlopedia/tests/water_absorption-D570.asp

3. During production testing the cure curves shall be compared to the qualification test cure curve. The production test curve shall be within the specification limits.

This requirement addresses the vulcanization behavior during the process of transforming a rubber compound from a viscous to an elastic material. The processing time to vulcanization completion and the temperature at which scorching occurs influence the mechanical properties such as hardness, tensile strength, damping, and shear modulus.

The test measures the torque applied to a rotating disc surrounded by the compound while it is heated at a constant temperature (320°F). The torque value is plotted against time as in Figure 7.

In Figure 7, the nomenclature has the following meanings:

- *t_s2: time to incipient cure (scorch time), measure of the time at which vulcanization begins. This point is defined by the standard as 2 lbf-in torque above the minimum torque, M_L.*
- *t(90): time to develop a torque that is 90% of the highest torque attained which is either M_{HF}, M_{HR}, or M_H.*
- *M_L: Minimum torque*
- *M_{HF}: Maximum torque where curve plateaus.*
- *M_{HR}: Maximum torque of reversing curve.*
- *M_H Highest torque attained during a specified period of time when no plateau or maximum torque is obtained.*

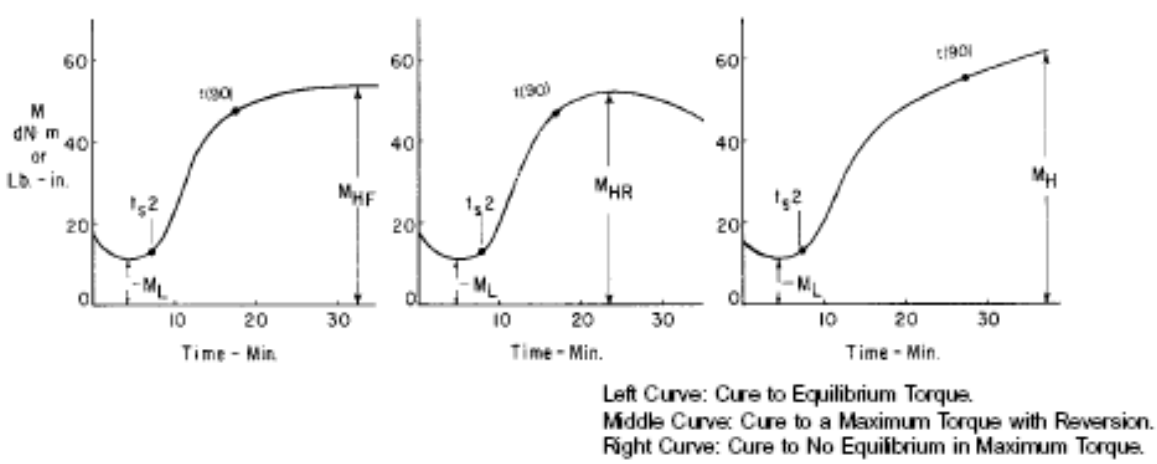


Figure 7. Typical Cure Curves, Test Torque vs. Time, by ASTM D2084 Test Procedure.

A test specimen of vulcanizable rubber compound is inserted into the cure meter test cavity and sealed under positive pressure. The cavity is maintained at the elevated vulcanization temperature for the compound. The rubber totally surrounds a biconical disk after the dies are closed (illustrated in Fig. 2 in the ASTM standard). The disk is oscillated through a small rotational amplitude (1° or 3°) and this action exerts a shear strain on the test specimen. The force required to oscillate or rotate the disk to maximum amplitude is continuously recorded as a function of time, with the force being proportional to the shear modulus (stiffness) of the test specimen at the test temperature. This stiffness first decreases as it warms up; then it increases due to vulcanization. The test is completed when the recorded torque either rises to an equilibrium or maximum value, or when a predetermined time has elapsed. The time required to obtain a cure curve is a function of the characteristics of the rubber compound and of the test temperature.

During the qualification procedures, the Rheology Test is performed on the proposed compound. The example specification implies that the Test will be performed on a representative number of compound samples to develop a family of curves that will establish the minimum and maximum envelope for the results from compounds for use during parallel testing of compounds provided for fastener production runs.

There are no guidelines that the Engineer may use as a reference for "approving" the acceptance envelope produced by this test. It is suggested that the Engineer engage a specialist to evaluate the results if the envelope appears large, such as the maximum torque varies by more than 25% at the same point in test time on the curve or the time between the beginning of vulcanization (t_s2) and the time for 90% vulcanization, t(90), has a broad range.

N. Specific Gravity Test:

1. Test the elastomer in accordance with ASTM D297.

2. During qualification testing the specific gravity of the elastomer shall be determined. During production testing the specific gravity shall be plus or minus 0.02 of the specific gravity determined during qualification testing.

Specific Gravity is the relative density of the elastomer to the density of water, a dimensionless value. This is used as a quality control benchmark for production elastomers, requiring the same specific gravity within a fairly small tolerance for all production elastomers.

2. TESTING ANCHOR ASSEMBLIES

Anchor assemblies are the anchor bolt and the anchor bolt insert which is imbedded in the concrete second pour.

The anchor bolt is almost always a 7/8 inch diameter UNC bolt. The mating insert has, obviously, a mating diameter and UNC thread pitch rate. The bolt size is based on the maximum lateral load and that load is applied in shear (assumes that the second bolt is absent).

2.01. TEST PREPARATION:

This example specification only portrays one of several test bed arrangements. Variations on the example test arrangement may be preferable for laboratory efficiency.

Other test bed arrangements are suggested under the fully assembled fastener test setup, section 4.01.

The anchorage inserts shall be embedded in a reinforced concrete test block. The test block size and configuration shall conform to one of the two test blocks shown in **Figure 8**. The size and configuration of the test block shall be determined by the Contractor, subject to approval by the Engineer. The sides shall be vertical and the top and bottom shall be horizontal. The inserts and reinforcing steel shall be positioned as they would be in track. The inserts shall be vertical, with the top face flush with the concrete surface. The inserts shall be set in the concrete before or during the concrete placing. Post-drilling and placing of inserts with resins or grouts shall not be permitted.

The concrete in the test block shall have a compressive strength of 4,000 to 6,000 pounds per square inch as determined by ASTM C39. The tests on the inserts shall not begin until the concrete has reached the specified compressive strength.

The reinforcing steel shall be placed as shown on **Figure 8**. Use ASTM A615/A615M, Grade 60 steel.

The anchor bolls shall be threaded into the inserts to at least 1-1/2 inch thread engagement before load application.

The number of test blocks required to perform the anchorage assemblies qualification testing shall be determined by the Contractor, subject to approval by the Engineer.

The test apparatus working drawings shall be submitted to the Engineer for approval with the test procedures.

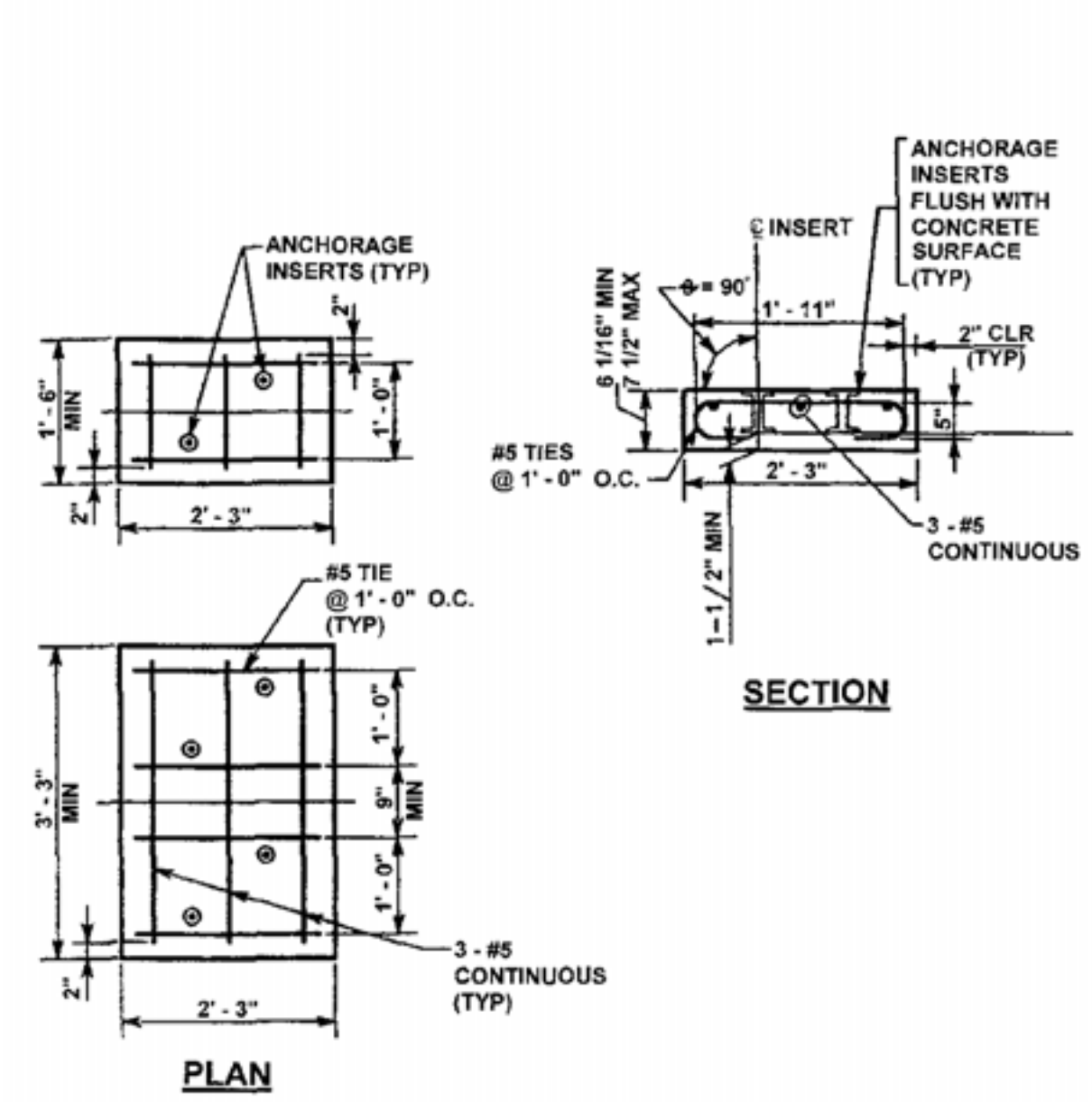


Figure 8. Test Block Arrangements for Direct Fixation Laboratory Test

(This figure should be replaced with the configuration conforming to local requirements.)

2.02. ANCHOR ASSEMBLY TESTS

A. Restrained Pullout Test:

1. Test Method: Place a 3-1/2 inch by 3-1/2 inch by 1/2 inch thick steel plate with a one inch diameter hole in its center, over an anchor bolt. Measure the bolt thread engagement length (the distance from the point of first thread engagement to the final position of the threaded bolt for testing). Apply for one minute an

upward vertical load, starting at 1,000 pounds and increasing to 20,000 pounds, to the anchor bolt with the reaction force bearing against the steel plate. Repeat the test on one other anchor bolt.

2. Acceptance Criteria: There shall be no evidence of bolt or insert thread damage. Slippage or cracking of concrete or failure of bond between either of the two bolts or inserts and concrete shall be noted.

3. Report the final test load and the tested thread engagement length.

The restrained pullout test measures the capacity of the anchor bolt insert to restrain tensile load of the bolt for the specified minimum thread engagement. This test does not evaluate the capacity of the concrete to restrain the insert.

While the maximum expected vertical load on the anchor bolt is 12,000 lb, the test is at 20,000 lb from possible anchor bolt tensile force. See Section 1, Direct Fixation Fastener Design, paragraph VI.E.5, Bolt Torque, for discussion.

It is essential to measure the thread engagement length in this test. The thread engagement length must be equal to or greater than the manufacturer's recommended minimum thread length.

ASTM and ASME standards for bolts and threads must be referenced in the test report. Variances in bolt and insert material or geometry standards are not acceptable. The bolts and inserts must be subjected to a QC inspection on delivery to a job site for compliance to the ASTM and ASME standards.

B. Unrestrained Pullout Test:

1. Test Method: Apply a vertical pullout load on an anchor bolt, in such a manner that no restraining load is applied to the concrete within a radius of six inches from the center of the bolt. The load application shall start at 1,000 pounds, be increased until a load of 16,000 pounds occurs, be held at 16,000 pounds for at least one minute and be released. Repeat the test on one other anchor bolt.

2. Acceptance Criteria: There shall be no evidence of concrete cracking or failure of bond between either of the two bolts or inserts, and concrete.

The unrestrained pullout test measures the capacity of the anchor bolt insert's resistance to being pulled out of its embedding concrete.

The test places a pullout load on the anchor bolt against a fixture with footings that are away from the insert. The fixture footings should be at least as far from the insert lateral extremities (not its center) as the insert's depth.

The design of insert depth is provided in the Direct Fixation Track Design (Section 1, VI.E.3). That reference establishes the insert resistance to pullout is based on insert depth, concrete compressive strength (actually tensile strength that is related to compressive strength), and insert body geometry as primary influence factors.

C. Torsion Test:

1. Test Method: An anchor bolt shall be subjected to a torque at least 100 percent greater than the design installation torque submitted with the installation requirements. The load shall be held for three minutes and released. Repeat the test on one other anchor bolt.

2. Acceptance Criteria: There shall be no evidence of failure of the bond between either of the two bolts or inserts, and concrete.

Typically, the Direct Fixation fastener manufacturer will recommend a bolt torque value between 200 ft-lb and 250 ft-lb for a 7/8 inch diameter bolt.

The test determines whether the external shape of the insert design has sufficient "keys" to interlock with the concrete. If the concrete fails any distance away from the insert, the insert may have passed the test with a faulty test installation.

3. BODY METAL QUALIFICATION TESTING

A. Test Method: Prepare three Charpy impact test specimens in accordance with ASTM E23 from the same metal used for the top and bottom metal elements of the fastener body. If different grades of steel or iron are used, prepare three specimens of each. Conduct a Charpy impact test on each specimen at a temperature of 21°C in accordance with ASTM E23. The test report shall include the information in Paragraph 12 of ASTM E23.

B. Acceptance Criteria: The fracture energy shall be greater than three foot-pounds for iron and 15 foot-pounds for steel.

The Charpy Impact test imposes an impact load by a weighted pendulum on a notched steel specimen. The test determines the effect of stress concentrations such as notches and cracks to impact loads.

*If the specimen were not notched, this procedure would produce the **impact toughness** of steel. Steel impact toughness is the strain energy a material can absorb in the plastic range.*

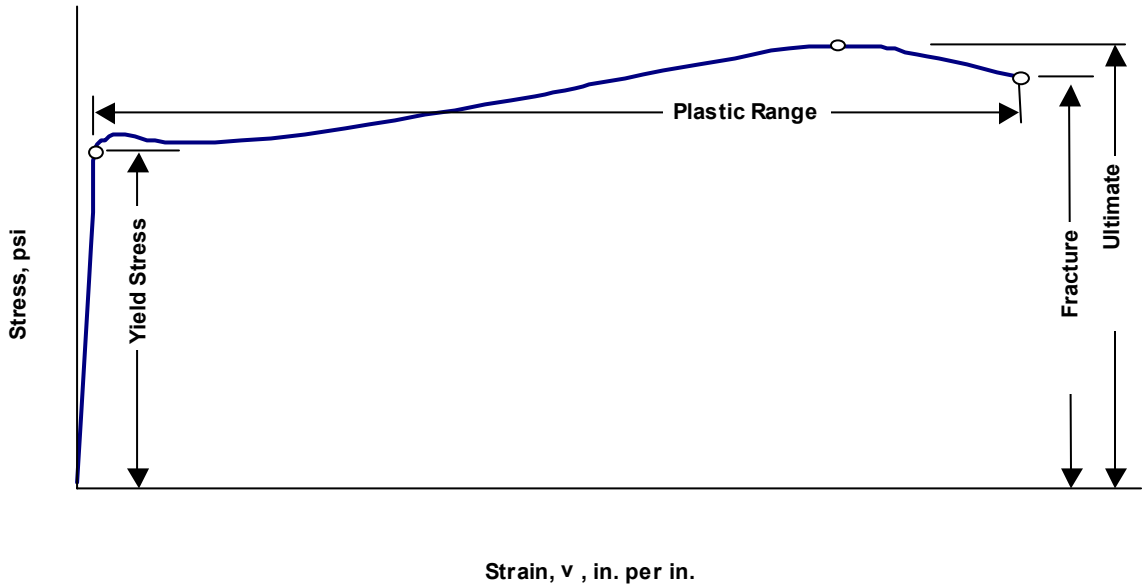


Figure 9. Stress-Strain Curve Illustration

The toughness value is the area under the stress-strain curve (Figure 9). The test reports the toughness value in units of energy.

Because the test bar is notched, the results are not a true value of impact toughness because the notch creates triaxial stresses[10], where an un-notched specimen creates essentially tensile stresses.

The notched-bar impact toughness values for various metallurgical treatments show large differences.[11]

For Direct Fixation fasteners, this test will indicate whether the steel (or iron) material used in fastener plates or castings have systematic inclusions (flaws) and whether the material is susceptible to failure at any sharp corners in the plate design.

[10] Triaxial stress: Stresses in the three principal planes. The principal planes do not necessarily coincide with the specimen axis.

[11] Joseph Marin, *Mechanical Behavior of Engineering Materials*, copyright 1962 by Prentice-Hall, Pg. 265

The specified minimum fracture energy is near expected values for cast iron materials. Rolled steel materials will produce fracture energies well above the specified acceptance criteria.

4. TESTING FASTENER ASSEMBLIES

4.01. TEST PREPARATION

There are two basic test approaches developed for Direct Fixation fastener qualification testing that are distinguished largely by the repeated load test requirements. One repeated load test uses a quasi-static vertical load with varying lateral load. The second repeated load test synchronizes varying vertical and lateral loads. The example specification is for the quasi-static vertical load approach. The synchronized load approach is in Attachment 3B.

A typical test bed arrangement for a quasi-static vertical repeated load test is illustrated in **Figure 8** *with alternatives. Test bed arrangements for a synchronized repeated load test are illustrated in Attachment 3B,* Figure 16 and Figure 17*.*

The example specification is a single fastener test configuration. A single fastener is not a preferred practice for design qualification testing purposes because it is more difficult to have true alignment of the test rail to the fastener. The longitudinal and other tests can produce incorrect results if the rail is skewed.

The preferred test configuration is the alternative set-up in the example specification (see paragraph 4.02).

Specification language for the configuration in **Figure 8** *follows.*

A. Except as described in paragraph 4.02 Alternative Test Preparation, a minimum of four complete fastener assemblies are required to conduct the tests. One fastener shall be assembled and mounted on each of four concrete test blocks, which shall be designated as A, B, C, and D. The tests shall be conducted in sequence, in accordance with Section 2, Direct Fixation Fastener Example Procurement Specification & Commentary, paragraph 2.02.F.2.

B. Except as otherwise specified herein, each test shall be performed on a completely assembled fastener with a section of *{enter rail size}* rail not less than one foot long mounted and clipped thereon. Before assembly, metal parts and elastomer shall be wiped clean and dry. The fasteners shall be assembled as shown on test apparatus working drawings, as approved by the Engineer and as detailed in the approved test procedures. Two 1/4-inch shim plates shall be placed under the fastener.

The anchor bolts shall be tightened to the installation procedure's torque. The torque of each bolt shall be measured and noted in the test report.

The example specification calls for two ¼ inch shims where the standard track arrangement uses one 3/8" shim. Either arrangement is suitable. The two shim arrangement would test the assembly under the more vulnerable condition of maximum shim height (=1/2") under the example specification.

C. The anchor inserts shall be spaced to match the fastener at the middle lateral adjustment setting. The inserts shall be set in a reinforced concrete block in accordance with Paragraph 2.01 above, except that only two anchor inserts shall be placed at the center of the block and the concrete block shall have a minimum length of 2.5 feet.

D. Before commencing each test, the fastener and concrete test block shall be stabilized at a temperature of 23°C, plus or minus 4°C, for at least four hours. Testing shall be performed within the same temperature range except as otherwise specified herein.

E. Except as otherwise noted, the test loading shall be applied to the rail at the centerline of the fastener. The test report shall clearly indicate the performance of each of the fasteners separately. Failure of any of the fasteners will be sufficient cause for the rejection of the fastener design.

4.02. ALTERNATIVE TEST PREPARATION *(Preferred)*

A. Instead of using one fastener, each test may be performed on a pair of fastener assemblies at thirty inch *{replace with the project's standard fastener spacing}* center-to-center spacing, with a section of 115RE *{insert correct rail section}* rail not less than 42 inches long mounted and clipped thereon. Each fastener shall be assembled as described in 4.01.A for one fastener.

B. For the two-fastener testing arrangement, the total loading specified for each test shall be doubled. Vertical or lateral loads shall be applied to the rail at a point centered between the fasteners to ensure that each fastener is equally loaded. Each fastener in the pair shall be distinctly labeled and the test report shall clearly indicate the performance of each fastener separately. For the acceptance of fastener design, each fastener shall satisfy the test requirements without failure.

C. The concrete test block shall be as described in Paragraph 2.01, above, except it shall have a minimum length of five feet, with two pairs of anchorage inserts at 30-inch *{insert the project's standard fastener spacing}* spacing center-to-center, centered within the test block.

4.03. FASTENER ASSEMBLY TESTS

Differences in Assembly Tests: *Quasi-Static Vertical Load vs. Synchronized Vertical Load Approaches.*

The example specification is the quasi-static vertical load test approach to fastener assembly testing. The alternative approach, a synchronized vertical and lateral load approach, is illustrated in Attachment 3B.

The principal differences between the two test approaches are summarized in Table A.

Table A
Primary Differences Between Test Approaches

Test	*Quasi-Static Vertical Load Approach*	*Synchronized Vertical Load Approach*
Lateral Load Application Point for Lateral Load Test and Repeated Load Test	*Top of the rail head*	*3 ½" above the rail base.*
Vertical Load (fastener stiffness), Vertical Uplift, Lateral Load (fastener stiffness)	*Fastener stiffness characteristics are determined by pure loading in the direction of interest*	*Fastener characteristics are determined under compound load conditions (lateral load present in vertical stiffness determination, vertical load is present in determination of lateral stiffness)*
Repeated Load Test	*Vertical Load is constant with varying lateral loads*	*Vertical and lateral loads both vary in prescribed sequence that simulates wheel approach in curving with varying L/V ratios.*

Quasi-Static Vertical Load Approach

This approach provides engineering data that are true measures of the fastener properties of stiffness and damping. The data will correspond properly to engineering modeling that may have been performed to determine the target specified stiffness value. The data is useful for specialists designing transit track facilities or evaluating a track.

The approach attempts to use loads that simulate loads that are representative of in-service values.

The difficulty in this approach is higher lateral loads and higher L/V ratios are not possible in the Repeated Load Test because lateral load is applied at the rail head. The rail will roll over absent rail torsional restraint that is present in track.

As a result, the vertical and lateral loads are constrained to those that will allow stable rail testing (an L/V ratio of 0.60).

The Lateral Load Test does exercise the rail clip and the fastener design of the rail clip retention, unlike the Synchronized test.

Synchronized Vertical and Lateral Load Approach

This test approach exercises the fastener's varying stiffness as will happen when a wheel approaches a fastener. The approach also applies a varying lateral load with a varying vertical load such that the fastener is exercised at the range of combined vertical and lateral stiffness values that is closer simulation of the field sequence.

This approach avoids the difficulty of rail rollover by loading the rail laterally in the web of the rail, making L/V ratios up to 0.90 possible in the testing without rail rollover.

However, this approach uses ganged fasteners disallowing affects of rail bending and related motions incurred by an individual fastener.

Because the test is designed to avoid rail rollover, the rail clip restraint is not exercised as it would in actual service. The fastener's design of the clip retention is not tested as a result. The predominant maintenance demand of Direct Fixation fasteners is from rail clips.

The Synchronous approach performs all characterizations using the same setup and the same cycling rate (1.1 Hz) allowing more of a dynamic test.

The following is language for the Quasi-Static Vertical Load Approach

A. Vertical Load Test:

1. Test Method: Each fastener shall be vertically loaded to 10,000 pounds for one minute. Thereafter, the load shall be released, and, after one minute, displacement gauges, one on each side of the load, shall be zeroed at zero load. A vertical load increasing in increments of 500 pounds to a maximum load of 10,000 pounds per fastener *[i.e. 20,000 lbs for a two fastener test]* at a rate not less than 100 pounds per minute nor more than 1,000 pounds per minute, shall be applied downward at the centerline of the rail head at the centerline of the fastener *[or centered between fasteners in multiple fastener tests]* and normal to the rail. For each increment of load, measure and record the vertical deflection of the rail head to the nearest 0.001 inch. The load shall be removed and the final position of the rail head measured and recorded.

2. Acceptance Criteria:

a. The fastener stiffness shall be calculated as the slope tangent to the load-deflection curve. The tangent to the load versus deflection curve at each deflection, X_n, and each load, P_n, shall be calculated by:

$$TangentStiffness = \frac{(P_{n+1} - P_{n-1})}{(X_{n+1} - X_{n-1})}$$

where P_{n-1}, P_n, and P_{n+1} are three consecutive loads that produce three consecutive measured deflections, X_{n-1}, X_n, and X_{n+1}.

The fastener tangent stiffness shall be within 20 percent of *{Insert the target stiffness value}* pounds per inch at loads between 2,000 lb/fastener and 6,000 lb/fastener.

The tangent stiffness data shall be plotted against load.

If the results of the tangent stiffness plot show non-uniform variations with load, the rate of data collection is likely high with data points too close together. It is legitimate to use data points 5 or 10 samples each side of the load in such cases. The results will be more accurate, and the tangent stiffness versus load will be a smoother curve.

b. The total compressive deflection of the elastomer at the 7,000 pounds per fastener load shall not exceed 25 percent of the uncompressed thickness. After removal of the maximum load, the fastener shall return to within 0.005 inch of its

original position within 1 minute. At no time during the tests shall a fastener component exhibit any sign of failure by slippage, abrasion, yielding, fracture, or bond failure. Slippage is defined herein to mean movement of any fastener component relative to its initial position not attributable to deflection of the elastomer.

The tangent to the load-versus-deflection curve at each load between and including 2,000 pounds and 8,000 pounds shall be within 20 percent of the fastener stiffness determined above.

The total deflection of the elastomer at the 10,000 pound load shall not exceed 30 percent of the uncompressed thickness of the fastener. After removal of the maximum load of 10,000 pounds, the fastener shall return to within 0.005 inch of its original position within one minute. At no time during the tests shall a fastener component exhibit any sign of failure by slippage, yielding, fracture, or bond failure. Slippage is defined herein to mean movement of any fastener component relative to its initial position not attributable to deflection of the elastomer.

The values obtained when this test is repeated, after performance of other tests, on a fastener shall be within 15 percent of the initial test values.

This test develops the quasi-static load-deflection curve and tangent stiffness values. Please see Direct Fixation Track Design, Section 1, for information on fastener stiffness and associated track design issues.

The load-deflection curve and the tangent stiffness are expected to be non-linear, meaning the stiffness can be stated with precision only at a given load.

The specification's requirement for non-linearity of the tangential stiffness is within 20% of the target stiffness value. The test should be repeated on several other fasteners if that criterion is not met. However, the fastener design should not be disqualified solely for exceeding the 20% requirement. However, the design may be flagged for disqualification if the majority of values are above the target stiffness and the resonant frequency (from the Dynamic Characterization Test) is non-compliant. There is less concern if the majority of the values are below the target stiffness.

The vertical load test also provides a compression set test. This test takes precedence over similar test results on the elastomer material only. This test in the full fastener configuration is the most valid test of fastener elastomer set. If the fastener does not rebound in accordance with the specification acceptance criteria, the fastener must be rejected. If the fastener is slow to rebound, then the Engineer should require re-testing under hot and cold conditions (ASTM D395, at a temperature of 70°C, and ASTM D1229 for 70 hours at a temperature of minus 10°C).

In the compression set test for softer fasteners, the specification preparation must set the compression limits carefully. A trend has been to attempt to develop softer fasteners that will by their nature have greater compression.

In instances where an agency requires different fastener stiffnesses for special locations, the specification must have different acceptance criteria for each stiffness that is specified. The specification must never require the same deflection criteria for fasteners having different stiffness requirements. This principle must be applied universally throughout the fastener assembly test requirements (lateral deflections, rotational deflections).

B. Vertical Uplift Test:

1. Test Method: Apply a vertical load to the center of the rail head at the centerline of the fastener *[at the middle point between fasteners in multiple fastener testing]* normal to the rail, alternating continuously from a downward load to an upward load. The loads shall be varied sinusoidally with the amplitude increasing 200 pounds each cycle up to a maximum load amplitude of 2,400 pounds per fastener. The frequency of the sine wave shall be 1 Hz or less. Two transducers on each side of the rail shall continuously measure the rail base vertical deflections beneath the point of load application. The deflections shall be measured relative to the support block, shall be to the nearest 0.001 inch, and shall be recorded simultaneously with load. At the completion of the test and with the zero load on the test rail, measure and record the final vertical position of the rail.

   After completing the foregoing procedure, a vertical uplift load of 2,000 lbs per fastener shall be applied to the rail. With the rail loaded, any gaps between the bottom of the rail base and top of the fasteners' rail seat shall be measured with feeler gages.

2. Acceptance Criteria: The absolute vertical deflection of the fastener for an upward load of 2,000 pounds per fastener shall be within 135 percent of the absolute deflection for the 2,000 pound per fastener downward vertical load as determined from the vertical load tests. When the vertical load is continuously varied from vertical downward to vertical uplift loads, there shall be no indication of backlash or freeplay at times when the load or the deflection changes direction. After removal of the maximum load, the rail shall, within two minutes, return to within 0.005 inch of its original position. At no time during the test shall a fastener component, including the anchor assembly and the test block, exhibit a sign of failure by slippage, yielding, or fracture.

3. Restraining rail or turnout direct fixation fastener assemblies *[if required elsewhere by the specifications]* shall be tested in accordance with this test method. The fastener manufacturer shall provide an appropriate table of measurements applicable to restraining rail or turnout fasteners as part of the submittal process and verify performance of the fastener to the requirements for Vertical Load Test and Lateral Restraint Test.

This procedure is inappropriate for resilient tie systems.

The vertical uplift test measures the tensile spring rate of the elastomer and is a check on the rail clip toe load and the clip's mounting integrity to the top plate. The test engages the top plate in bending, the bonding of the elastomer to the top plate, and tensile loading of anchor bolt as well; the loading in this test is insignificant to be a true test of the plate bending, elastomer bonding and anchor bolt.

If the rail clip is a spring-type clip, the combined toe load of the rail clips is 3,600 lb to 6,000 lb, depending on the clip design and tolerances among components. A 2,000 lb. uplift force is much less than these values and there should never be a gap between any components.

A better procedure is to increase the uplift load until a 1/16" gap occurs between rail and fastener, and record that load value. That value should be 5,100 lb, minimum for all rail clip designs and 6,600 lb for most clips. That load still will be insignificant to exercise measurable plate bending, anchor bolt strain or top plate metal to elastomer bond stress.

If the rail clip is a rigid clip design, it is likely that there will be free play between the rail and some of the clips. If the specification allows rigid rail clips, the parameters of this test should be modified to recognize any permissible gaps between the rail and clip.

C. Lateral Load Test:

1. Test Method: While applying a constant vertical load of 10,000 pounds downward at the center of the rail head, a lateral load, increasing in increments of 500 pounds to a maximum load of 6,000 pounds at a rate not less than 100 pounds per minute, shall be applied horizontally to the gauge side of the rail head at the location of vertical load. The horizontal force shall be applied 0.625 inch below the top of the rail. For each lateral load increment, the lateral deflection of the rail head at a point 0.625 inch below the top of the rail shall be measured to the nearest 0.001 inch and recorded. At completion of the measurement load cycle with the load removed, the final position of the rail head shall be measured and recorded. The values for lateral load versus deflection shall be plotted.

2. Acceptance Criteria: The lateral load versus deflection curve shall lie within the envelope shown in **Figure 15**. After removal of the lateral load, the difference between the original and final positions of the gauge line shall not exceed 0.062 inches. At no time during the test shall a fastener component exhibit a sign of failure by slippage, yielding, or fracture.

3. Restraining rail direct fixation fastener assemblies *[if required elsewhere by the specifications]* shall be tested in accordance with this test method. The Contractor shall provide an appropriate table applicable to restraining rail fasteners as part of the submittal process and verify performance of the fastener in accordance with the approved version of the submitted process.

The Lateral Load Test measures the combined lateral rail translation and rotation. The following Lateral Restraint Test measures the true lateral stiffness of the fastener.

Properly designed Lateral Load Tests will select a maximum L/V ratio that will exercise the rail clips and the fastener's design of the rail clip retention without causing the rail to roll over. See Attachment 3A for values used by various transit agencies.

The Quasi-static test method is not able to test L/V loads that will occur in the field because the connected rail provides rotation resistance not provided in this test.

Revised, the test can replicate field deflections, and therefore component stress and strain that will occur in service. The proper test is a "deflection limited test", where the example specification is a load limited test. In a deflection limited test, the test is run to reach specified rail deflection values while measuring the load that produce the deflections.

A missing element in this procedure is measuring how much the rail rolls relative to the fastener. 2 additional transducers would be required to measure the top plate deflection relative to the test bed.

D. Lateral Restraint Test:

1. Test Method: With the rail seated without lateral slack between the rail and fastener and with the lateral head and base deflection measurements zeroed, two equal lateral loads increasing simultaneously in increments of 500 pounds per fastener up to a maximum load of 3,000 pounds *(6,000 lbs in a two fastener test)* for each load, for a total load of 6,000 pounds *(12,000 lbs in a two fastener test)*, shall be applied to the base of the rail in the same lateral direction, normal to the rail base. Loads shall be symmetrical on each side of the fastener centerline *[or centered on each fastener in a two fastener test]*. The lateral deflection shall be measured to the nearest 0.001 inch at the intersection of the centerline of the fastener *[at the center of each fastener in a two fastener test setup]* and *[both]* the gauge line of the rail *[and the rail base]*. Measurements shall be recorded *[and plotted]* after each increment of loading.

2. Acceptance Criteria: The difference between the original *[fully seated]* and final positions of the gauge line after removal of load shall not exceed 0.062 inch. The lateral deflection of the rail head when fully loaded shall be between 0.0625 and 0.125 inch from the original gauge line of the rail. At no time during the test shall a component show signs of slippage, yielding, or fracture.

3. Restraining rail direct fixation fastener assemblies *[if required elsewhere by the specification]* shall be tested in accordance with this test method.

The Lateral Restraint Test measures the lateral fastener stiffness.

The lateral deflections at the rail head are somewhat irrelevant in this procedure, although it is recommended that both rail head and rail base deflections are measured as a test control check.

The example specification adds the requirement to plot the load deflection to the generally used specification. This data measures the lateral stiffness of the fastener, the best justification for the test. The load-deflection data should be submitted in spreadsheet format in Microsoft excel spreadsheet format (or similar) to permit calculation of the lateral fastener stiffness.

The load levels in the example are likely maximum load levels per fastener that will occur in service. However, it is useful to extend the lateral load per fastener to 6,000 lb to assure that a complete load-deflection curve is measured for all circumstances (such as if one fastener failed and adjacent fasteners carry higher percentages of the wheel load).

E. Longitudinal Restraint Test:

1. Test Method: For a fastener assembly with two rail clips, apply a load longitudinally to the rail at its base increasing in increments of 200 pounds up to a total load of 5,000 pounds per fastener or until the rail slips through the fastener a minimum of 0.5 inch from the initial position but not greater than the travel of the deflection measurement transducer. Maintain each load increment constant until the longitudinal movement of the rail ceases before increasing the load by the next increment. For each load, measure and record the longitudinal deflection of the rail to the nearest 0.001 inch. Then remove the longitudinal load gradually while simultaneously measuring and recording the rail deflection. Plot the recorded values for longitudinal loading and unloading versus deflection.

2. Acceptance Criteria: The difference between the loaded and unloaded final positions of the rail during removal of load shall not exceed 0.125 inch of the rail relative to the fastener top plate. The longitudinal load versus deflection curve, when plotted on a graph similar to *Figure 10*, shall lie entirely within the shaded limits. At no time during the test shall a fastener component exhibit a sign of failure by slippage, yielding, or fracture, except for the slippage which occurs between the rail and the fastener top element and clips.

Note that the applied longitudinal force of 5,000 lbs must be increased by the number of fasteners in the test. The applied force must be reduced if low longitudinal restraint fasteners are being tested.

The Longitudinal Restraint Test in this example specification varies from other Direct Fixation specifications by removing the upper limit longitudinal rail restraint. Track performance benefits from the greatest longitudinal restraint available by reducing longitudinal rail forces into turnouts, curves and bottom of grades.

Figure 10 shows that the acceptance criteria increase for fasteners that will be used on steeper gradients. The criteria for the various gradients assume that the track design has not incorporated in supplemental longitudinal restraint.

The Figure shows a lower boundary based on a fastener longitudinal stiffness of 32,000 lb/in. This value is somewhat arbitrary, selected as a value that is expected to be lower than that of most fasteners. This value can be reduced without consequence for fasteners that have low vertical stiffness.

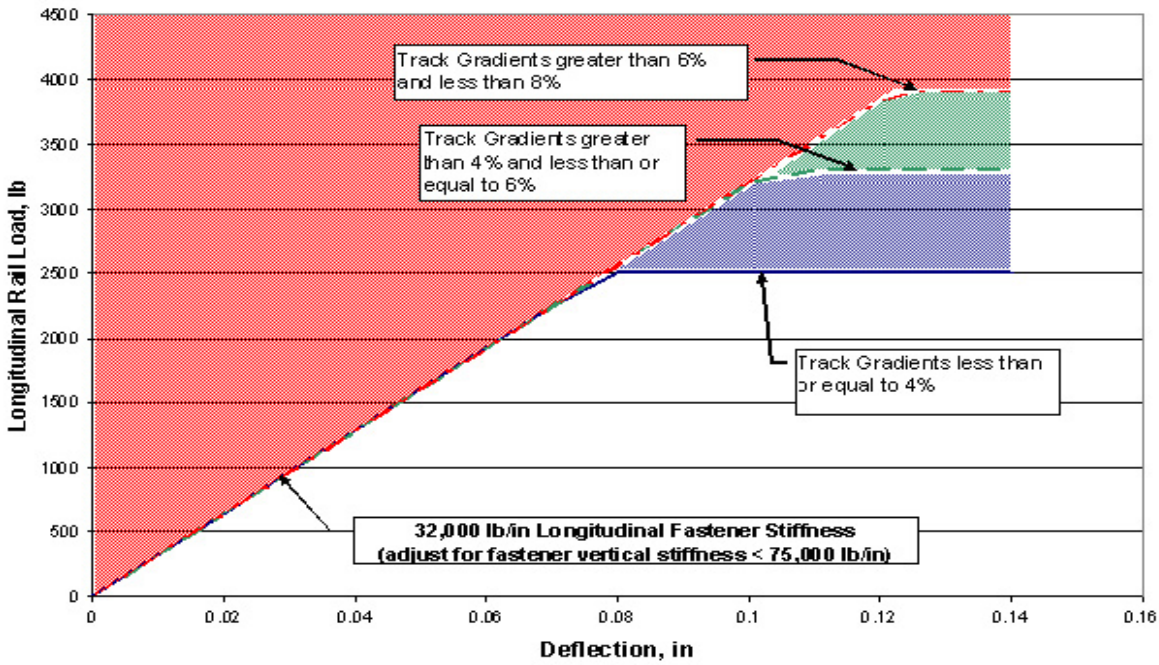


Figure 10. Longitudinal Restraint Acceptance Criteria Where There is No Structural Constraint.

An acknowledged difficulty in applying the criteria in Figure 10 is that fasteners on steep gradients will likely be in the minority among the fasteners being acquired. A track design issue is whether to require the fastener to meet the higher longitudinal restraint requirement or to supplement the longitudinal restraint in steeper grades by methods not involving the fastener (i.e. rail anchors).

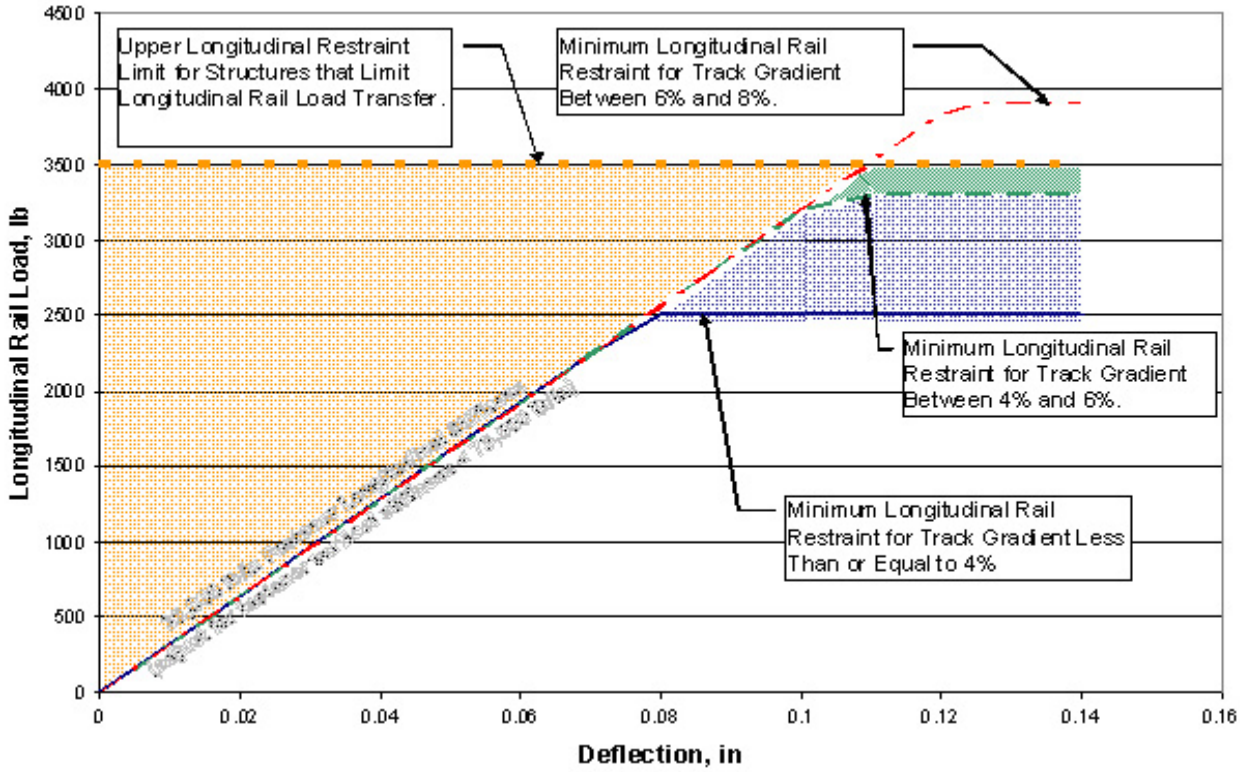


Figure 11. Longitudinal Restraint Acceptance Criteria Where There is a Structural Constraint.

There are cases where the longitudinal rail force that can be transferred to the structure will be a governing force for the design of the structure. The criteria for these cases are shown in Figure 11. Generally, depending on the structural codes in force, the rail longitudinal force will not be a governing force for structural design for piers less than 20 feet tall. Section 1, Direct Fixation Track Design, presents the issues and methods for determining longitudinal rail loads transferred to aerial structures.

The upper limit of 3,500 lb Figure 11 is a common value, but not a fixed value. It is poor practice to reduce this value for the majority of applications.

When the longitudinal rail force transfer to structures does become a governing force for structural design, the resolution may take several approaches:

- *Strengthen the affected piers (recommended) to meet the rail load. This will increase the structure construction cost, requiring an economic decision to choose this resolution*

- *Use a combination of increased fastener spacing and reduced longitudinal restraint to spread the potential longitudinal force into multiple piers. This approach may create conflicts with other criteria, particularly the rail break gap criteria.*

Attention is drawn in Figure 11 to a difficulty when gradients are greater than 6% and there is a structural constraint. In this case, the minimum longitudinal fastener restraint is that required to restrain forces created by the gradient. Alternatively, there must be supplemental longitudinal restraint designed into the track independent of the fastener design (such as rail anchors).

The criteria in Figure 10 and Figure 11 are single fastener longitudinal restraints. The criteria thresholds must be adjusted for multiple fastener tests.

F. Voltage Withstand Test:

1. Test Method: Prepare a fully assembled fastener and apply a DC potential of 10,000 volts between the rail head and the metal base element and/or fastener insert assemblies for one minute.

2. Acceptance Criteria: The elastomer shall withstand this test with no visible damage such as splits, cracks, pinholes or fractures. There shall be no evidence of arcing, arc tracking, or other voltage breakdown.

Normal transit voltage between rail and ground are less than 2,000 volts. This test determines whether a design is susceptible to damage from an anomalous voltage, such as from a lightning strike.

The most likely failure in this test would not be from the fastener design. A failure would most probably be the result of a manufacturing flaw that created pin holes or other flaws that could provide an arc path between top and bottom plates. Fasteners for qualification tests are not likely to have such manufacturing flaws because of the obvious scrutiny that the test fasteners will undergo prior to submittal by the manufacturer to the battery of tests.

This test is a manufacturing quality control test, rather than as a design qualification test.

G. Electrical Resistance Test:

1. Test Method:

a. A complete, fully assembled fastener, as specified herein, shall be tested for electrical resistance. Before assembly, metal parts, anchoring devices, rail clips, elastomer surfaces and all other ancillary parts associated with the fastener shall be clean and dry. Assemble the fastener with a section of *[Insert rail size]* rail, not less than one foot in length. Mount the test fastener on a 1/4 inch thick metallic ground plate sized to extend 1/2 inch beyond all edges of the fastener. Use anchor assemblies supplied for use in actual field installation to mount the fastener to the ground plate. Use the same number of bolts (or other devices) as will be used to anchor the fastener in service. Verify that all parts which should be in electrical contact do not exhibit excessive contact resistance because of improper assembly or other causes. This shall apply to, but not necessarily be limited to, the areas specified below.

1) Rail to rail-plate interface.

2) Rail clip and rail.

3) Anchor bolts and bottom fastener plates (if present).

4) Anchor bolts and ground plate.

b. Dry Conditions: Twenty-four hours prior to testing, store the assembled fasteners in a clean, dry environment with ambient conditions of 60°F to 80°F and 50 to 70 percent relative humidity. Apply 100 volts (minimum) dc between the rail head and the ground plate for three minutes. Measure the applied voltage and resulting current flow, or directly measure the resistance with an accuracy of plus or minus two percent. Instrumentation used for direct measurement shall have a minimum 100 volt output capability.

c. Wet Conditions: Perform this test on the same fasteners that passed the dry electrical resistance tests. Place the assembled fastener in a nonmetallic trough or other suitable container. Size the container such that there is a minimum of two-inches between the sides and bottom of the fastener/ground plate assembly and the sides and bottom of the container. In the event more than one fastener is placed in the same container, maintain a two-inch clearance between the edges of the ground plates on adjacent fasteners and the clearances cited above. Pour water into

the container to a level midway up the rail web covering all surfaces of the fastener. Maintain this level of immersion for ten minutes. Ambient temperature of fastener surfaces (prior to immersion), water and air shall be 60°F to 80°F. Relative humidity shall be 50 to 70 percent. Water resistivity shall be 1,000 to 1,500 ohm-cm (use potable water and adjust resistivity by addition of sodium chloride). Drain the water from the container to a level 1/2 inch below the ground plate, and without drying or otherwise disturbing the fasteners or creating a condition that causes the fastener surfaces to dry, measure the resistance within 15 seconds after draining specified below.

1) Apply 100 volts between the rail head and the ground plate for a period of 15 seconds.

2) Measure the applied voltage and resulting current flow between the rail head and the ground plate with an accuracy of plus or minus two percent and calculate the dc wet resistance, or directly measure the resistance with an accuracy of plus or minus two percent. Instrumentation used for direct measurement shall have a minimum 100 volt output capability.

3) Repeat the resistance measurement every five minutes for the first hour, every ten minutes for the second hour, and every 15 minutes thereafter to establish the wet resistance versus time characteristics of the fastener. Make the tests for at least two hours after wetting. The tests can be terminated after the two hour test period when any three consecutive measurements are at least one megohm, or after another two hour test period, whichever comes first.

2. Test Acceptance Criteria:

a. Dry Conditions: The minimum dc resistance shall be 20 megohms.

b. Wet Conditions: A minimum resistance of one megohm for the average of three consecutive readings within two hours after wetting. The difference between each of the three readings and the average shall not exceed ten percent of the average.

The test is important for stray current mitigation.

The dry tests show whether the design is a proper insulator. The wet condition tests for water ponding on the fastener and water entrapment. Please see Section 1, Direct Fixation Track Design, paragraph VI.B.3, Stray Current for a discussion of fastener electrical resistance.

H. Electrical Impedance Test:

1. Test Method: A complete, fully assembled fastener shall be tested for electrical impedance. A potential of 50 volts AC RMS shall be applied to the rail head for three minutes for each increment of measurement for frequencies from 20 Hz to 10 kHz, in increments of 20 Hz up to 100 Hz, 200 Hz up to 1,000 Hz, and 2,000 Hz up to 10 kHz. The impedance after three minutes shall be measured with an accuracy of plus or minus two percent and recorded for each frequency. Upon approval by the Agency, electrical resistance may be calculated by measuring current flow, and impedance may be calculated from the measurements of resistance and capacitance using the impedance equation that applies to a resistance and capacitance in parallel.

2. Acceptance Criteria: The minimum impedance for any frequency between 20 Hz and 10 kHz with 50 volts AC RMS shall be 10,000 ohms.

This test fundamentally determines whether the fastener has sufficient resistance (impedance is the correct term) for track circuits (signaling, train presence detection). Please see Section 1, Direct Fixation Track Design, paragraph VI.B.3.b for a discussion on track impedance for track circuits.

I. Corrosion Test:

1. Test Method: The fastener, without loose components, shall be photographed with full frame color pictures of exposed fastener metal. The fastener then will be exposed to a five percent chloride solution in accordance with ASTM B117 for 744 hours. The fastener shall be re-photographed at the same pictorial framing and angles as the initial photographs.

2. Acceptance Criteria: Acceptance shall be based upon visual comparison between actual metal surface condition after completion of the test and the pre-exposure pictorials. The condition of the metal surfaces shall show no more than light surface rust, that mill scale has only begun to flake, and there is no pitting. There shall be no evidence of adhesion loss of adhesive

coating. In areas where prior testing has removed the protective coatings, the surface rust grade specified above shall be used for judging acceptance.

J. Vertical and Lateral Repeated Load Test:

This example specification is the Quasi-Static Vertical Load Test. See Attachment 3B for an example of the Synchronized Vertical and Lateral Load Test specification.

The test load values and acceptance criteria should reflect each agency's actual load distribution. The discussion following the example specification presents a method for defining the test loads from actual loads. See Attachment 3A for a listing of the loads and acceptance criteria used by different agencies for this test.

1. Apply load on the rail head center so as to produce a vertical downward load of 14,000 pounds per fastener. Apply lateral loads to the gauge side of the rail head 0.625 inches below the rail head. Lateral loads shall be applied at the centerline of the fastener and normal to the rail. Lateral loads from the field side shall be 2,500 pounds per fastener and from the gauge side, 4,000 pounds per fastener. Application of the lateral loads shall be alternate, each combined with the application and release of the vertical load. Application of the field side load together with the vertical load, loads release and then the gauge side load together with the vertical load and loads release shall constitute one cycle. For the qualification testing program, the test shall be conducted for 3 million cycles. The anchor bolts may be retorqued to their initial torsion once during this test prior to 500,000 cycles. The loading frequency shall be regulated to prevent the temperature of components from exceeding 50 degrees C. The rail clips shall not be repositioned nor threaded elements retorqued without written approval of the Engineer.

2. The fastener shall withstand the specified total number of cycles of load application with no evidence of failure. Upon visual inspection, no component of the fastener shall exhibit any evidence of failure by slippage, yielding, abrasion, fracture, or bond failure at any time during the test. The rail shall exhibit no evidence of wear or grooving that could contribute to failure of a rail. The rail clip shall not exhibit any evidence of vibrating loose from the rail clip holder.

The example specification presents the Quasi-Static Vertical Load approach to repeated load testing. That and the alternative Synchronized

Vertical and Lateral Load approach are compared at the beginning of this commentary section. An example of the Synchronized Vertical and Lateral Load specification is included in Attachment 3B.

These test approaches attempt to simulate loads and motions that are representative of those the fastener will encounter in service. To the extent possible in laboratory conditions, this test is intended to be a fatigue test.

This test's cost has been a burden on suppliers and owners.

To reduce costs and increase the relevancy of either test approach, it is suggested the loads only include the damaging load levels, and the number of load cycles is reduced to the fraction of damaging loads that are predicted in a 30 year service period. Fatigue may be determined using only loads at the upper level of an agency's load distribution.

The method for defining these loads follows[12]*. The method uses an empirical distribution of wheel loads from commuter rail traffic, adjusted to a transit's expected wheel load distribution. The commuter rail distribution characteristic likely produces higher loads than a transit distribution characteristic, but those statistics are unavailable. The following is therefore a presentation of the methodology, where the resulting test values may be questionable because they are high.*

Figure 12 presents the expected number of wheel loads for one year of operation at a representative transit agency. The loads are the static loads in the agency's design criteria for AW0, AW1… AW4 vehicle loads. The count of the axles at each load is determined from the expected load (AW0 through AW4) that is likely to occur at the different operating periods (peak, off-peak) of a day or weekend/holiday.

[12] The underlying basis for the procedure presented here is in Part B, Final Research Report, paragraph 6.1.2. The procedure will be most beneficial if an individual transit has measured its annual service dynamic wheel load population and constructed a statistical distribution of that population. Those annual dynamic wheel load populations are a recommended research task for each agency.

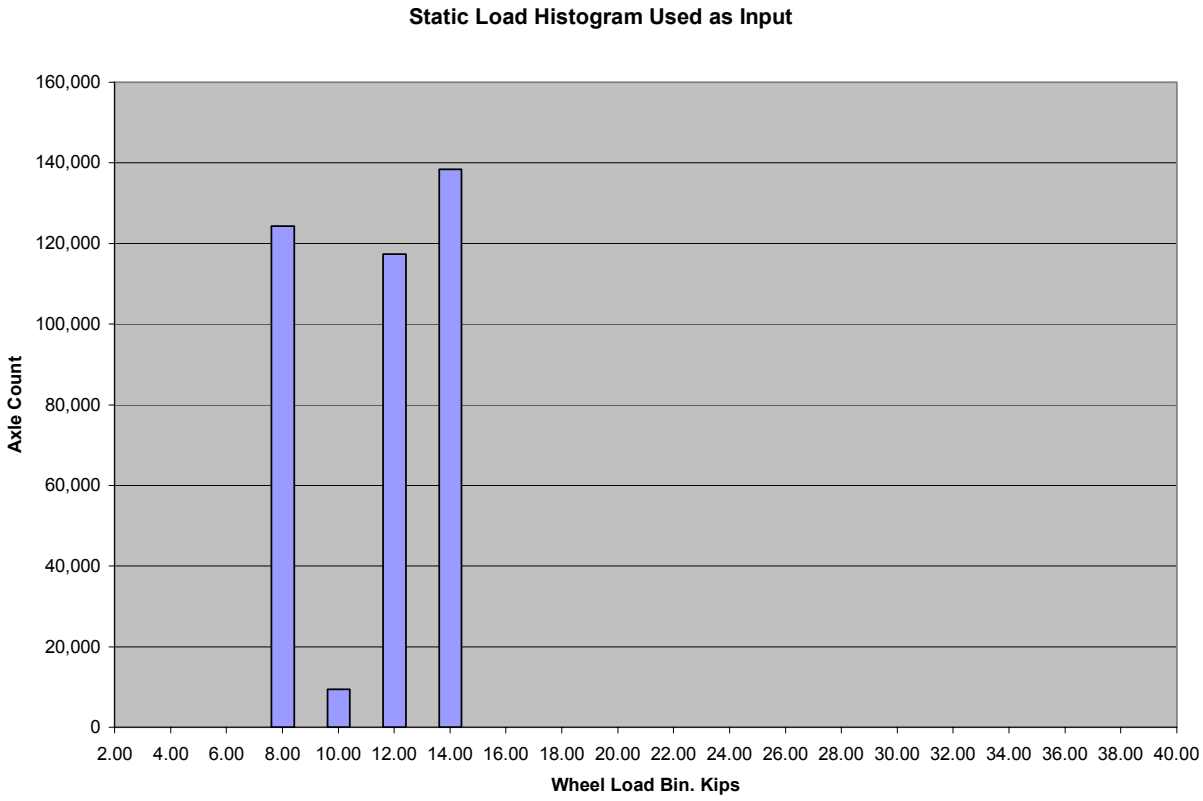


Figure 12. Annual Axle Count by Load (illustration is based on Santa Clara VTA's design criteria axle loading and operating conditions (peak hours and off-peak hours train frequencies).

The following sheet shows the assumed operating conditions and loads associated with those operations (left cells) and the resulting wheel loads and annual occurrence ("frequency") estimates (right cells).

Table B. Entry Data and Results for Annual Wheel Load Occurrence.

Data for Wheel Load Frequency Estimation

Operations			
	Operating Hours/day	*Headways (min)*	*Cars/ Train*
Weekdays			
Peak	*6*	*10*	*4*
Off-peak	*18*	*30*	*2*
Weekends & Holidays	*24*	*30*	*2*

Expected Life (yrs)
30

Vehicle Weight					
	AW0 Loads	*AW1 Loads*	*AW2 Loads*	*AW3 Loads*	*AW4 Loads*
	Empty	*75 patrons*	*165 patrons*	*210 patrons*	*Maximum Load (256 patrons)*
	(lb)	*(lb)*	*(lb)*	*(lb)*	*(lb)*
Vehicle Weight	*98,700*	*110,325*	*124,275*	*131,250*	*138,380*
Assumed Car Capacity Loading					
Weekdays					
Peak			*5%*	*90%*	*5%*
Off-peak	*5%*	*40%*	*55%*		
Weekends & Holidays	*5%*	*45%*	*50%*		

Axles		
	No. Axles Per Car	*Max. Axle Load*
Driven Axles, P1	*4*	*28800*
Idler (center) Axles, P2	*2*	*18200*

Analysis Results

Agency Results	
Annual Wheel Loads and Frequency	
Wheel Load	*Frequency*
(lb)	*(Loads/Yr)*
5,925	*2,898*
6,622	*24,248*
7,460	*34,434*
7,878	*65,578*
8,306	*3,644*
9,375	*5,796*
10,479	*48,496*
11,804	*68,868*
12,467	*131,156*
13,144	*7,288*
Year Total	*392,406*

User Notes:

1. *Operations Entries: Enter the standard operating hours, headways and car consists, ignoring special trains, test trains, etc.*
2. *Vehicle Weight Entries: Enter the loads stated in the Design Criteria. Enter 0 if there is no AW4 load in the Criteria.*
3. *Assumed Car Capacity Loading: Enter whole numbers (i.e. "5" for 5%, not "0.05") for the number of cars loaded to the different AW categories. Each row (Peak, Off-Peak, Weekends & Holidays) should sum to 100%.*
4. *Axles: Enter the maximum axle load data from the vehicle load diagram in the Agency's Design Criteria. The Idler (center) Axles row is used for low floor cars and some articulated vehicles. If all axles are driven but some axles have different maximum loads, use both rows to enter the number of axles and the respective maximum loads.*
5. *Expected Life: Enter the number of years that you wish the test to simulate.*

Table C. Agency Annual Wheel Load Assembled into Integer Load Bins

Axle Count After Redistribution to integral load "bins"	
Wheel Load, Kips	***Enter Axle Count for Each Load Bin***
2.00	*0*
4.00	*0*
6.00	*0*
8.00	*124,260*
10.00	*9,440*
12.00	*117,364*
14.00	*138,444*
16.00	*0*
18.00	*0*
20.00	*0*
22.00	*0*
36.00	*0*
38.00	*0*
40.00	*0*
Total Axle Count	*389,508*

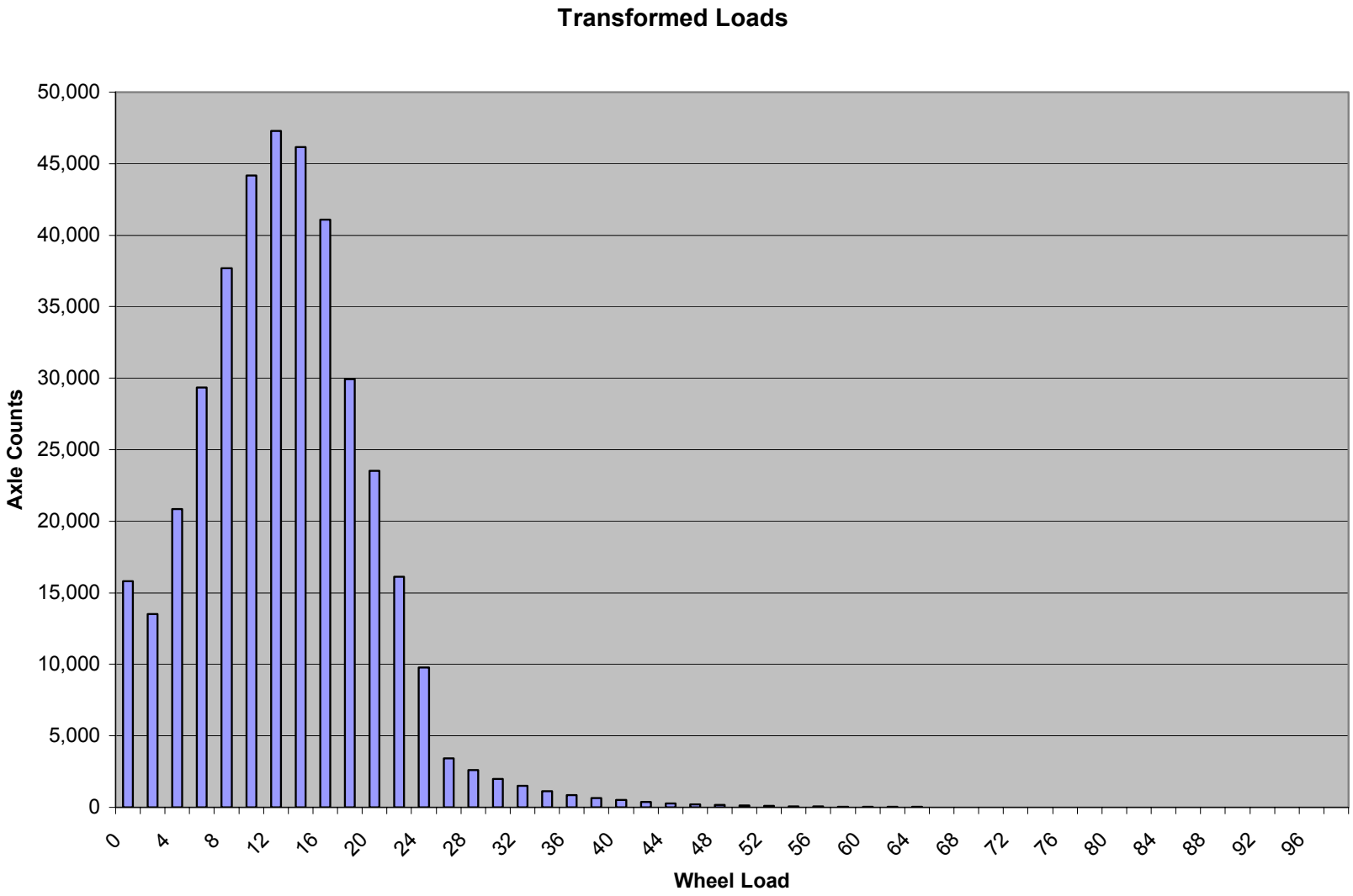


Figure 13. Transformed Agency Data into the Predicted Annual Dynamic Load Distribution

The loads and their annual frequencies are then grouped into integer load values (Table C) as a necessary prelude for the following step. The data in Table C is then transformed into a distribution that predicts the full spectrum of the agency's dynamic wheel loading during a year (Figure 13 and Table D). The transformation is a statistical distribution function empirically developed from several years of wheel load data on a commuter rail operation. If a transit has a measured wheel load database, the statistical distribution of that database should be used to transform the data.

Table D. Tabular Results of the Transformed Load Distribution for Fastener Testing

Test Regimen		
Total No. Test Cycles for 30 year life simulation		***1,910,880***
Wheel Load	*No. Test Cycles*	
(lb)	*(1 year)*	*(30 years)*
20,000	*23,520*	*705,600*
22,000	*16,128*	*483,840*
24,000	*9,768*	*293,040*
26,000	*3,432*	*102,960*
28,000	*2,604*	*78,120*
30,000	*1,980*	*59,400*
32,000	*1,500*	*45,000*
34,000	*1,140*	*34,200*
36,000	*864*	*25,920*
38,000	*660*	*19,800*
40,000	*504*	*15,120*
42,000	*384*	*11,520*
44,000	*288*	*8,640*
46,000	*216*	*6,480*
48,000	*168*	*5,040*
50,000	*132*	*3,960*
52,000	*96*	*2,880*
54,000	*72*	*2,160*
56,000	*60*	*1,800*
58,000	*48*	*1,440*

Test Regimen		
Total No. Test Cycles for 30 year life simulation		***1,910,880***
Wheel Load	*No. Test Cycles*	
(lb)	*(1 year)*	*(30 years)*
60,000	*36*	*1,080*
62,000	*24*	*720*
64,000	*24*	*720*
66,00	*12*	*360*
68,000	*12*	*360*
70,000	*12*	*360*
72,000	*12*	*360*
74,000	*0*	*0*
76,000	*0*	*0*
78,000	*0*	*0*
80,000	*0*	*0*
82,000	*0*	*0*
84,000	*0*	*0*
86,000	*0*	*0*
88,000	*0*	*0*
90,000	*0*	*0*
92,000	*0*	*0*
94,000	*0*	*0*
96,000	*0*	*0*
98,000	*0*	*0*

Table D shows the upper third of the predicted wheel loads for the transit agency represented in this case. The table shows that the Repeated Load Test could be conducted for 1.9 million of the loads and load counts rather than 3 million loads as currently in the specification.

Under the principals suggested, the test could legitimately represent fastener design acceptability by choosing the top 10% (or other) of the predicted loads. For example, test loads beginning with 42,000 lbs up to the maximum, with the frequency for each load as shown in Table D, would total 48,000 load cycles to represent a 30 year fastener service life.

All loads are wheel loads in the foregoing tables and illustrations. The test load per fastener is typically about 45% of the wheel load values.

This test regimen is suggested as an economical approach to obtaining the necessary performance under loads encountered in service.

This approach may be further refined by measuring the agency's actual wheel load occurrence and using that information to compile a full dynamic distribution directly rather than through the transform used in the foregoing example. The development of the statistical dynamic wheel load distribution for individual agencies is suggested as an important research need.

The distribution used to transform the data in the foregoing example is that of Via Rail from several years of wheel load measurements. The statistical shape (not the actual load levels) of that data is believed to be representative of the distribution shape that would occur for transit agencies' wheel load population.

K. Repeated Load Test With One Anchor Bolt Loosened:

1. Test Method: After completion of the vertical and lateral repeated load test, reassemble the fastener using only the original components previously tested. Then, with the gauge side anchor bolt loosened and backed out 1/4 inch, repeat the vertical and lateral repeated load test for one year's load cycles (J.1.a through J.1.c).

2. Acceptance Criteria: The fastener shall withstand the specified total number of cycles of loading with no evidence of failure by slippage, yielding, or fracture. The rail shall exhibit no evidence of wear or grooving that could contribute to failure of a rail.

The comments provided for the Repeated Load Test apply equally to this test.

L. Uplift Repeated Load Test:

1. Test Method:

a. A fully assembled fastener shall have loads applied to the rail head so as to produce alternately a vertical downward load of 10,400 pounds per fastener and a vertical upward load of 4,000 pounds per fastener at the centerline of the fastener *[or at the midpoint of the fasteners in multiple fastener setups]* normal to the rail. Apply the loads alternately for a total of 100 complete cycles. The rail vertical deflections shall be measured between the rail base and the top fastener plate, and between the rail base and the base concrete, with two transducers at each edge of the rail base for the top plate and the concrete base (four transducers). The frequency shall be regulated to prevent component temperature reaching 50°C. The rail clips shall not be repositioned or the threaded elements re-torqued during this procedure.

b. During the final 50 cycles, a longitudinal load shall be applied to the rail at its base. The longitudinal load shall be increased in uniform increments up to 2,000 pounds per fastener. The longitudinal load and deflection and the vertical load and vertical deflections shall be measured and recorded continuously and simultaneously throughout this procedure. At the completion of the procedure, remove all loads while continuing to record all measurements until the loads are completely removed. Remove the longitudinal load and measure and record the longitudinal position of the rail. Plot the recorded values for the longitudinal load versus deflection on a graph.

c. The test controls shall terminate the procedure immediately if rail slip greater than ½ inch occurs.

2. Acceptance Criteria: The fastener shall withstand the test procedure with no evidence of failure. Upon visual inspection, no component of the fastener shall exhibit evidence of failure by yielding, abrasion, slippage, or fracture. The rail shall exhibit no evidence of wear or grooving that could contribute to its failure. The plot of the load versus deflection curve shall indicate the elastic deformation and the residual deflection. The residual deflection shall not exceed 0.005 inch.

If the rail slips ½ inch at any time during the procedure, the rail restraint arrangement shall be rejected. If the vertical deflection

difference between the two vertical measurement transducers averages more than 10% of the total upward rail deflection, the rail restraint arrangement shall be rejected.

Note that the applied loads are per fastener, requiring stated loads in multiples of the number of fasteners in the test.

The test affirms that the fastener assembly design has adequate load capacity in an upward direction.

The example specification adds the deflection measurement of the fastener relative to the rail base not normally included in this procedure.

The upward vertical load (4,000 lb) is about 65% of the toe load of typical rail clips from one fastener. The rail motion relative to the fastener top plate should be zero throughout the test.

The maximum longitudinal load (2,000 lb) is about 65% of the typical rail clip longitudinal restraint for one fastener. There should be no longitudinal rail slippage from these loads (there will be resilient longitudinal deflection from the fastener's elasticity).

If resilient ties are being tested, the embedded block should be mechanically restrained from vertical uplift motion.

The test loads must be reduced if low longitudinal restraint fasteners are being tested.

M. Push-Pull Test:

1. Test Method:

a. The rail end shall be supported on a roller or other frictionless support properly elevated to prevent the longitudinal load from binding the rail in the fasteners. Apply a cyclic longitudinal load at the base of the rail to slip the rail approximately 1/2 inch back and forth about its initial position for a total of 2,000 cycles per fastener without repositioning rail clip or retorquing bolts. The 1/2 inch slip shall be measured with respect to a fixed point on the testing machine. Following this, components shall be checked against the acceptance criteria. Next, a cyclic longitudinal load at the rail base shall be applied to slip the rail approximately 1/8 inch back and forth about its initial position for a total of one million cycles.

b. Repositioning of the rail clip will not be allowed during the second phase of the test. Loading frequency shall be regulated to prevent the temperature of components from exceeding 50°C. Clean water may be applied occasionally as a spray in order to keep the temperature below 50°C.

2. Acceptance Criteria: The fastener shall withstand the specified number of cycles of load application with no evidence of failure. Upon visual inspection, no component shall exhibit evidence of failure by slippage, yielding, or fracture at any time during the test, nor shall a rail clip show evidence of sliding out or backing out of its hold-down housing more than 1/16 inch. The rail shall exhibit no evidence of wear, beyond minor polishing and grooving, that could contribute to failure of a rail.

This test determines if a clip will walk out of the fastener's clip holder if the rail slips and whether the rail clip will damage the rail during slip. For non-bonded fasteners, the test determines whether the elastomer pad is properly constrained against longitudinal motion.

Some opinions on the test suggest that rail does not slide through the fastener, or does so in rare circumstances. The author believes longitudinal rail slip is a common occurrence but is usually difficult to detect because the slippage is very small. The test is justified because it is effective in its fundamental purpose and is simple.

This test could be a useful fatigue test for rail clips. If an agency begins observing an increased number of rail clip failures (either breakage or fallout), this test can be used to determine if the cause is rail clip fatigue. To test for rail clip fatigue, the procedure is performed as stated except for 250,000 test cycles, or for the estimated number of axle loads per year, whichever is higher.

For non-bonded fasteners, the test verifies whether the design properly constrains the elastomer.

N. Dynamic Characterization Test:

1. Test Method:

a. A vertical preload shall equal the target load stipulated in the Vertical Load Test, and shall be applied at the centerline of the fastener *[or at the center of the fastener assemblies in multiple fastener setups].* Two transducers, located each side of the rail and at the load point, shall measure the vertical deflections of the rail base or the fastener top plate relative to the test bed. An oscillating downward load shall

be applied at the centerline of the rail head at the centerline of the fastener *[at the center of a multiple fastener setup]* to produce a sinusoidal load with an amplitude of 3,000 pounds at a fixed frequency rate of one Hertz through 30 complete load cycles. The load, deflection and time shall be continuously recorded digitally.

b. The foregoing test shall be repeated at frequency rates of five, 10 and twenty Hertz.

c. The data from each frequency test run shall be treated separately as follows:

i. The load data shall be averaged and the average used as the reference preload value. The average of load values minus the preload value for each data point shall be the oscillating load amplitude, F_o

ii. The two deflection transducer measurements shall be averaged at each time interval, then all the averaged time interval deflection values shall be averaged and used as the reference as the zero deflection value. The maximum deflection of the deflection values minus the reference zero deflection value for each data point shall be the deflection amplitude, x_o.

iii. For every load cycle, the time that a descending load crosses the reference preload value will be subtracted from the time that the descending deflection crosses the reference zero deflection value. This value is the time lag between the applied load and the fastener response.

iv. The time lag for all cycles will be averaged.

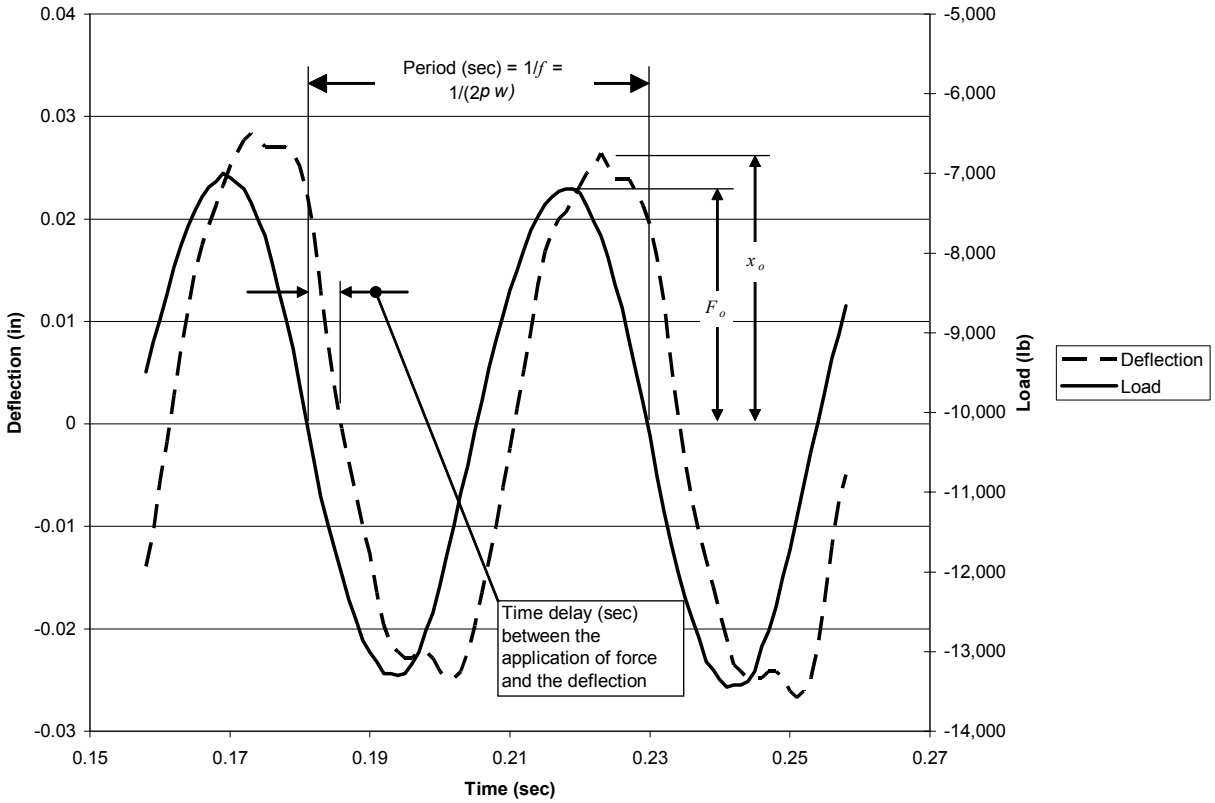


Figure 14. Phase Shift Measurement for Fastener Dynamic Stiffness and Damping Characterizations[13].
This example is 100 data samples for a 3,000 lb amplitude sinusoidal load (= F_0) applied at 20 Hz (=ω), with a vertical preload slightly more than 10,000 lbs.

v. Mass. The weight of the rail shall be estimated from its length and size. The weight of the fastener top plate shall be obtained from the manufacturer. Any other objects in the test configuration between the load cell and the fastener elastomer shall be weighed. The sum of these weights shall be converted to mass units for use in the following relationships.

vi. The phase shift angle, dynamic stiffness, damping coefficient, critical damping coefficient and damping ratio shall be calculated as illustrated in **Figure 14** using the relationships:

[13] J.M. Tuten III, *Final Report*, Appendices, data files, TCRP Project D-5, Performance of Direct Fixation Fasteners, April 1999.

(1) $$Tan\psi = \frac{TimeDelay}{Period}$$

where ψ = phase shift angle

(2) $$k = \frac{F_0}{x_0\left(1+\tan\psi\right)^{1/2}} + m\omega^2$$

where

k	=	dynamic stiffness (lb/in)
F_o	=	amplitude of the oscillating force (lb)
x_o	=	deflection amplitude (in)
ψ	=	phase shift angle
m	=	mass of the test rail, top plate of the fastener and any other mass in the test configuration between the load cell and the fastener's elastomer (lb-sec^2/in)
ω	=	forcing frequency (radians/sec)

The fastener damping is calculated from k:

(3) $$c = \frac{\left(k - m\omega^2\right)\tan\psi}{\omega}$$

where c = Damping coefficient (lb-sec/in)

The fastener critical damping is calculated using

(4) $$c_{cr} = 2\sqrt{km}$$

where c_{cr} = Damping coefficient (lb-sec/in)

and the damping ratio is calculated using

(5) $$\gamma = \frac{c}{c_{cr}}$$

where

γ = damping ratio

vii. The resonant frequency, ω_r, shall be calculated at each test frequency. The resonant frequency is determined

differently for an underdamped (γ<1), critically damped (γ=1), and overdamped (γ>1) conditions. The units for resonant frequency are radians per second.

(6) For $\gamma < 1$**:** $$\omega_r = \sqrt{\frac{k}{m} - \frac{c^2}{2m^2}}$$ [14]

When $\omega = \omega_r$, the response is a resonant response, with the deflections amplified. The maximum deflection will be

(7) $$x_0(\max) = \frac{F_0}{\sqrt{(\omega_r c)^2 + \left(\frac{c^2}{2m}\right)^2}}$$ [15]

(8) For $\gamma = 1$**:** $$\omega_r = \sqrt{\frac{k}{m}}$$ [16]

When $\omega = \omega_{cr}$ there is no amplification of deflections.

(9) For $\gamma > 1$**:** $$\omega_r = \frac{c}{2m} - \sqrt{\left(\frac{c}{2m}\right)^2 - \frac{k}{m}}$$ [17]

For this condition, deflections will attenuate for frequencies above ω_r.

viii. Loss Tangent.

The loss tangent shall be calculated at each test frequency using the following relationship:

$$\tan\delta = \frac{\omega c}{k}$$

2. The phase shift angle, ψ, dynamic stiffness, k, the damping coefficients, c and c_{cr}, the resonant frequency, ω_r, and loss tangent, tan δ, shall reported in a table by test frequency. The resonant

[14] *Engineering with Rubber*, Ed. A.N. Gent, Hanser Publishers, 1992, pp. 78, 79

[15] Gent, pg. 79, eq. 4.24

[16] S. Timoshenko, D.H. Young, W. Weaver, *Vibration Problems in Engineering*, Fourth Edition, John Wiley & Sons, 1974, pg. 69

[17] Timoshenko, pg 69 & 71

frequency shall be reported both in radians per second and in Hz[18]. Plots shall be constructed with test frequency on the ordinate axis and each parameter on the abscissa axis.

3. Acceptance Criteria: The resonant frequency shall not be greater than 160,000 Hz at any test frequency using the test mass (test rail, fastener top plate, any other component or test apparatus between the test load cell and the test rail).

This procedure replaces the "Dynamic to Static Stiffness Ratio Test" in current Direct Fixation specifications. That test defines the dynamic stiffness as F_o/x_o, which is numerically identical (for all practical purposes) to the dynamic stiffness, k, from the foregoing procedure.

The only difference between the test procedures is this procedure performs the test at a number of frequencies, where the current practice tests at only one frequency, usually ten Hz.

The primary difference between this procedure and the procedure in the current practice is the data treatment to measure the phase shift angle and using that to provide accurate damping coefficients. The correct resonant frequency can then be calculated for the different masses that will be present in service.

The Dynamic to Static stiffness ratio is calculated by dividing the dynamic stiffness by the static stiffness from the vertical load test at the preload test value for this test (there are variations on which load is selected for defining the static stiffness).

The acceptance criteria for the Dynamic to Static Stiffness Ratio is a value of 1.4 (different values are used somewhat arbitrarily between 1.3 and 2).

The current practice does not provide any insight into why a high ratio is good or bad because it compares a test influenced in part by frequency and mass with a test not having those influences. The technical meaning of such a ratio is not useful as an indication of fastener design or performance. Some fasteners that are dynamically much softer than others have ratios that are among the highest of any fastener on the market.

There are several benefits to adopting the procedure shown here. The procedure provides far more information on the fastener's dynamic characteristics over a range of frequencies. This is important because elastomer damping properties are dependent on frequency.

[18] frequency, f in Hz = $\omega_r/2\pi$

Perhaps the most useful result is the resonant frequency. This value establishes the point at which the fastener begins to filter vibrations.

The Dynamic to Static Stiffness Ratio is a qualitative measure with no technical basis indicating fastener behavior in service. It does measure how much different a fastener is from a true spring, which will have the same dynamic stiffness as static (ratio of 1). However, elastomers are very different from springs and must be treated differently.

Please refer to the Direct Fixation Track Design [Part A, Section 1, paragraph VI.B.2] for a full discussion of fastener dynamic characteristics. Derivation of equations in this section is in that section's Attachment 1E .

O. Heat Aging Test:

1. Test Method: Age test the fastener body, without rail, concrete test block, rail clips or anchor assemblies, in an air oven for 336 hours at a temperature of 70°C in accordance with ASTM D573.

2. Acceptance Criteria: This is a conditioning process that is required for the test sequence and there is no acceptance criteria.

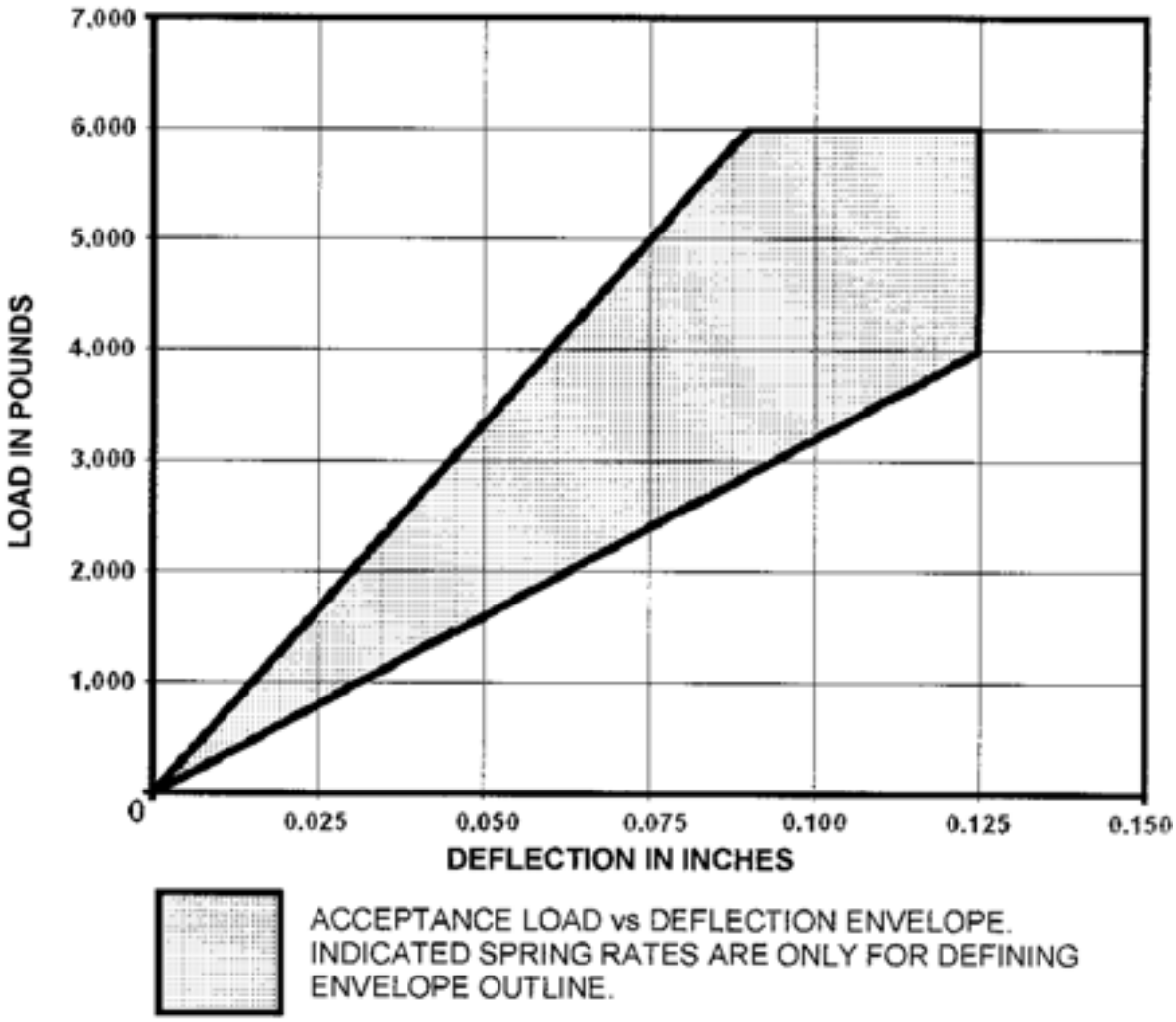


Figure 15. Lateral Load Test Acceptance Envelope

This figure must be amended for the vertical static stiffness specified for the fastener and the selected vertical preload (=10,000 lb in the example specification).

Attachment 3A. Typical Test Load Parameters

The lateral load test is one of the most important of the test series. Load values from procurement documents at a number of agencies are presented in Table E.

Table E. Comparison of lateral load test requirements

Agency	Vertical Load (lb)	Lateral Load (lb)	L/V Ratio	Acceptance Criteria Deflection (inches)
FERP	a. 9,000	4,000	0.44	0.13
	9,000	6,000	0.67	0.30
	b. 14,000	4,000	0.29	0.13
	14,000	8,000	0.57	0.30
WMATA & Buffalo	13,500	4,000	0.29	0.125
	13,500	10.000	0.74	0.30
BART	0	3,000	not defined	0.10
Pittsburgh	13,500	3,000	0.22	0.125
	13,500	10,000	0.74	0.35
Calgary & Edmonton	12,000	4,000	0.33	0.125
	12,000	7,000	0.58	0.30
Vancouver & Monterey (Mexico)	13,500	8,000	0.59	0.30
New York City	12,000	5,000	0.42	0.25
	12,000	8,000	0.67	0.30
	12,000	10,000	0.83	0.40
Chicago	16,200	4,800	0.29	0.125
	16,200	12,000	0.74	0.30
Boston	16,200	4,800	0.29	0.125
	16,200	8,000	0.49	0.30
Miami	16,200	4,000	0.25	0.20
	16,200	12,000	0.74	0.50
Los Angeles Red Line	10,400	5,900	0.56	0.20
Baltimore MTA	16,200	12,000	0.74	
Baltimore Light Rail	9,000	4,000	0.44	0.37
Atlanta	13,500	7,500	0.56	

Attachment 3B. Synchronized Repeated Load Test

SPRING RATE AND DEFLECTION TEST.

(1) The set of fasteners shall be tested as follows:

(a) The two fasteners shall be loaded and have the deflections measured as shown in Exhibit D. The modified rail section shall be instrumented for rotation about its longitudinal axis. The vertical and lateral response loads will be the load values measured on the vertical and lateral load cells, respectively, between the loading rams and the load points. Exhibit E shows the vertical and lateral response loading as a function of time. The vertical load point shall be loaded with a vertical load that varies as shown by Curve V. The occurrence of one wave as shown by Curve V shall be considered as one cycle. The lateral load point shall be loaded with a lateral load that varies as shown by Curve L. The vertical and lateral load shall occur simultaneously as shown in Exhibit E. The direction of the lateral load shall be as shown by Curve L in Exhibit E. There may be a no load pause between cycles of no longer than one half of the cycle length.

(b) The fasteners shall be preloaded with 1000 cycles of Case 1 vertical loading only. After the preload cycles, the instruments used to monitor deflection and rotation shall be zeroed in a no-load condition. Then the Case 1 vertical loading shall be begun and Curve L lateral loading shall be applied up to a 22,000 pound response load at point E and cycled until the deflections stabilize. Points D and F response loads shall be as determined as shown in Exhibit E (2 of 2) for Case 1 - L. After stabilizing, and with point E at 22,000 pounds (11,000 pounds per fastener), the average rail base lateral deflection at point E shall be recorded and plotted. The lateral load shall then be increased and the process repeated until the intersection point between the data and the upper limit shown on Exhibit B can be determined. Two data points shall be within 1000 pounds per fastener of either side of the upper limit in order to determine the intersection point. The per fastener load at the intersection point shall be doubled and the doubled value shall be the response load LI shown in Exhibit E (2 of 2). The response load at points D and F shall then be found as indicated in Exhibit E (2 of 2).

(c) The fasteners shall be preloaded with 1000 cycles of Case 1-L loading. After the preload cycles, the instruments used to monitor deflection and rotation shall be zeroed in a no-load condition. Then the Case 1-L loading shall be cycled 5 times during which data of vertical and lateral loads, deflections and rotation as functions of time shall be recorded in a manner such that both analog graphs and digital

data can be presented. The analog graphs shall be recorded directly from the instrumentation's output signal. At the completion of the 5 cycles the load shall be removed and data shall be continuously collected for one minute after the loads are removed.

(d) The test data shall be presented in both analog and digitized form. The analog graphs shall be drawn at a rate of not less than 100 mm per second during the 5 cycles and not less than one mm per second during the one minute period after the loads are removed. The vertical scale shall be set to make full use of a strip chart which is at least 40 mm wide per channel. Analog graphs of loads (for each load cell), deflections (for each deflection) and rotations at each end shall include calibration (scales) and annotation which fully describe the graphs. Digitized data shall show vertical and lateral fastener loads, average vertical deflection, average lateral deflection at base of rail, average lateral deflection 6.75 inches above the base of rail, and average rotation values at every 0.01 seconds for each cycle and at one minute of rest after release of the loads. The fastener load shall be computed as one half of the response load. The digitized data may be a computer printout formatted in accordance with the Engineer’s instructions. The lateral deflection to be reported on Exhibit F is the average value at the base of the rail.

(e) All deflection and rotation instrumentation shall measure, relative to the test block, to the nearest 0.001 inch and 0.02 degrees, respectively. The instrumentation for measuring the response loads (the total load applied to both fasteners) shall have an accuracy of plus and minus two percent or plus and minus 50 pounds whichever is larger. The test operator shall perform the tests so that the instrumentation indicates that the response load is within plus and minus 100 pounds of the specified loads.

(f) The fastener set shall also be tested as in the preceding steps (a) through (e) but with the direction of the lateral response load reversed as shown by Reverse Curve L in Exhibit E (1 of 2). Response load RL1 at point E and the response loads at points D and F for Case 1 -RL shall be found.

(2) Each fastener in the two fastener test set shall satisfy the following acceptance criteria.

(a) The fastener shall demonstrate response repeatability for each loading case, 1-L and 1-RL. Repeatability shall be demonstrated if the deflections for a fastener at each load level indicated by the lettered points on Curves V and L do not vary by more than plus or minus 0.002 inch or plus or minus seven percent whichever is larger, from the average for the 5 cycles. Once repeatability has been demonstrated, the third cycle of the 5 recorded shall be chosen from each of the loading cases for further analysis as follows:

(b) For each case, the spring rate for the fastener shall be determined from the maximum downward vertical fastener load (occurrence of Point C) and the downward vertical fastener deflection which occurs at that time. The average spring rate for the two fasteners shall be between 150,000 and 300,000 pounds per inch.

(c) The digital data shall be grouped into increments in the following manner:

[1] Vertical:

- Three equal time increments from zero deflection near 0.22 seconds to peak deflection near Point C at 0.44 seconds.

- Three equal time increments from peak deflection near Point C at 0.44 seconds to zero deflection near 0.66 seconds.

[2] Lateral:

- Three equal time increments from zero deflection near 0.24 seconds to peak deflection near Point E at 0.34 seconds.

- Three equal time increments from peak deflection near Point E at 0.34 seconds to Point F near 0.44 seconds.

- Three equal time increments from Point F at 0.44 seconds to zero deflection near 0.61 seconds.

[3] Linear regression shall be used to determine the incremental fastener spring rate for each increment as previously defined. The incremental spring rates shall be shown on Exhibit F. The minimum incremental spring rate shall not be less than 80 percent for vertical and 70 percent for lateral of the maximum incremental spring rate for the first three increments beginning near 022 seconds for the vertical and 0.24 seconds for the lateral. The criteria shall be applied individually to both the vertical and lateral data for Cases 1L and 1-RL.

(d) The vertical deflection at Point A on Curve V for Cases 1-L and 1-RL shall not be less than 0.000 inches and shall indicate a deflection in the up direction.

(e) Maximum elastomer compressive and shear strains shall not exceed 24 percent and 50 percent respectively for Case 1 shown on Exhibit E.

(f) The peak average lateral deflections measured 6 3/4 inches above the rail base for Case 1 shall not exceed 0.25 inch. The maximum angle of rotation of

the modified rail section about the longitudinal axis shall not exceed 0.50 degree for Case 1. For each case the lateral spring rate for the fastener shall be determined from the maximum lateral fastener load (occurrence of Point E) and the lateral deflection at base of rail which occurs at that time. The average spring rate for the two fasteners shall be less than 963,000 pounds per inch and greater than 62,200 pounds per inch.

(g) After completion of the loading cycles and with one minute of rest with no load, the vertical deflections shall not exceed 0.005 inch and the average lateral deflections at both the rail base and 6 3/4 inches above the base shall not exceed 0.01 inch.

(h) The rail base shall remain in full contact with the rail seat of the fastener during the cycling.

(i) The analog data shall show uniform deflection and load indicating no free play.

(j) At no time during the test shall any fastener component, including the anchorage to the test block, exhibit any sign of failure by slippage, yielding or fracture. Analog data shall be reviewed for indications of slippage, yielding or fracture.

(k) When this test is repeated in the test sequence the deflections shall not have increased by more than 10 percent and the spring rate shall not have decreased by more than 10 percent from the initial performance.

REPEATED LOAD TEST-PROCEDURE

(1) The test fasteners shall be set up, loaded and instrumented as described for the Spring Rate and Deflection Test except that in Exhibit E (2 of 2), Cases 3, 4 and 5 shall be used and the direction of the lateral load, Curve L, shall not be reversed at any time. The direction of the lateral load relative to the fasteners shall be the same for all three cases and for all occurrences of this test in the sequencing.

(2) No adjustments (retorqueing, reapplication or resetting) of any component during a 1.5 million cycle sequence shall be made without approval from the Engineer. All adjustments shall be reported.

(3) For every 100 cycles of testing each case shall be cycled the number of times shown in Exhibit E (2 of 2). Each time this test is required in the test sequence it shall be performed for 1.5 million cycles. The analog and digital instrumentation and recording devices for the lateral and vertical response loads and deflections shall be operative and used to monitor the test. For every 250,000 cycles, the last 100 continuous cycles of vertical and lateral response loads and deflections shall be recorded as analog load data and shall be reported in the test report. Of the 100 cycles, one

sample of each of the three cases shall be digitized in increments of 0.01 seconds and reported in the test report as shown in Exhibit F. The digitized data may be formatted similar to Exhibit F with a computer printout.

(4) Acceptance Criteria: At no time during the test shall any fastener component, including the anchorage to the test block, exhibit any sign of failure by slippage, yielding or fracture. More than a 10 percent increase in deflection or decrease in spring rate during the test is a sign of failure.

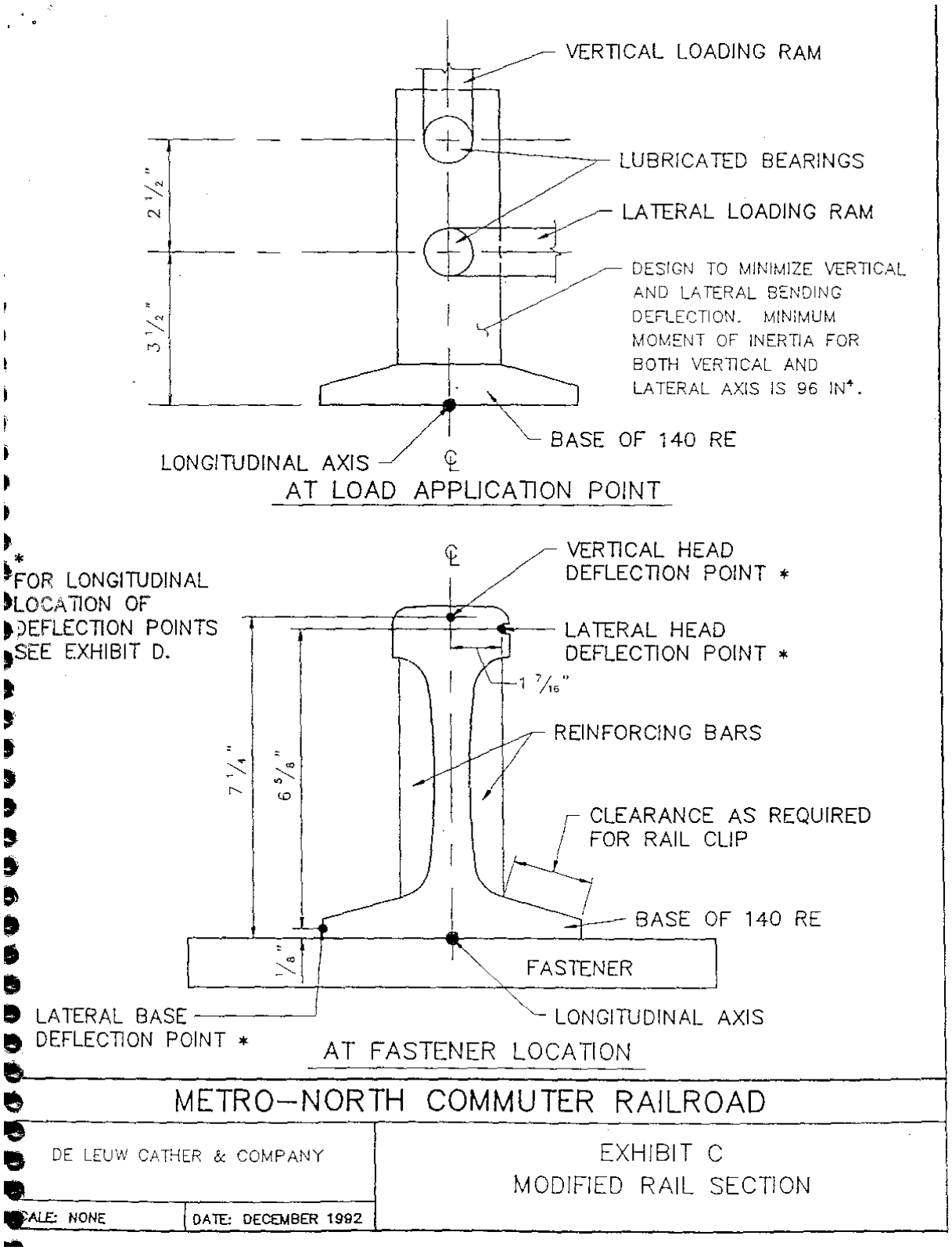


Figure 16. Rail Section for Synchronized Vertical and Lateral Load Test Approach

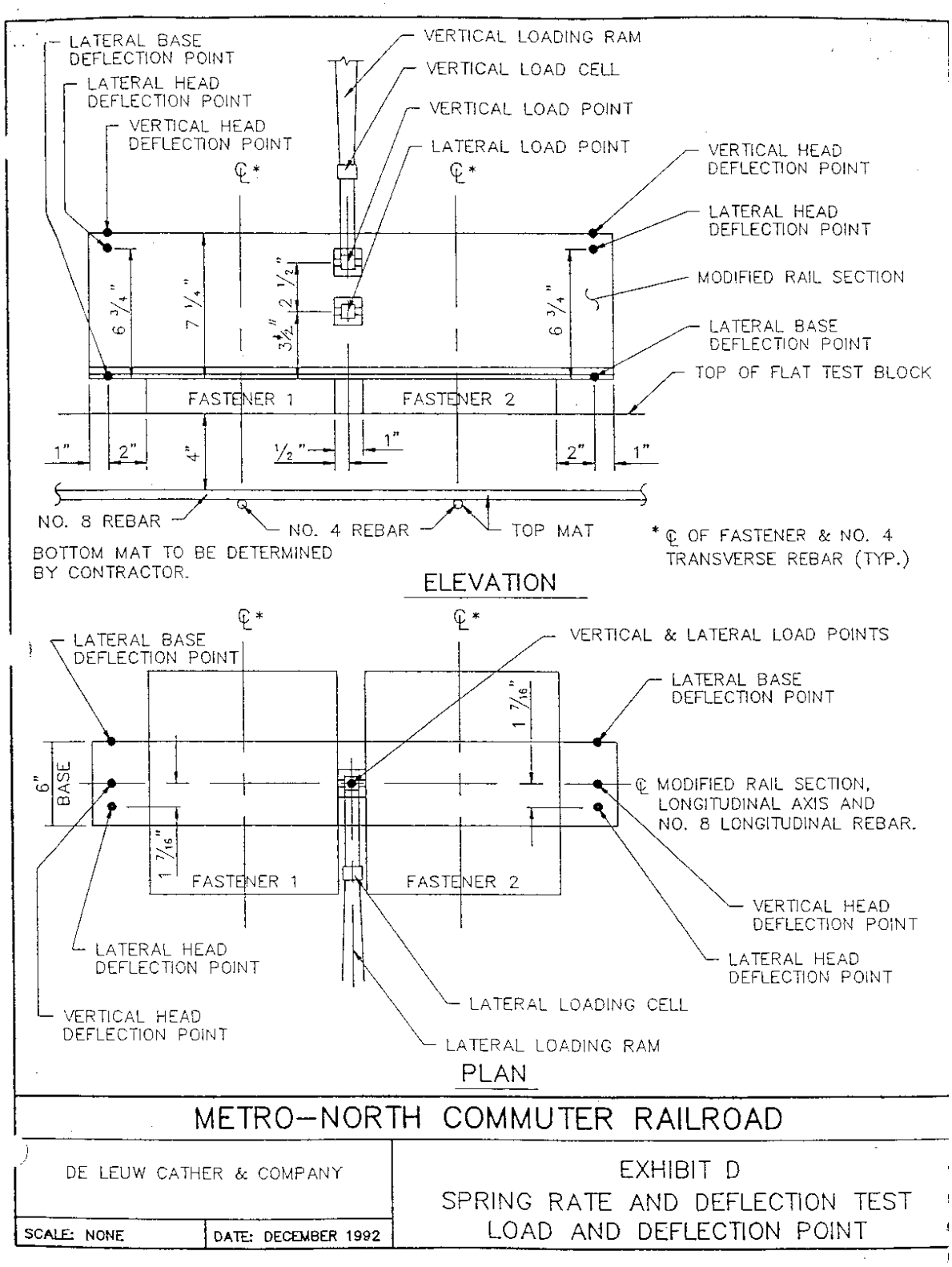


Figure 17. Example Test Bed Setup for the Synchronized Vertical and Lateral Load Test Approach

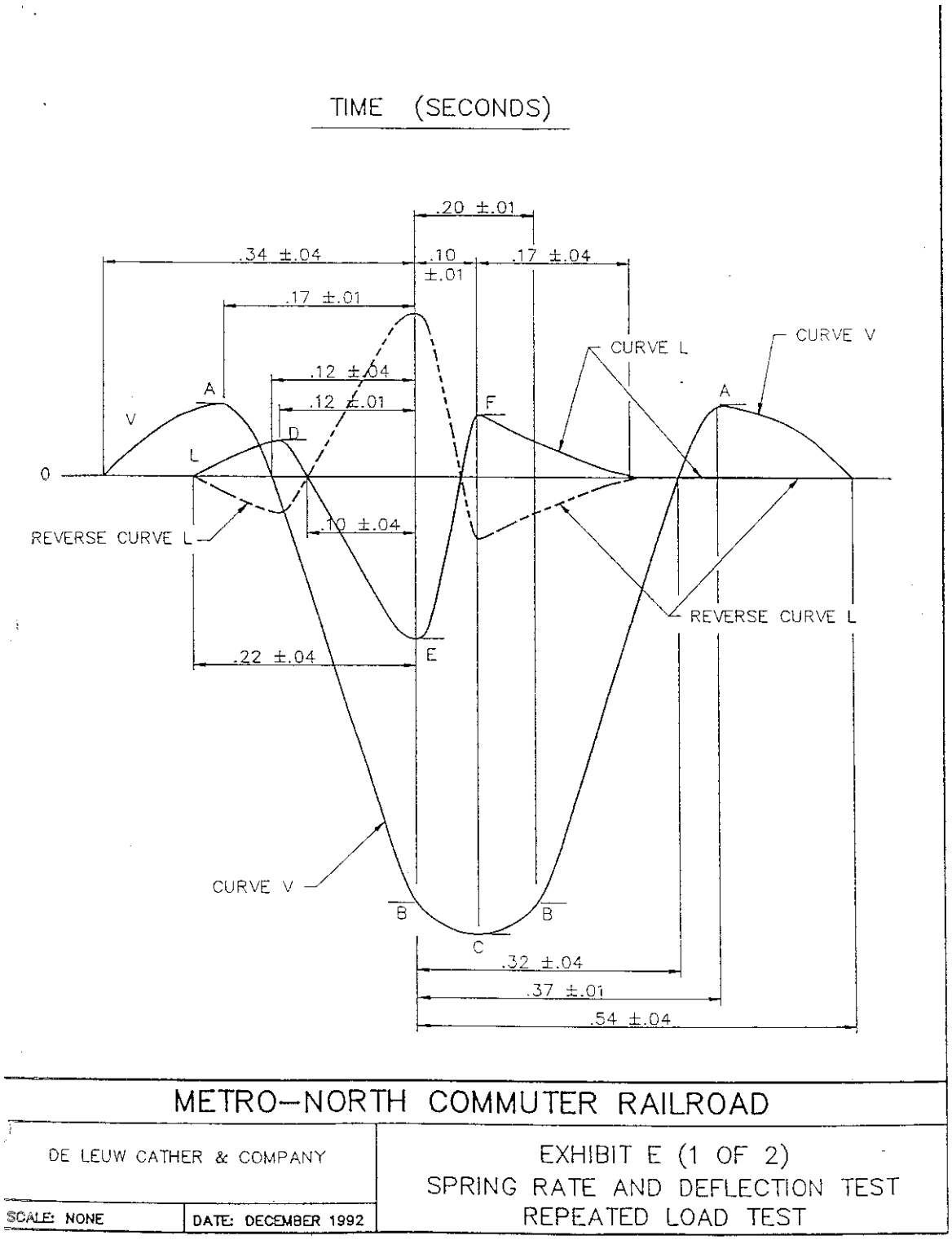


Figure 18. Spring Rate and Deflection Test, Repeated Load Test (1 of 2)

		SPRING RATE AND DEFLECTION TEST		REPEATED LOAD TEST				
		CASE						
		1		3	4	5		
		L	RL					
VERTICAL CURVE V	A	−1.4	−1.4	−1.2	−1.4	−1.1	KIPS	RESPONSE LOAD
	B	+32.0	+32.0	+28.0	+32.0	+24.3	KIPS	
	C	+36.4	+36.4	+31.8	+36.4	+27.6	KIPS	
LATERAL CURVE L	D	$-L1/20$	$-RL1/20$	$-(1)/20$	$-(2)/20$	$-(3)/20$	KIPS	
	E	+L1	+RL1	+(1)	+(2)	+(3)	KIPS	
	F	$-L1/2.9$	$-RL1/2.9$	$-(1)/2.9$	$-(2)/2.9$	$-(3)/2.9$	KIPS	
NO. OF CYCLES OF EACH CASE PER 100 CYCLES OF REPEATED LOAD TEST.				98	1	1		

(1) = 0.51 x (2)
(2) = THE GREATER OF L1 AND RL1
(3) = 0.77 x (2)

METRO–NORTH COMMUTER RAILROAD

DE LEUW CATHER & COMPANY

EXHIBIT E (2 OF 2)
SPRING RATE AND DEFLECTION TEST
REPEATED LOAD TEST

SCALE: NONE DATE: DECEMBER 1992

Figure 18. Spring Rate and Deflection Test, Repeated Load Test (2 of 2)

SECTION 4

Direct Fixation Trackwork Example Construction Specification and Commentary

For

TCRP Project D-07/Task 11

Development of Direct-Fixation Fastener Specifications and Related Material

by

Laurence E. Daniels
Railroad Consulting Engineer

William H. Moorhead
Principal
TRAMMCO, LLC

May 2005

Section 4

Direct Fixation Trackwork Example Construction Specification and Commentary

The purpose of this example specification is to provide a framework for discussion of Direct Fixation track construction issues. The implementation of any portion of the example specification in a project should be carefully considered to meet the project's circumstances and contractual requirements.

This example applies to track construction using Direct Fixation fasteners. This may apply to Direct Fixation track on slabs, aerial structures, and tunnels. It may also apply to embedded track (street track) using Direct Fixation fasteners. The specification is not suitable for track constructed with embedded blocks or resilient ties.

This example specification suggests language drawn from prior construction specifications considered either as demonstrations of good practice or useful expositions of common practice that allows discussion of misunderstandings or misperceptions in the industry.

The example specification language is in normal *text. The commentary is in italicized text, generally following each stipulation. Where there is no commentary for a stipulation, the requirement is considered to be self-explanatory or no comment is warranted.*

Please also see Section 1, Direct Fixation Track Design, Section 2, Direct Fixation Fastener Example Procurement Specification and Commentary, and Section 3, Direct Fixation Fastener Example Qualification and Production Test Specification and Commentary for additional background on Direct Fixation issues.

Section 4

Direct Fixation Trackwork Example Construction Specification and Commentary

TABLE OF CONTENTS

Direct Fixation Trackwork Example Construction Specification and Commentary

1. GENERAL

1.01. DESCRIPTION

A. This Section specifies the installation of direct fixation track.

B. The Work includes furnishing and placing reinforced cast-in-place concrete plinth pads on concrete track slabs and bridge decks; joining of Owner furnished, Contractor welded continuous welded rail (CWR) strings by mobile electric-flash butt and/or thermite welding; installing and testing direct fastener inserts; and laying Owner furnished continuous welded rail (CWR) *{insert other or additional track configurations in a project covered by this section. Example: "Owner furnished restraining rail and Contractor furnished single inner emergency guardrail"}* utilizing Owner furnished direct fixation fasteners.

C. The track to be constructed is an electrified Light Rail Transit (LRT) system with an overhead catenary system (OCS). The rail in the track is the ground return for the OCS. Care shall be taken by the Contractor to reduce the possibility of stray currents *{replace with appropriate description of the service type and general configuration}*.

1.02. RELATED SECTIONS

[Insert appropriate section titles from the project's specifications, such as:

01300 - Submittals
01310 - Project Schedules
03100 - Concrete Formwork
03200 - Concrete Reinforcement
03300 - Cast-in-Place Concrete
05651 - Trackwork - Owner Furnished Material
05655 - Trackwork - Field Rail Welding
05660 - Trackwork - Ballasted Track Construction
05692 - Trackwork - Field Fabricated Bonded Insulated Joints
16109 - Traction Electrification and Signal Bonding
16641 - Trackwork Electrical Isolation]

1.03. REFERENCES

Sponsor	Number	Subject
AREMA		Manual for Railway Engineering (AREMA Manual)
ASTM	A 36	Specification for Structural Steel
ASTM	A 153	Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware
ASTM	A 307	Specification for Carbon Steel Bolts and Studs, 60,000 psi Tensile
ASTM	A 653	General Requirements for Steel Sheet, Zinc-Coated (Galvanized) by the Hot-Dip Process
ASTM	A 563	Specification for Carbon and Alloy Steel Nuts
ASTM	A 591	Steel Sheet, Electrolytic Zinc-Coated, for Light Coating Mass Applications
ASTM	A 1011	Hot-Rolled Carbon Steel Sheet and Strip, Structural Quality
ASTM	A 775	Epoxy Coated Reinforcing Bars
DOD	21035	Repair Paint, Galvanizing
AASHTO	T277	Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride
ACI	SP15(99)	Field Reference Manual
ACI	MCP 2004	Manual of Concrete Practice

1.04. DEFINITIONS

{This paragraph is typically not included in Direct Fixation construction specifications}

1.05. SUBMITTALS

A. Refer to Section *[insert reference specification section and title for submittal procedures]*, and Section *[insert reference specification(s) and title(s) for shop drawings, product data and sample submittal requirements and procedures.].*

B. Work Plans: Submit construction work plans for DF track and special trackwork construction. Work plans shall be submitted within 60 days of the planned commencement of work included within the scope of a particular work plan. Agency work plan review will be conducted within 30 days from the date of work plan submittal. The contractor shall submit revised work plans and obtain the Engineer's approval of the final work plans prior to commencing work under that plan.

Each work plan shall, at a minimum, include the following applicable items.

1. Step by step construction sequence.

2. Survey control plan.

3. Material handling procedure.

4. Special equipment and tools.

5. Shop Drawings of forms, jigs and supports.

6. Method of protecting supports to allow removal after concrete installation.

7. Method of treating holes in the concrete created by temporary supports.

8. Concrete surface and dowel preparation.

9. Proposed methods of repairing damaged concrete base caused by over water-jetting.

10. Methods of protecting existing drainage from deleterious material during construction.

11. Methods of collecting and removing washed material, debris and dust.

12. Mixing, transporting, forming, placing, finishing, and curing of track concrete.

13. Repair procedures for non-conforming concrete.

14. Method of measuring and repairing any voids in the bearing area (concrete support area that is contact with the Direct Fixation fastener).

15. Replacement procedures for damaged or incorrectly installed anchor bolt and third rail inserts, including torque and pull out testing that ensures compliance with the requirements.

16. Installation of DF rail fastener, including the anchor bolt installation torque and the sequence of shimming, torquing anchor bolts, and applying rail clips in accordance with the manufacturer's instructions.

17. Coordination between the installation of various track types, including standard and special trackwork.

18. Repair procedures for deviations in track gage, surface, rail cant, alignment, skewed DF fastener assemblies and for non-conforming insert locations.

19. Methods of installing switch normal to the tangent line and within location tolerances.

20. Methods of installing switch points, stock rails, and switch rods to conform to required tolerances and to provide the proper clearances between rods and track concrete.

21. Coordination of the plan for installing the switch machine and all rods with trackwork.

22. Equipment and method to be used to install the DF fastener assemblies to correct surface, alignment and gage and crosslevel.

23. Shop drawings of purpose manufactured gage supports to support track, fasteners and/or inserts prior to and during concrete placement.

24. Method and equipment for holding stock rails, switch rails, or frog wing rails when welding to adjacent rails.

25. Methods for rail anchoring and rail welding.

26. CWR handling and installation.

27. CWR adjusting, rail welding, and anchoring to conform to the neutral rail temperature requirements and to protect the aerial structure girders and piers.

28. Field testing and inspection to conform to the quality requirements and tolerances specified herein.

29. A comprehensive drainage plan.

30. Each construction work plan shall include written approval of the plan by the manufacturers of the DF fasteners, as applicable, and from the manufacturer(s) of the track support jig system, when applicable.

C. Demonstration Section *{optional for small projects}*

1. Upon receiving the Engineer's permission to proceed, the Contractor shall verify its work plan by constructing a demonstration section of track for approval by the Engineer before beginning construction of trackwork on a production basis.

2. The exact methods the Contractor proposes to use shall be employed for the demonstration section.

3. Separate demonstration sections shall be installed for each type of track construction used.

4. Separate demonstration sections shall be provided for each type of special trackwork construction.

5. Demonstration sections for standard track shall be between 100 and 1000 feet long and for special trackwork, at least one complete turnout.

6. The manufacturers' representatives of the DF fasteners, as applicable, shall be present throughout the construction of and any repairs made to the demonstration section. Each representative shall submit its approval of the demonstration section, in writing, to the Engineer. Any recommendation for changes to the work plan, by the manufacturer's representative, shall be integrated into the revised work plan.

7. If the demonstration section does not meet the indicated requirements, the Contractor shall submit a revised work plan and construct another demonstration section or sections at no additional cost to the Agency.

8. Non-conforming demonstration sections shall be removed or repaired by methods approved by the Engineer.

9. Location of the demonstration section(s) shall be as indicated on the Contract Drawings.

10. The Engineer will approve or disapprove each demonstration section within two weeks of completion.

11. The demonstration section shall include examples of the various forms of repair described in the work plan.

D. Production Work

1. The Contractor shall use only approved methods and procedures as shown and demonstrated for production work.

2. Product Data: Submit product data for non-shrink grout and metal preservative for the Engineer's approval within 30 days prior to the planned commencement of work.

3. Second pour concrete mix design. Submit the proposed concrete mix design for the Engineer's approval within 30 days prior to planned commencement of work. The mix design and mixing procedures will conform to ACI 201.2R-01 Guide to Durable Concrete.

E. Special Provisions for Hot Weather or Cold Weather Concreting *[ACI SP-15(99)].*

F. Provide additional submittals as required herein.

1.06. QUALITY ASSURANCE

A. Concrete quality. The Contractor shall use procedures as specified in ACI 121R, "Quality Management System for Concrete Construction", which requires that the contractor shall submit independent tests on delivered concrete batches in accordance with Section 3300, Concrete *{insert proper section and title}*.

B. Installation testing. The contractor shall conduct testing *{alternative language: cooperate with the agency's independent laboratory testing}* specified in Paragraph 3.11, Field Tests:

1. Unrestrained Pullout Test

2. Torsion Test

1.07. CONSTRUCTION METHOD QUALIFICATIONS

A. The Work of this Section shall be supervised by a superintendent and a foreman in charge of trackwork operations, each with a minimum of 5 years' documented experience in direct fixation track construction and a thorough knowledge of the provisions of ACI SP-15(99).

1.08. DELIVERY, STORAGE AND HANDLING

A. Delivery, storage and handling shall be in accordance with Section *{insert reference section and title, such as "*05651, Trackwork – Owner Furnished Material"*}*.

1.09. MAINTENANCE DURING CONSTRUCTION

A. Maintenance shall be performed on track under construction through formal notice of substantial completion in accordance with Section *[insert boiler plate reference for this subject]*.

2. PRODUCTS

2.01. AGENCY-FURNISHED MATERIAL

A. Refer to Section *[insert appropriate Section]*, Agency-Furnished Materials and Equipment, of the Contract Specifications for description and quantity of Agency-furnished materials.

2.02. CONTRACTOR FURNISHED MATERIALS

A. All products, tools, materials, equipment and labor required to complete all aspects of the work shall be furnished by the Contractor, and the following.

B. Reinforced Track Concrete:

Please see Section 1, Direct Fixation Track Design, for detailed discussion of concrete materials and admixtures.

1. Except for the modifications indicated herein and on the Contract Drawings, all work shall be in accordance with the following Sections: *{insert section no.}*, Concrete Accessories, *{insert section no.}*, Concrete Reinforcing, *{insert section no.}* Cast-in-place Concrete, and *{insert section no.}*, Portland Cement Concrete.

2. Provide Portland Cement concrete for track concrete conforming to the following requirements:

   a. Provide Class 4000-3/4 inch concrete, unless otherwise indicated.

   b. Cement content shall be a minimum of six-and-a-half 94-pound sacks of Portland cement per cubic yard.

   c. Coarse aggregate shall be washed clean and graded within the limits shown in **Table A**.

Table A. Coarse Aggregate Cleaning and Grading Limits

Sieve Size	Percentage Passing Sieve
3/4 inch	100
1/2 inch	90-100
3/8 inch	0-100
No. 4	0-15
No. 8	0-5

3. Grading limits for combined coarse and fine aggregates shall be within the limits shown in Table B.

Table B. Combined Coarse and Fine Aggregates Grading Limits Sieve

Size	Percentage Passing Sieve
3/4 inch	100
1/2 inch	95-100
3/8 inch	45-100
No. 4	35-60
No. 8	30-45
No. 16	20-35
No. 30	10-25
No. 50	5-15
No. 100	2-5
No. 4	0-15
No. 8	0-5

4. Slump: The average slump shall not exceed 3 inches. *{This may be modified if a high-range water reducer additive is proposed.}*

5. Unit water content shall not exceed 325 pounds of free water per cubic yard.

6. Conform to the aggregate reactivity requirements of Section *[insert Section]*, Portland Cement Concrete, Paragraph *[insert paragraph]*, Special Aggregates for Reducing Shrinkage and Creep.

7. Additional Requirements for Direct Fixation Track

   a. For the purpose of increasing the electrical resistivity of the concrete in order to reduce the effect of stray currents, the concrete mix design shall incorporate the use of silica fume or other approved pozzolan admixture. The dosage rate shall be a minimum of 5 percent by weight of the Portland cement used in the mix. The water cement ratio shall be calculated on the basis of the combined weight of Portland cement and silica fume or other approved admixture that is classified as a cementitious material. *{Use of pozzolan admixtures should be addressed with stray current specialists within the context of the project.}*

   The practice of adding pozzolan admixtures such as silica fume as a stray current mitigation measure is questionable based on its practical value for its

substantial increase in the concrete cost. These admixtures reduce conductivity in concrete but the contribution is negligible for the levels of voltages and current in electrified railways. Concrete admixtures will not prevent corrosive damage if there is a short circuit or leakage path between the rail and the structure. Short circuits must be located and repaired.

b. Provide evidence that the Rapid Chloride Permeability Test, AASHTO T-277, has been performed to the proposed concrete mix and that a rating of very low (100 to 200 coulombs) has been achieved at 56 days by discrete testing and not by interpolation of test data. Such evidence shall consist of data from the following tests: two sets of specimens shall be prepared and tested using the AASHTO T-277 procedure. The first set of specimens shall be moist cured for a period of 28 days, then placed in an air drying facility maintained at 73 degrees F, plus or minus 3 degrees, and 50 percent relative humidity, plus or minus 5 percent, until an age of 56 days, then tested. The second set of specimens shall be cured in a manner identical to that applied to the actual track concrete (damp cure for 7 days), then placed in the air-drying environment noted above until an age of 56 days. A 2-inch thick slice shall be obtained from the central portion of each cylinder and used for the test specimen. No fewer than three test specimens shall be prepared and tested for each mix to be evaluated.

C. Steel Reinforcement

1. All reinforcing steel shall be epoxy coated as specified in *[insert Section]*.

   The practice of using epoxy coated rebar to reduce rebar corrosion has come into question within the structural disciplines. The views are the construction processes (cutting, joining) defeat the epoxy purpose by having exposed ends and creating nicks in the coating.

D. Drainage and Electrical Conduits

1. All openings through the track concrete for electrical wires or drainage shall be formed from PVC electrical conduits in accordance with applicable requirements of Section *[insert structural construction section]*.

E. Shims

1. Shims shall be used only where approved. Shims shall be galvanized steel shims in general conformance with shape, size, and configuration of the direct fixation fastener, and as designed by the direct fixation fastener Supplier.

2. Material shall be ASTM A 1011 steel sheet for shims 1/8" and over in thickness, galvanized in accordance with ASTM A 653, Grade G 165. Material shall be ASTM A 591, commercial quality, coating class C for shims less than 1/8" thickness.

3. The maximum shim height shall be ½".

   Maximum shim height is a topic of enthusiastic debate in the majority of Direct Fixation construction projects when a construction deviation occurs needing more shim height. The owner's view is that the presence of excessive shim stacks means the construction quality and quality control is poor. Limiting the shim height is a means of calling attention to the need for quality support construction.

4. Shims shall conform to the following:

   The following is for galvanized steel shims. The requirements in Part A, Section 2, Direct Fixation Example Specification & Commentary also allow high density polyethylene shims. Those material requirements may be inserted here as an alternative to, or replacement for, the following galvanized shims.

   a. Shim width and length shall be the same as direct fixation fastener, plus the fastener adjustment length.

   b. Shim thicknesses shall vary to meet the requirements for fastener bearing tolerances and rail alignment tolerances using the fewest shims per fastener and no more than three shims per fastener.

   c. Flatness on both surfaces not to exceed 0.020" at the mid-ordinate of the shim surface.

   d. Sheared edges painted with galvanize repair paint conforming to DOD-P-21035.

   e. Smoothly finished, free of warps, projecting fins and other imperfections caused by shearing, drilling or punching.

   f. Shims shall be slotted for anchor bolts in a manner that permits shim insertion without removal of the fastener but

shall not be able to slip out of place if the anchor bolts loosen in service.

g. The following tests shall be performed prior to delivery to the site:

i. Test at least one per 200 shims for conformance to coating thickness specified in Subparagraph 2 above.

ii. Submit certified test reports substantiating conformance to the specified requirements.

3. EXECUTION

3.01. REQUIREMENTS

A. Refer to Section *{insert section no.}*, Agency-Furnished Materials and Equipment, of the Contract Specifications for description and quantity of Agency-furnished materials.

3.02. SUPPORT STRUCTURE SURFACE

A. The concrete substrate on which the track concrete is placed shall only vary from the design elevation within the range shown in Table C.

Table C. Allowable Variance Prior To Placing Track Concrete

Type of Construction	Allowable Variance
Subway, U-Wall invert or At-grade slab	Plus 1 inch to minus 2 inches
Aerial structure decks on spans up to and including 100 feet	Plus 1 inch to minus 3 inches
Aerial structure decks on spans exceeding 100 feet	Plus 1 inch to minus 5 inches.

3.03. CONCRETE SURFACE PREPARATION

A. Prepare and clean the concrete substrate to receive the track concrete using high-pressure water blast methods.

B. Preparation, cleaning, and high-pressure water blasting shall be performed prior to placing rail, DF assemblies and formwork.

C. High-pressure water blasting shall expose a minimum 1/8” of the aggregate without causing damage to the aggregate. The Contractor shall determine the water pressure and nozzle type. The Contractor

shall demonstrate that the proposed pressure is adequate to expose the required amount of aggregate.

D. The water jetting shall be restricted solely to the area directly under the track concrete. Any over jetting shall be repaired as approved by the Engineer.

E. Immediately prior to concreting, the supporting structure concrete shall be thoroughly cleaned with clean water and compressed air to remove all loose material and dirt.

F. Deleterious material shall not be flushed down the drainage.

G. Washed material and resulting debris and dust shall be collected and removed by means proposed by the Contractor and approved by the Engineer.

3.04. EXISTING FACILITIES

A. Protect dowels, drainage facilities, and electrical conduits from damage and plugging. Repair promptly all damage due to Contractor's operations.

B. The Contractor shall conduct his trackwork operations to avoid damage to bridge decks, ditches, drainage structures, fences, and existing utilities. The Contractor shall be responsible for coordinating his work with the other Contractors in the area. The Contractor at his own expense shall repair all damages to existing facilities.

3.05. FORMS

A. Design and install forms in accordance with Section *[insert section number]*, Concrete Forming.

3.06. PRE-POUR SURVEY AND INSPECTION *{for top down construction}*

A. Immediately prior to pouring track concrete, the formwork and supporting jigs shall be surveyed for readiness.

B. The survey shall take place no more than 4 hours prior to placing track concrete.

C. The survey shall be performed by, or under the direction of, a professional land surveyor or civil engineer currently licensed or registered in the State of *(insert state)*.

D. Measurements shall be taken at each support location and shall include, at a minimum, alignment, surface and elevation and cant of both rails, gage and crosslevel.

E. The track shall be fully inspected for track gage and rail cant.

F. Each fastener insert shall be inspected for cleanliness and damaged coating. The insert external surface shall be free of grease, dirt and foreign objects. Damaged insert coating shall be painted with a minimum of two coats of an approved, non-conductive epoxy coating.

G. Each fastener shall be inspected for the proper location stipulated herein and in the contract drawings.

H. No track concrete may be placed prior to repairing any deviations found during the inspection.

I. All measurements shall be recorded and submitted to the Engineer on the same day that the measurements are made.

3.07. FASTENER INSERTS

A. Direct fixation fastener anchor bolt inserts shall be cast into concrete as shown and in accordance with approved Shop Drawings and the following:

1. All inserts shall be free of loose scale, grease, or other foreign matter.

2. All inserts will be coated with epoxy coating. The Contractor shall inspect insert coating before installation and, if necessary, apply an approved epoxy paint to damaged coating areas.

3. Templates shall be used to accurately locate inserts, and positively secure the inserts against displacement during concrete placement. Inserts shall be placed 3/16” below top of concrete plus 0" or minus 1/8".

3.08. INSTALLATION

A. Install DF fasteners in accordance with the following requirements and the approved Contractor's work plan specified herein.

B. Rail and fasteners shall be clean and free of all dirt, mortar, and other substances.

C. Any reinforcing bar that will contact an insert shall be relocated prior to placing the second pour concrete.

D. Fasteners shall be located directly across from each other on opposite rails at the indicated spacing and tolerances.

E. Lateral adjustment of fasteners is exclusively for future Agency maintenance activities. The Contractor shall not use more than plus or minus 1/8 inch of lateral adjustment during construction and defect repair.

F. All fastener components shall be installed to ensure the field side of the rail base will be tight against the outside shoulder.

G. Support Prior to and During Concreting *{for top-down construction only}*

1. The installation support method shall ensure, both prior to and during concreting, that track is adequately supported at the designed vertical and horizontal alignment by supports specifically manufactured for this purpose. The supports shall be spaced, at a maximum, on 10 feet centers and be fixed in location in all directions.

2. The track shall be supported for not less than 100 feet beyond a track section being concreted and in such a manner that will ensure that the track section will not be stressed.

3. The track shall be held to gage and the correct alignment, level, and cant by the supports.

4. The supports shall be capable of withstanding all applied load without any detrimental effects.

5. The supports shall be capable of withstanding thermal expansion and contraction loads, and effects of construction personnel, tools, and equipment that the Contractor uses prior to and during concrete placement.

6. The supports shall have rail-clamping devices and be fabricated from at least 3 inch by 4 inch by 3/8 inch thick hollow tube section or equivalent sections approved by the Engineer.

7. Each support shall, as a minimum, provide the following to the assembled track prior to and during concreting:

   a. Hold both rails to the required gage, grade, surface, crosslevel, alignment and cant.

b. Allow the track to be adjusted by provision of threaded screws or similar continuous means of incremental adjustment.

c. Be supported directly on to the support structure. The use of Precast concrete, or similar, supports for the gage supports may be permitted under the superelevated rail on curves if the method is included in the approved work plan.

d. Be removable without disturbing the track.

e. Allow monitoring the track continuously during concrete placement to make sure it is not misaligned by temperature, vibration, or other cause.

f. The supports shall not be removed until the track concrete has attained a compressive strength of at least 2000 psi.

g. The portion of the gage supports that will be temporarily concreted in shall be coated/protected using the approved method.

h. All holes left by the gage supports in the track base after concreting shall be cleaned, prepared, and filled by an approved non-shrink cementitious grout. The surface finish of the grout shall be to the same standard of surface finish as that of the finished track base.

3.09. CONCRETE FINISHING AND FINAL ADJUSTMENTS

A. General

1. The concrete finishing and final adjustments shall place all adjacent rail seats within 1/16” of the same plane.

B. Concrete Finishing

1. Finish the track concrete in accordance with the requirements of Section *[insert section]*, Concrete Finishing, and the following requirements:

2. Finish shall conform to "smooth form finish" on the sides and "floated finish" on the top surface.

3. Cure track concrete with waterproof sheet material or damp burlap for the minimum specified time in Section 3300 *{insert proper section reference}*.

4. Concrete shall be free of cracks, with particular emphasis in the vicinity of inserts; all cracks shall be repaired using the approved method, at no additional cost to the Agency.

5. Concrete voids due to trapped water or air in the rail fastener bearing seat shall not exceed the following limits:

   a. Single void: 1/2 inch diameter.

   b. Total voids: 10 percent of the total area.

6. No traffic whatsoever shall be permitted to run over the track nor shall manufactured gage supports be removed, for any reason, until the concrete has achieved a minimum compressive strength of 2000 psi. The Contractor shall demonstrate, to the satisfaction of the Engineer, when the concrete has reached the minimum compressive strength to allow the gage supports to be removed or traffic to run over the track.

7. Completing Track

   a. Remove forms.

   b. Expose the entire rail fastener bearing seat of every fastener for the Engineer's inspection.

   c. The fastener assembly, including shim(s) shall not be recessed into the concrete.

   d. Finish all rail seat areas in accordance with a plan submitted to and approved by the Engineer.

   e. The concrete surface under the DF rail fastener shall be have no more than 10% voids as a percentage of underside area of the fastener, and no void within the footprint of the rail larger than ½ “.

   One of the most important results of Direct Fixation construction is the fastener’s proper bearing on the support with the rail full seated on the fastener.

   This a partial definition of “bearing area”, the mating area of the fastener and concrete.

   The following is the remainder of the bearing area requirement, covering the bearing area or mating areas of the rail, fastener and any shims.

f. Within the foot print of the rail, the rail, fastener rail seat, and shims shall have 90% contact between mating surfaces.

This requirement means that there must be no gaps between the rail base and any of the components supporting the rail. This requirement is among the most critical in assuring proper fastener performance.

g. The fastener rotation about the transverse fastener centerline shall be within 1° of rail base plane.

h. The difference in cant between adjacent fasteners shall be within $1/2^{o}$.

i. The fastener skew (angle to a line normal to the rail) shall be within 1°.

The fastener skew is placed here with the other tolerances, although the tolerance has less effect on fastener performance. A fastener skewed more than 0.5^{o} will cause the rail to bind between the fastener's shoulders (depending on the fastener shoulder configuration). That event is beneficial in adding longitudinal rail restraint where elastic clips are the most vulnerable. For low longitudinal restraint systems, adding longitudinal rail restraint is undesirable.

j. Difference in height between adjacent rail fastener seats shall be within 1/16 inch of the same plane.

Adjacent rail seats should be in the same plane with the bolts fully torqued. The preferred tolerance to assure rail clips are not over-stressed is rail seat height difference between adjacent fasteners of 1/32". However, 1/32" is not practical in most construction.

k. The top of the track concrete shall be free of depressions that will cause water to pond.

l. The concrete between adjacent rail fasteners shall be uniform and not vary more than 1/16 inch as measured with a 12 inch straight edge.

The reason to have the concrete between fasteners finished to a close tolerance is that these locations may be used for future Direct Fixation fasteners if the fasteners fail. Typically, fastener bolts corrode from stray current and freeze after a period of 30 or more years. Some transits simply install a new fastener

between the existing fasteners, leaving the old fasteners in place because the latter are hard to remove.

C. Final Adjustments

1. Set anchor bolts with calibrated wrenches according to the bolt tension values recommended by the manufacturer. The Contractor shall calibrate the wrenches by tightening, in a device capable of indicating actual bolt tension, not less than three typical bolts from each lot to be installed. Power wrenches shall be adjusted to stall or cutout at the selected tension. If manual torque wrenches are used, the torque indication corresponding to the calibrating tension shall be noted and used in the installation of all bolts of the tested lot. Bolts shall be in tightening motion when torque is measured. All bolts shall be coated with metal preservative.

3.010. DISPLACED OR MISALIGNED INSERTS

A. Displaced, misaligned, or damaged inserts, or inserts replaced as a result of failure to pass field tests shall be carefully removed by core drilling or other approved means in a manner that will prevent spalling or compromising the structural integrity of surrounding concrete. The Contractor shall submit a procedure for resetting the insert, including grout materials for setting the insert and alignment method. All displaced or misaligned inserts shall be reset at no cost to the Agency.

3.011. FIELD TESTS

A. Direct fixation fastener inserts shall be subjected to the following tests conducted during the construction period at the rate of 3 inserts for every 800 inserts installed except inserts that have been reset shall all be tested (100% testing of reset inserts). Inserts other than reset inserts shall be randomly selected, unless otherwise directed by the Engineer.

The rate of testing is about one production day (800 inserts installed per day). The testing should try to stay up with the production so that systematic flaws in procedures can be caught as soon as possible.

1. Unrestrained Pull-out Test

a. An anchor bolt shall be installed in the insert and an upward vertical load of 12,000 pounds applied to the bolt in such a manner that no vertical load is applied to the plinth concrete within a radius of 6" from the centerline of the insert. The load shall then be released.

b. Acceptance criteria: There shall be no evidence of concrete cracking or failure of bond between the insert, grout, and concrete.

2. Torsion Test

a. 400 foot-pounds of torque shall be applied to an anchor bolt installed with at least 1" thread engagement in the insert but not threaded to the bottom of the insert.

b. Acceptance criteria: There shall be no evidence of failure of the bond between the insert, grout, and surrounding concrete.

B. Should any insert fail to meet the above tests, 6 additional inserts from the same 800-insert lot shall be tested. Failure of any of these inserts to pass the tests will signify that the installation procedure is defective and 100 percent of the remaining lot will be rejected. Additional tests as specified above and other tests as required shall be performed on concrete and other materials associated with insert installation to determine cause of defective installation. Further insert installation shall not proceed until the cause of failures has been determined and a modified procedure ensuring satisfactory installation has been established. Remedial Work shall be performed at no additional costs to the Agency.

C. Failure of a reset insert shall be investigated by the Contractor prior to any remedial work and any additional inserts shall not be reset without the Engineer's approval. The Contractor shall submit revised procedures and Materials for resetting inserts for the Engineer's approval.

D. The Engineer shall be notified 24 hours in advance of the location and time of insert testing. Results of insert tests shall be submitted to the Engineer.

4. MEASUREMENT AND PAYMENT

Insert the appropriate measurement and payment stipulation for the contract.

4.1 Direct Fixation track will not be measured separately for payment, and all costs in connection therewith will be considered as included in the applicable Contract lump sum price or the Contract unit price per linear foot for trackwork of the different types indicated as listed in the bid item in the Bid Schedule of the Bid Form.

SECTION 5

Example Concrete Specification

For

TCRP Project D-07/Task 11

Development of Direct-Fixation Fastener Specifications and Related Material

This example specification is verbatim from a SEPTA contract. The example is provided without comment in support of references in Section 1, Direct Fixation Track Design.

May 2005

SECTION 03300

CAST-IN-PLACE CONCRETE

PART 1 - GENERAL

1.01 DESCRIPTION

A. The work specified in this Section consists of designing mix, furnishing, placing, finishing and curing and sealing portland cement concrete, reinforced and non-reinforced, as indicated.

B. The work also includes preconstructing guideway deck units with plinth pads in preparation for being lifted and placed on the installed bents.

C. Related Work Specified Elsewhere:
1. Other (Direct Fixation) Track Construction: Section 02452.
2. Track Appurtenances: Section 02456.
3. Concrete Forms and Accessories: Section 03100.
4. Concrete Reinforcement: Section 03200.
5. Structural Precast Concrete: Section 03410.
6. Grout: Section 03600.

1.02 DEFINITIONS

A. Precast Concrete: Concrete that is cast at a precasting plant in the form of a structural element (as a slab, pile, panel, or beam) before being shipped to the job site and placed in final position; work performed under Section 03410.

B. Preconstructed Concrete: Concrete that is cast on the job site in the form of a structural element and then moved to its final location and placed in its final position; work performed under this Section. Manufacturing procedures shall be in general compliance with PCI MNL-117.

1.03 REFERENCES

A. American Association of State Highway and Transportation Officials:
1. AASHTO M182, Burlap Cloth made from Jute or Kenaf.

B. American Concrete Institute.

1. ACI 211.1, Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete.
2. ACI 226.3R, Use of Fly-Ash in Concrete.
3. ACI 301, Specifications for Structural Concrete.
4. ACI 304R, Guide for Measuring, Mixing, Transporting and Placing Concrete.
5. ACI 305R, Hot Weather Concreting.
6. ACI 306R, Cold Weather Concreting.
7. ACI 308, Standard Practice for Curing Concrete.
8. ACI 318M, Building Code Requirements for Structural Concrete.

C. American Society for Testing and Materials:

1. ASTM C31, Practice for Making and Curing Concrete Test Specimens in the Field.
2. ASTM C33, Specification for Concrete Aggregates.
3. ASTM C39, Test Method for Compressive Strength of Cylindrical Concrete Specimens.
4. ASTM C42, Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.
5. ASTM C94, Specification for Ready-Mixed Concrete.
6. ASTM C143, Test Method for Slump of Hydraulic Cement Concrete.
7. ASTM C150, Specification for Portland Cement.
8. ASTM C156, Test Method for Water Retention by Concrete Curing Materials.
9. ASTM C171, Specification for Sheet Materials for Curing Concrete.
10. ASTM C172, Practice for Sampling Freshly Mixed Concrete.
11. ASTM C173, Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method.
12. ASTM C192, Practice for Making and Curing Concrete Test Specimens in the Laboratory.
13. ASTM C231, Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.
14. ASTM C260, Specification for Air-Entraining Admixtures for Concrete.
15. ASTM C309, Specification for Liquid Membrane - Forming Compounds for Curing Concrete.
16. ASTM C494, Specification for Chemical Admixtures for Concrete.
17. ASTM C618, Specification for Coal Fly-Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete.
18. ASTM C920, Specification for Elastomeric Joint Sealants.
19. ASTM D695, Test Method for Compressive Properties of Rigid Plastics.
20. ASTM D1190, Specification for Concrete Joint Sealer, Hot-Poured Elastic Type.

21. ASTM D1751, Specification for Preformed Expansion Joint Filler for Concrete Paving and Structural Construction (Non-extruding and Resilient Bituminous Types).
22. ASTM D1752, Specification for Preformed Sponge Rubber and Cork Expansion Joint Fillers for Concrete paving and Structural Construction.
23. ASTM D3405, Specification for Joint Sealant, Hot-Applied, for Concrete and Asphalt Pavements.

D. U.S. Army Corps of Engineers:
1. CRD-C 572, Specification for Waterstop.

E. Federal Specifications (FS):
1. TT-S-00230(2), Sealing Compound, Elastomeric Type, Single Component (For Caulking, Sealing, and Glazing in Buildings and other Structures).

F. Commonwealth of Pennsylvania, Department of Transportation (PennDOT), Specifications, Pub 408/2000.

1.04 SUBMITTALS

A. In accordance with Section 01300, submit the following:
1. Samples of materials being used when requested by the Project Manager including names, sources and descriptions.
2. Test Reports:
   a. Two copies of laboratory trial mix designs proposed in accordance with ACI 301, Section 4.2.3.4 or one copy each of 30 consecutive test results and the mix design used from a record of past performance in accordance with ACI 301, Section 4.2.3.2.
   b. Other concrete test reports specified in Article 3.12 herein.
3. Design Mix: Prior to production of concrete, submit for approval, on form attached at the end of this Section, all mix designs proposed for use. The mix designs must be accompanied by completed standard deviation analysis, on form attached at the end of this Section, or trial mixture test data. Use materials in such proposed design mix as specified herein. Make such adjustments in the proposed design mix as directed by the Project Manager. Make such adjustments at no additional cost to SEPTA.
4. Certificates: Furnish the Project Manager certificates originated by the batch mixing plant certifying ready mixed concrete as manufactured and delivered to be in conformance with ASTM C94.
5. Schedule showing methods, construction joint location, and sequence locations of

pours.

a. Submit schedule a minimum of 10 days prior to commencing concreting operations.

6. Manufacturer's product data for the concrete accessories specified herein (admixtures, joint fillers, curing materials, waterstops, etc).

7. Testing program developed specifically for this project adequate for support of the proposed concrete placement schedule. Testing program shall include, but not be limited to, details regarding the number of test cylinders to be performed per batch, the types of tests to be performed, the handling of those test cylinders, assurance that testing will be performed under conditions similar to that experienced by the structure and the name and qualifications of the testing laboratory (including field personnel). Testing program shall cover all cast-in-place concrete associated with the project.

B. Delivery Tickets: A delivery ticket shall accompany each load of concrete from the batch plant. Information presented on the ticket shall include the tabulation covered by ASTM C94, 15.1.1 through 15.2.8, as well as any additional information the local codes may require. Tickets must be signed by the Contractor's representative, noted as to time and place of pour and kept in a record at the site. Make such records available for inspection upon request by the Project Manager.

C. Submit the following if Fly-Ash is used in the concrete mix:

1. History of the Fly-Ash to be used for this concrete mix.
2. Quality control program of Fly-Ash producer to ensure that Fly-Ash consistency meets the requirements of ASTM C618.
3. Certification that maximum loss on ignition of Fly-Ash shall be limited to less than 4 percent.
4. List of projects within the last ten years where concrete installer has used Fly-Ash concrete; include telephone number and point of contact.
5. Procedures to be used by concrete installer in curing concrete with Fly-Ash during hot weather.
6. Certification that Fly-Ash to be used at this site will be from a single source to ensure concrete strength compatibility and color consistency.
7. Certification that the use of Fly-Ash will meet all the requirements of ACI 226.3R.

D. Submit the following if micro-silica fume is used:

1. Batching sequence with material ratios.
2. Mixing parameters.

1.05 QUALITY ASSURANCE

A. Design Basis:

1. Make trial mixes and computations for each class of concrete, including the molding and curing of test specimens.
2. Prepare and compute designs in the presence of the Project Manager or the Project Manager's assigned representative. Make arrangements with the Project Manager at least one week in advance of the concrete design.
3. Submit each design for review, prior to its use in the work. Do not change an accepted design unless reviewed by the Project Manager.
4. Base the concrete design on the materials to be used in the work. If the specified requirements cannot be met, furnish other acceptable materials and/or make necessary changes in the mixing procedure to meet the specified requirements.
5. At the start of construction, mix a full-sized batch, using the type of mixer and the mixing procedure planned for the project. This batch will provide the basis for final adjustment of the accepted design.
6. The Contractor may present for approval a concrete mix previously approved for SEPTA work provided such mix is made with proposed ingredients that meet requirements and provided that concrete has complied with compressive strength requirements based on control record of at least 30 consecutive strength tests recently obtained.

B. Field Mockup:

1. At a location determined by the Project Manager, construct a 1800 mm wide by 2400 mm high by 150 mm thick field mockup panels with the light sand-blasted finish. Use procedures, equipment, materials, mixes and quality control plan submitted for cast-in-place concrete. Cure the concrete in the mockup panel by same method(s) and with same time lapse after placement as will be applied to the work.
2. Demonstrate all joint conditions, exposed edge conditions, reveals and chamfers.
3. Apply light sand-blasted finish to mockup panel for approval by the Project Manager.
4. Construct mockup panels in sufficient quantities to allow for possible unacceptable finishing trials. Apply light sand-blasted finish to as many mockup panels as is necessary to achieve conformance with the specified requirements.
5. Mockup shall be standard of quality for architectural precast concrete work as specified in the PCI Manual for Architectural Precast Concrete Section 3.2.4.
6. After approval, by the Project Manager, of the light sand-blasted finish on the mockup, the field mockup shall remain as the quality standard for visual characteristics.
7. When directed by the Project Manager, demolish the mockups and remove the debris from the site.

C. Pre-Concrete Conference:

1. At least 35 days prior to start of concrete construction, the General Contractor shall convene a meeting to review the detailed requirements of the concrete design mixes and to determine the procedures for producing proper concrete construction. Attendance shall include but shall not be limited to the following:
   a. General Contractor's superintendent.
   b. Laboratory responsible for the concrete design mix.
   c. Laboratory responsible for field quality control.
   d. Concrete subcontractor.
   e. Ready-mix concrete producer.
   f. Admixture manufacturer(s).
   g. Concrete pumping contractor.
   h. SEPTA's representative.
   i. Representative of SEPTA's design/consulting Engineer.
      (1) Notify Consultant Engineer at least 10 days prior to the scheduled date of the conference.
2. The General Contractor shall record the minutes of the meeting, type the minutes and distribute copies to all concerned parties within 5 days after the meeting.
   a. The minutes shall include a statement by the admixture manufacturer(s) indicating that the proposed mix design and placing techniques can produce the concrete quality required by these specifications.

D. Silica Fume Concrete Demonstration Pour.

A. Perform a demonstration pour of slab 3860 mm wide by 5000 mm long, of 180 mm thickness, with reinforcing matching in size and position the standard deck reinforcing. Have present during the demonstration, technical representatives of the silica fume and admixture suppliers. Materials, equipment, batching, placement, finishing, and curing are to be consistent with proposed structural silica fume concreting.

B. Perform field tests of demonstration pour in accordance with Section 3.12.

C. Provide written reports on the adequacy of the demonstrated materials and method, by the concrete testing agency.

E. The Project Manager will have the authority to inspect concrete supplier's plant and will have the authority to inspect delivery trucks to verify that plant conforms to the "Check List for Certification of Ready Mixed Concrete Production Facilities" published by the National Ready Mixed Concrete Association, and to verify delivery trucks conform to requirements specified in ASTM C94.

F. Testing Agency: Retained and paid by the Contractor and meeting requirements of the

American Society for Testing and Materials "Specification for Agencies Engaged in the Testing and/or Inspection of Materials used in Construction", ASTM E329. The testing agency shall also be approved by the Project Manager.

1. The concrete inspector for concrete placed in the guideway decks shall be certified by the National Institute of Certified Engineering Technicians as Level 3, with 7-10 years experience in concrete placement work.

G. Source Quality Control:

1. Laboratory Tests: Materials stated herein require advance examination or testing according to methods referenced, or as required by the Project Manager.
2. Compression Test Cylinders: For laboratory trial batches, make in accordance with American Concrete Institute ACI 301. Test to consist of four compression test cylinders for each class of concrete with two broken at seven days and two broken at 28 days; ASTM C192 and ASTM C39.
3. If trial batches are used, the mix design shall be prepared by an independent testing laboratory and shall achieve an average compressive strength of 8 MPa higher than the specified strength. This over-design shall be increased to 10 MPa when concrete strengths over 34 MPa are used.

H. Fly-Ash producer shall have a quality control program in place to ensure Fly-Ash consistency meets the requirements of ASTM C618. If Fly-Ash is used, the Fly-Ash producer and concrete installer must be approved by the Project Manager.

1.06 JOB CONDITIONS

A. Do not commence placement of concrete until mix designs have been approved by the Project Manager.

B. Sequencing: Where other construction work is relative to concrete pours, or must be supported by or embedded in concrete, those performing such related work must be given 3 working days notice to introduce or furnish embedded items before concrete is placed.

C. Provide certification of deck structure to the Project Manager at least 30 days prior to installation.

D. Use high early strength concrete only where construction sequencing to restore rail service dictates, or as otherwise approved by the Project Manager. Any use of high early strength concrete is to be submitted to the Project Manager for prior approval.

PART 2 - PRODUCTS

2.01 MATERIALS

A. Cement:
   1. Portland Cement: ASTM C150 of the following types:
      a. Type I or Type II, low alkali.
      b. Use Type III for high early strength applications.
   2. Use only one brand and manufacturer of approved cement.

B. Fly-Ash:
   1. Material Requirements:
      a. Conform to the requirements of ASTM C618, Class F. except that Loss On Ignition (L.O.I.) shall not exceed 4% maximum, and Pozzolanic Activity Index with cement, not lime, shall govern.
      b. Pretest all Fly-Ash shipped for L.O.I. and fineness at no greater intervals than 45 tonne lots. Document test results on each mass ticket with a certification that all material meets the specified physical and chemical requirements.
   2. Proportioning:
      a. Use Fly-Ash at the rate of 15 percent to 25 percent of the total cementitious material. Decrease amount during cold weather.
      b. In Fly-Ash concrete, for computation purposes, apply the water-cement ratio as the water-cementitious ratio (cement and Fly-Ash).
      c. Prepare extensive laboratory trial mixtures to demonstrate physical properties of the Fly-Ash concrete, including compatibility of admixtures, 28 day compressive strength, air content, and slump and workability.

C. Normal Weight Concrete Aggregates:
   1. Aggregate for normal weight concrete: ASTM C33.
   2. Coarse Aggregate Size:
      a. Guideway Deck Slab, Walkway, Parapet Concrete: Use size No. 67.
      b. Concrete Plinth: Use size No. 8.
      c. Except as specified in Article 2.01.C.2.a., 2.01.C.2.b., and 2.01.C.2.c. above, Maximum size of coarse aggregate shall not exceed:
         (1) One-fifth narrowest dimension between sides of forms within which concrete is to be cast.
         (2) Three-fourths of the minimum clear spacing between reinforcing bars or between reinforcing bars and forms.
         (3) One-third the slab thickness for unreinforced slabs.

D. Water: Clean and potable.

E. Concrete Admixtures:

1. Prohibited Admixtures: Only the specified non-corrosive, non-chloride accelerators shall be used. Calcium chloride, thiocyanates or admixtures containing more than 0.05% chloride ions are not permitted.
2. Provide admixtures produced and serviced by established, reputable manufacturers and use in compliance with manufacturer's recommendations.
3. Air-Entraining Admixture: Use a product conforming to requirements of ASTM C260.
4. Water-Reducing Admixture: Unless high temperatures occur and/or placing conditions dictate a change, all concrete shall contain a water-reducing admixture. Use a product conforming to requirements of ASTM C494.
   a. Acceptable Manufacturers:
      (1) Eucon WR-75; The Euclid Chemical Company.
      (2) Pozzolith 200N; Master Builders.
      (3) Plastocrete 160; Sika Corporation.
      (4) WRDA with HYCOL; Grace Construction Products.
      (5) Or Approved Equal.
5. Water-Reducing and Retarding admixture: When high temperatures occur and/or placing conditions dictate, the Project Manager may require a change from the water-reducing admixture (Type A) to a water-reducing and retarding admixture (Type D). Use a product conforming to requirements of ASTM C494, Type D.
   a. Acceptable Manufacturers:
      (1) Eucon Retarder-75; The Euclid Chemical Company.
      (2) Pozzolith 100XR; Master Builders.
      (3) Plastiment; Sika Corporation.
      (4) WRDA 64; Grace Construction Products.
      (5) Or Approved Equal.
6. Water-Reducing and Accelerating Admixture: When low temperature occurs and/or placing conditions dictate, the Project Manager may require a change from the water-reducing admixture (Type A) to a water-reducing and accelerating admixture (Type E). Use a product conforming to requirements of ASTM C494, Types C or E.
   a. Acceptable Manufacturers:
      (1) Accelguard 80; The Euclid Chemical Company.
      (2) Pozzutec 20; Master Builders.
      (3) Plastocrete 161 HE; Sika Corporation.
      (4) Or Approved Equal.
7. Water-Reducing, High Range Admixtures (Superplasticizer): Use a product

conforming to requirements of ASTM C494, Types F or G. Do not use plasticizer in concrete mix intended for slabs which are indicated or specified to receive a floor hardener treatment.

a. Acceptable Manufacturers:
   (1) Eucon 37; The Euclid Chemical Company.
   (2) Rheobuild; Master Builders.
   (3) Sikament; Sika Corporation.
   (4) Duracem 100; Grace Construction Products.
   (5) Or Approved Equal.

8. Corrosion Inhibitor (For guideway decks and plinths): Use a product conforming to requirements of ASTM C494, Type C and as follows:
   a. The corrosion inhibitor shall contain 30± 2 percent of calcium nitrite by mass.
   b. Active corrosion shall be inhibited to 7.71 kilograms of chlorides, at the bar level, per cubic meter of concrete.
   c. Upon request, the manufacturer shall submit test method(s) which determine the plastic and hardened concentration of the active component in the inhibitor.
   d. Acceptable Manufacturers:
      (1) DCI or DCI S; Grace Construction Products.
      (2) Or Approved Equal.

9. Silica Fume (To be used in concrete mix for guideway deck and plinths): Dry densified microsilica powder.
   a. Acceptable Manufacturers:
      (1) Force 10,000D; Grace Construction Products
      (2) Eucon MSA; The Euclid Chemical Company
      (3) MBSF; Master Builders
      (4) Or Approved Equal.

10. Prior to the mix design review by the Project Manager, provide written conformance to the specified requirements and the chloride ion content of the admixture.

F. Preformed Expansion Joint Fillers:
   1. Non-extruding and Resilient Bituminous Types (exterior use only): ASTM D1751.
      a. Acceptable Manufacturers:
         (1) Hornboard; Tamms Industries.
         (2) Sealtight Fiber Expansion Joint Filler; W. R. Meadows, Inc.
         (3) Cane Fiber Expansion Joint; Sonneborn
         (4) Or Approved Equal.
   2. Sponge Rubber: ASTM D1752, Type I.

a. Acceptable Manufacturers:
   (1) Cementone (Grey) or Darktone; Tamms Industries.
   (2) Sealtight Sponge Rubber Expansion Joint; W. R. Meadows, Inc.
   (3) Williams Concrete Gray Sponge Rubber; Williams Products, Inc.
   (4) Bondtex 941; Rubatex Corporation.
   (5) Or Approved Equal.

G. Joint Sealants:
1. Hot-poured (for Concrete and Asphalt Pavements): Rubberized joint sealing material; ASTM D1190 or ASTM D3405.
2. Cold-applied:
   a. Single component, polyurethane based, non-sag, elastomeric sealant: ASTM C920, Type 3 Grade NS, Class 25; Federal Specification TT-S-00230(2), Type II, Class A:
      (1) Sikaflex - 1a; Sika Corporation.
      (2) Vulkem 922; Mameco International.
      (3) Or Approved Equal.
   b. Single component, self-leveling, polyurethane sealant: ASTM C920, Type S, Grade P, Class 25; Federal Specification TT-S-00230(2), Type I, Class A:
      (1) Sikaflex - ICSL; Sika Corporation
      (2) Or Approved Equal.
   c. Two component, non-sag, self-leveling, polyurethane-based, elastomeric sealant (For joints deeper than 13 mm and any joint over 25 mm wide): ASTM C920; Federal Specification TT-S-00227E.
      (1) Sikaflex 2c, NS/SL; Sika Corporation
      (2) Or Approved Equal.

H. Waterstops:
1. Ribbed type manufactured from virgin polyvinyl chloride plastic compound conforming to U.S. Corps of Engineers CRD-C572.
2. Surface Waterstop (Paste and Gasket type):
   a. Paste: Cartridge type which swells on contact with water.
      (1) Duroseal Paste; Absolute Waterproofing Systems, Inc.
      (2) Or Approved Equal.
   b. Gasket Waterstop: Soft pliable water-swelling vinylester.
      (1) Duroseal Gasket; Absolute Waterproofing Systems, Inc.
      (2) Or Approved Equal.

I. Curing Materials, Sheet Form: Use curing materials that will not stain or affect concrete

finish or lessen the concrete strength and comply with the following requirements:

1. Burlap: Use materials conforming to AASHTO M182.
2. Sheet Materials: Use materials conforming to ASTM C171.

J. Liquid Curing Compounds:

1. Liquid Membrane - Forming Compounds: For any concrete surfaces and where a finish material will be applied over the concrete, the following shall apply:
   a. Use material meeting the requirements of ASTM C309, Type 1, free of wax or other adhesive bond breaking ingredients, and manufactured from an acrylic-copolymer base compound:
      (1) Masterkure; Master Builders.
      (2) Kurex Formula E-100; The Euclid Chemical Co.
      (3) L&M Cure; L&M Construction Chemicals Inc.
      (4) Or Approved Equal.

K. Liquid Curing and Sealing Material: Except as specified in Article 2.01.J., above, for all exterior slabs, sidewalks, curbs, and any concrete where total resistance to yellowing and blushing from ultra-violet light and water exposure is required, the following shall apply:

1. Liquid Membrane-Forming and Sealing Compounds: Use curing and sealing compounds meeting the requirements of ASTM C309, Type 1, free of wax and manufactured from chlorinated rubber base material with a minimum of 18 percent solids contents, with dust-proofing and sealing qualities.
   a. Super Floor Coat; The Euclid Chemical Co.
   b. MB 429; Master Builders.
   c. Surfseal; L&M Construction Chemicals Inc.
   d. Or Approved Equal.

L. Penetrating Sealer:

1. Provide a one (1) part blend of poly siloxane; tradename "Sikagard 70 Penetrating Sealer" as manufactured by Sika Corporation, P.O. Box 297, Lyndhurst, NJ 07071, Telephone: (201) 933-8800, or approved equal.

M. Non-Shrink Non-Metallic Grout: Section 03600.

N. Epoxy Adhesive (For Grouting Dowels): Provide a high-modulus, moisture insensitive epoxy adhesive of thick consistency having the following characteristics:

1. Mix Ratio: 100 percent solids, two-component; mixed one part by volume component B to two parts by volume component A.
2. Ultimate Compressive Strength: 76 MPa after cure at 23 °C and 50 percent relative humidity determined in accordance with ASTM D695.

3. Acceptable Manufacturers:
   a. Sika Corporation; Sikadur 31 Hi-Mod Gel.
   b. Or Approved Equal.

2.02 CONCRETE QUALITY

A. Provide 31 MPa concrete for all concrete work except where otherwise indicated on Contract Drawings or specified.

B. Selection of Proportions for Normal Weight Concrete: ACI 211.1.

C. Proportions of Ingredients: Establish proportions, including water-cement ratio on the basis of either laboratory trial batches or field experience, with the materials specified herein.
   1. Trial Mixtures: ACI 301, Section 4.2.3; and ACI 318M, Section 5.3.
   2. Standard Deviation: ACI 301, Section 4.2.3; and ACI 318M, Section 5.3.

D. Water-Cement Ratio:
   1. Except as specified in Article 2.03.D.2 below all concrete shall have a maximum water/cement ratio of 0.45.
   2. All guideway deck concrete shall have a maximum water/cement ratio of 0.40.

E. Minimum Cement Content:

Class	Minimum Cement Content per Cubic Meter
17 MPa to 21 MPa	279 kg
24 MPa	303 kg
28 MPa	326 kg
31 MPa	350 kg
34 MPa	374 kg
41 MPa	397 kg

F. Slump: Except when superplasticizer is used, proportion and produce concrete to a slump as indicated below.

Types of Construction	Slump, mm Maximum	Slump, mm Minimum
Electrical Platforms	75	25
Guideway Deck	75	25
Guideway Plinth	75	25

1. When the high-range water reducing admixture (superplasticizer) is used, the concrete shall arrive at the job-site at a slump of 50 mm to 75 mm. The mix shall be verified by slump tests and rejected if not meeting this requirement. Then the high-range water-reducing admixture shall be added to increase the slump to the approved slump produced in the laboratory tests of design mix, and slump tested for verification.
2. Pumped concrete shall have a 125 mm maximum slump, measured prior to pumping.

G. Air Entraining: Air-entrain all concrete. Required air content shall be as follows:

Maximum-size coarse aggregate, mm	Air content percent by volume
37.5, 50 or 63	5 ± 1 ½
19 or 25	6 ± 1 ½
9.5 or 12.5	7 ± 1 ½

H. Corrosion Inhibitor: For guideway deck and plinth concrete, incorporate corrosion inhibitor into the mix at a rate of 14.9 L/m^3 to 24.8 L/m^3 or as otherwise recommended by an approved equal product manufacturer in order to provide equal protection.

I. Silica Fume: Use at the rate of 24 kg/m^3.

PART 3 - EXECUTION

3.01 INSPECTION

A. Inspect work to receive cast-in-place concrete for deficiencies which would prevent proper execution of the finished work. Do not proceed with placing until such deficiencies are corrected to the satisfaction of the Project Manager.

B. Verify that all reinforcing, including welded wire fabric, is secured in place prior to placement of concrete.

3.02 JOINTS AND EMBEDDED ITEMS

A. Construction Joints:
1. Install construction joints as shown on the Contract Drawings and as follows:
2. Where locations of construction joints are not indicated on the Contract Drawings,

the Contractor shall select joint locations, subject to the Project Manager's approval.

a. Locate such joints to least impair the strength of the structure and near the middle of the span of slab or beams except that maximum joint spacing shall be 9100 mm in each direction.

3. Maximum joint spacing for slabs-on-grade shall not be greater than 6100 mm.
4. Joints in elevated slabs shall not be constructed within 900 mm from centerline of the steel beam.
5. Place grade beams and slabs and walls in alternate sections allowing at least two days elapsed time before concrete is placed against an adjacent vertical joint.
6. Submit requests for approval of joint locations ten days prior to scheduled concrete pours. Do not make concrete pours unless joint locations have been approved.
7. Methods for the positioning and securing of track attachments, as identified in Section 02452 and Section 02456 shall be developed and demonstrated capable of consistently meeting track tolerances in "top down" construction.
8. There will be no exceptions to the above requirements without written approval by the Project Manager.

B. Expansion Joints and Contraction Joints:

1. Install where indicated on the Contract Drawings.
2. Construct contraction joints by means of a wood strip, plastic strip, metal plate, or other approved material to be subsequently removed.
3. Do not extend reinforcing or other embedded metal items through expansion and contraction joints, except where indicated otherwise for placing dowels.
4. Fill expansion joint full depth with expansion joint material approved by the Project Manager.
5. Sawcutting contraction joints will not be permitted.

C. Bond new concrete with hardened concrete with one of the following methods:

1. Grout Method:
   a. Roughen and clean hardened concrete of foreign matter and laitance and dampen with water.
   b. Cover the hardened concrete with a 10 mm layer of grout. Use grout of same material composition and proportions of concrete being poured except coarse aggregate omitted. Use the specified bonding admixture as 50% of the liquid requirement.
   c. Place new concrete on grout before it has attained its initial set.
2. Other bonding methods must be approved by the Project Manager.

D. When concreting is to be discontinued for more than forty-five (45) minutes and if the construction plane is to be horizontal, install keyways and embed dowel bars in the concrete before initial hardening. Use keyways and dowels in vertical concrete construction except when indicated or directed otherwise by the Project Manager.

E. Other Embedded Items: Place sleeves, inserts, anchors and embedded items required for adjoining or related work prior to concreting. Place accurately, and support against displacement.

3.03 DRILLING AND GROUTING DOWELS

A. Construction Methods:

1. Drill holes for each dowel to the size and depth indicated on the Contract Drawings. Do not drill into or cut or otherwise damage existing reinforcement bars. If existing reinforcement bars are encountered during the drilling operation, relocate the hole to clear the existing reinforcement as directed by the Project Manager.
2. Blow clean each finished hole with an air jet and then flush with a jet of clean water.
3. Immediately prior to the grouting operation, remove all water from the hole and from the walls of the hole.
4. Mix and place the epoxy adhesive completely around the dowel bar in strict accordance with the manufacturer's recommendations, with particular attention given to manufacturer's specified time limit within which the material must be placed after mixing. Do not retemper grout that has begun to stiffen; discard such grout.

3.04 PRODUCTION OF CONCRETE

A. Ready-Mixed Concrete:

1. Batched, mixed and transported in accordance with ASTM C94.
2. Plant equipment and facilities shall conform to the "Check List for Certification of Ready Mixed Concrete Production Facilities" of the National Ready Mixed Concrete Association.

3.05 PLACING

A. Place concrete for the guideway deck slab sections in accordance with the applicable portions of PennDOT Pub 408/2000 Sections 1001.3(k)1., 1001.3(k)5., 1001.3(k)10., 1001.3(m), 1001.3(p), and the following Articles 3.05.C through 3.05.H. except where

in conflict with these sections referenced from Pub 408/2000.

1. After the concrete is placed and consolidated, finish the top of the slab sections using an approved adjustable power driven finishing machine. Hand finishing may be used if approved by the Project Manager for irregular areas where the use of a machine would be impractical.
2. After finishing as specified in Pub 408/2000, Section 1001.3(k)5, the entire surface shall be checked by an independent laboratory certified inspector as specified in Article 1.05 above. The surface shall be checked with a 3 m metal straightedge operated parallel to the centerline of the guideway slab and shall show no deviation in excess of 3 mm from the testing edge of the straightedge. Correct any deviation in excess of this requirement before the concrete sets. Progress the checking operation by overlapping the straightedge at least ½ the length of the preceding pass.
    a. Provide certification of compliance to the Contractor.

B. Place all other concrete in accordance with ACI 304R and the following.

C. Preparation:
1. Prepare formwork in advance and remove snow, ice, water and debris from within forms.
2. Pre-position expansion joint material, anchors and embedded items.
3. Thoroughly moisten subgrades to the satisfaction of the Project Manager prior to placing concrete in slabs-on-grade to eliminate water loss from bottom of concrete slab.
4. Do not place concrete on frozen ground.

D. Conveying:
1. Handle concrete from mixer to final deposit rapidly by methods which will prevent segregation or loss of ingredients to maintain required quality of concrete.
2. Do not convey concrete through aluminum or aluminum alloy.
3. Do not place concrete by pumps or other similar devices without prior written approval of Project Manager.
    a. When pumping is permitted, use pumping and pneumatic conveying equipment designed to handle without segregation, types, classes and volumes of concrete to be conveyed.
    b. Operate pump or pneumatic equipment so that a continuous stream of concrete without air pockets is produced. Position discharge end of line as near final position of concrete as possible but in no case more than 1500 mm away.
    c. At completion of placement, clean equipment. Discharge debris and

flushing water outside of forms.

E. Depositing:

1. Concrete shall not be dropped freely where reinforcing will cause segregation, nor shall it be dropped freely more than 1200 mm.
2. Deposit in approximately horizontal layers of 300 mm to 450 mm.
3. Do not allow concrete to flow laterally more than 900 mm.
4. Make placement within sections continuously to produce monolithic unit.
5. Proceed with placing at such a rate that concrete which is being integrated with fresh concrete is still plastic.
6. Do not deposit concrete on concrete which has hardened sufficiently to cause the formation of seams or planes of weakness within sections.
7. Do not use concrete which has partially hardened or has been contaminated by foreign materials.
8. Do not begin placing of concrete in beams or slabs until concrete previously placed in walls or columns has attained initial set.
9. Do not subject concrete to procedures which will cause segregation.
10. Do not bend reinforcement out of position when placing concrete.
11. Do not place concrete in forms containing standing water.

F. Consolidation:

1. Consolidate concrete by vibration, spading, rodding or other manual methods. Work concrete around reinforcement, embedded items and into corners; eliminate all air or stone pockets and other causes of honeycombing, pitting or planes of weakness.
2. Use vibration equipment of internal type and not the type attached to forms and reinforcement.
3. Use vibrators capable of transmitting vibration to concrete in frequencies sufficient to provide satisfactory consolidation.
4. Do not leave vibrators in one spot long enough to cause segregation. Remove concrete segregated by vibrator operation.
5. Do not use vibrators to spread concrete.
6. Have sufficient reserve vibration equipment to guard against shutdown of work occasioned by failure of equipment in operation.

G. Cold Weather Concreting:

1. Temperature of concrete delivered at the job-site shall conform to the following temperature limitations:

Air Temperature deg. C.	Minimum concrete temperature, deg. C. For sections with least dimension less than 300 mm	For sections with least dimension 300 mm or greater
-1 to 7	16	10
-18 to -1	18	13

2. If water or aggregate is heated above 38 °C, combine water with aggregate in the mixer before cement is added. Do not mix cement with water or with mixtures of water and aggregate having a temperature greater than 38 °C.
3. Provide equipment for heating concrete materials and protecting concrete during freezing or near freezing weather. Do not use foreign materials or materials containing snow or ice.
4. Surfaces which the concrete is to come in contact with must be free of frost, snow or ice.
5. Concrete placed in forms shall have a temperature of 10°C or higher after placement. Maintain this temperature a minimum of 5 days. Provide additional time if necessary for proper curing.
6. Housing, covering or other protection used in curing shall remain intact at least 24 hours after artificial heating is discontinued. Do not place dependence on salt or other chemicals for the prevention of freezing.
7. Perform cold weather concreting work in accordance with ACI 306R.

H. Hot Weather Concreting:
1. Temperature of concrete delivered at the job-site shall not exceed 32 °C.
2. Cool ingredients before mixing to prevent temperature in excess of 32 °C.
3. Make provisions for windbreaks, shading, fog spraying, sprinkling or wet cover when necessary.
4. Perform hot weather concreting work in accordance with ACI 305R.

3.06 CONCRETE PLINTHS

A. Prepare the base concrete surface to receive the concrete plinth as a construction joint, using high-pressure water blast or other method approved acceptable.

B. Repair, by touch up painting epoxy reinforcing bar hoops where existing bar coatings are damaged, cracked or chipped. Replace hoops that are too high or low to provide the proper connection of concrete plinth.

C. Cast direct fixation fastener anchor bolt inserts into concrete to the proper spacings according to Section 02452, and as shown and in accordance with the approved shop drawings.

D. The concrete plinth surface area that will be covered by the grout pad shall be provided with a rough texture finish to permit a better bond with the grout pad. The remaining surface area that will be exposed shall have a uniform steel troweled cement mortar finish to provide a smooth and uniform surface free from voids and other defects. Verify that concrete surface is at the longitudinal and cross slopes to a variation of not more than plus 6 mm in 3050 mm.

E. To protect the threaded anchor inserts upon removal of forms or supports, install a threaded plastic plug in each insert to seal the threaded hole.

3.07 CONCRETE DECK CLOSURE PLACEMENTS

A. Prepare the base concrete surface at the locations of the closure placements as a construction joint using high-pressure water blast or other acceptable method.

B. Insure proper location and installation of the previously placed deck reinforcing steel mechanical splices and joint sealing material. Notify the Project Manager immediately of any conditions that may impact the placement of the deck closure.

C. The following schedule of shall be maintained for each deck closure placement;
   1. Finish concrete operations twenty-four (24) hours prior to scheduled rail traffic. Scheduled rail traffic shall include SEPTA employee trains, SEPTA maintenance trains or any other test train as directed by the Project Manager.

D. The following concrete strength shall be obtained for each deck closure placement;
   1. Concrete is to have attained a minimum strength of 24 MPa prior to restoration of scheduled rail traffic. Deck closure pour concrete design mix, including all materials and any proposed admixtures, shall be in accordance with previous sections of this specification. The concrete for the deck closure placement must also reach the minimum required 28 day strength per these specifications.

3.08 DEFECTIVE CONCRETE WORK

A. Porous areas, open or porous construction joints and honeycombed concrete will be considered to indicate that the requirements for mixing, placing and handling have not been complied with and will be sufficient cause for rejection of the members of the structure thus

affected.

B. Defective work exposed upon removal of forms shall be entirely removed or repaired within forty-eight hours after forms have been removed.

C. Repaired areas will not be accepted if:
   1. The structural requirements have been impaired by reducing the net section of compression members;
   2. The bond between the steel and concrete has been reduced; and
   3. The area is not finished to conform in every respect to the texture, contour, and color of the surrounding concrete.

D. If the above requirements are not satisfied, the Project Manager may require that the members of unit involved be entirely removed and satisfactorily replaced at no additional expense to SEPTA.

3.09 REPAIR OF DEFECTIVE CONCRETE

A. General: The Project Manager will determine the extent and manner of action to be taken for the correction of defective concrete as may be revealed by surface defects or otherwise determined as affecting the durability of the concrete or structure.
   1. For guideway structural units, complete inspection and make necessary repairs prior to installation and placing the unit in service.

B. Repair of Formed Surfaces:
   1. As soon as possible after stripping forms, thoroughly clean and fill holes left by form ties, and other temporary inserts, and perform corrective work.
   2. Immediately after removing forms, in a manner and by a method accepted by the Project Manager in writing prior to start of repair operation, repair and patch defective areas with cement mortar of mix proportions and materials identical to those used in the surrounding concrete. Produce a finish on the patch that is indistinguishable from the finish of the surrounding concrete.
   3. Cut-out honeycomb, rock pockets, and voids having a diameter more than 13 mm to solid concrete but not shallower than 25 mm. Make edges of cuts perpendicular to concrete surface. Before placing cement mortar, thoroughly clean, dampen, and brush-coat area to be patched with neat cement grout. Proprietary patching compounds may be used if accepted by the Project Manager in writing prior to start of repair operation.
   4. Remove imperfect texture, laitance, fins and roughness by rubbing affected areas with concrete block or carborundum stone until smooth and uniform.

C. Repair of Unformed Surfaces:

1. Test unformed surfaces for smoothness and to verify conformance of surface plane to tolerances specified. Correct low and high areas.
2. Test unformed sloped surfaces for trueness of slope and smoothness, using a template having required slope. Correct high and low areas as specified.
3. Repair finished unformed surfaces which contain defects which adversely affect durability of concrete.
4. Grind high areas in unformed surfaces after concrete has cured sufficiently to permit repairs without damaging adjacent areas.
5. Cut-out low areas in unformed surfaces either during or immediately after completion of surface finishing operations, and replace with fresh concrete. Finish repaired areas to blend into adjacent concrete using specified bonding compounds.
6. Cut-out defective areas, except random cracks and single holes not exceeding 25 mm diameter, and replace with fresh concrete. Remove defective areas to sound concrete with clean, square cuts, and expose reinforcing steel with at least 20 mm clearance all around. Dampen concrete surfaces in contact with patching concrete and brush with neat cement grout coating or use concrete bonding agent. Place patching concrete before grout takes initial set. Mix patching concrete of same materials and in same proportions as adjacent concrete. Place, compact, and finish as required to blend with adjacent concrete. Cure in same manner as adjacent concrete.
7. Repair isolated random cracks and single holes not over 25 mm in diameter by the dry-pack method. Groove tops of cracks, cut-out holes to sound concrete, and remove dust, dirt, and loose particles. Dampen cleaned concrete surfaces and apply the specified bonding compound. Mix dry-pack, consisting of one part portland cement to 2 ½ parts fine aggregate passing 1.18 mm sieve, using only enough water for handling and patching. Place dry-pack before grout takes initial set. Compact dry-pack mixture in-place and finish to match adjacent concrete. Keep patched areas continuously moist for not less than 72 hours.
8. Obtain approval of the Project Manager before performing repair work other than the removal of imperfect texture, filling of pin holes, holes less than 19 mm wide, and insert holes. The Project Manager will determine whether the defective area is sufficiently imperfect to warrant rejection of the structural unit.
9. Repair methods not specified above may be used, subject to acceptance by Project Manager in writing.

D. Repair of Surfaces Damaged by Other Trades:

1. Where the Mechanical and Electrical Trades damage sidewalks, curbs, or pavement when installing their related conduits, etc., such surfaces shall be repaired by the General Construction Contractor and restored to original condition

to the satisfaction of the Project Manager.

3.10 FINISHING

A. Finishes: Finish exposed concrete surfaces true and even, free from open or rough areas, depressions or projections. Bring concrete up in vertical pours to the required elevation, strike-off with a straight edge and float-finish.

1. Spade Finish: Obtained by forcing a flat spade or similar device, down adjacent to the form and pulling the top of the spade away from the form to bring mortar to the surface next to the forms. After forms are removed satisfactorily, correct concrete surface irregularities.
2. Floated Finish: After concrete has been placed, consolidated, struck off and leveled, do not work further until ready for floating. Begin floating when water sheen has disappeared and when the surface has stiffened sufficiently to permit the operation. During or after first floating, check planeness of surface with a 3000 mm straightedge applied at not less than two different angles. Cut down high spots and fill low spots during this procedure to produce a surface with true planes within 4.76 mm in 3000 mm as determined by a 3000 mm straightedge placed anywhere on the slab in any direction. Following straightedge checking, refloat slab immediately to a uniform sandy texture.
3. Smooth Rubbed Finish: Obtained by rubbing a "Spade Finished" vertical surface not later than one day after form removal. Wet surface and rub with carborundum brick or other abrasive until uniform color and textures are produced. Do not use cement grout other than the cement paste drawn from the concrete itself by the rubbing process.
4. Flat Trowel Finish: Obtained by hand or power troweling a "Floated Finish" with a single troweling. This troweling (first after power floating) shall produce a smooth surface which is relatively free of defects but which may still show some trowel marks.
5. Fine Trowel Finish: Obtained by performing additional hand and power trowelings to a "Flat Trowel Finish". Perform an additional troweling by hand or power trowel after the surface has hardened sufficiently. Perform the final troweling when a ringing sound is produced as the trowel is moved over the surface. Thoroughly consolidate surface by hand trowel operations. Produce finished surface to a tolerance of F_F 25/F_L 20 (F_L17 on elevated slabs), essentially free of trowel marks, and uniform in texture and appearance.
6. Broom Finish: Immediately after concrete has received a "Floated Finish", give surface a coarse transverse scored texture by drawing a broom across the surface in the direction of the paved slope. Texture shall be as approved by the Project Manager.

7. Light Sand-Blasted Finish: After removal of the forms, provide a light sand blasting to remove the cement skin from the surface to achieve a smooth, sand-textured surface. Apply sealer to sand-blasted finish in accordance with approved procedures.

B. Application for Finishes:

1. Spade Finish:
   a. Surfaces not exposed to general view.
   b. Surfaces to be rubbed.
2. Floated Finish:
   a. Surfaces to receive "Flat Trowel Finish".
   b. Surfaces to receive "Broom Finish".
3. Smooth Rubbed Finish: As indicated on the Contract Drawings and as follows:
   a. Exterior: Exposed surfaces of structures.
4. Flat Trowel Finish:
   a. Curbs
   b. Other areas as indicated on the Contract Drawings.
5. Steel Trowel Finish (includes both flat trowel and fine trowel finish):
   2. Areas as indicated on the Contract Drawings.
6. Broom Finish:
   a. Areas as indicated on the Contract Drawings.
   3. Guideway decks.
7. Light Sand-Blast Finish:
   a. Areas as indicated on the Contract Drawings.

3.11 CURING AND PROTECTION

A. General: Immediately after placement, protect concrete from premature drying, excessive hot or cold temperatures and mechanical injury. Curing shall be by water or liquid membrane-forming compound, in accordance with ACI 308. Cure concrete continuously for a minimum of 7 days at ambient temperature above 4 °C. Do not use liquid membrane forming compounds where bond to subsequent concrete work will be adversely affected.

B. Silica Fume Concrete: Strictly employ curing methods as necessary to ensure proper curing. Follow the procedures demonstrated in accordance with Section 03300, 1.05D, and recommendations of the associated report. Adjust curing methods for ambient placement conditions. All adjustments must be approved by the Project Manager.

C. Hot Weather Curing: See Hot Weather Concreting this Section.

D. Cold Weather Curing: See Cold Weather Concreting this Section.

E. Application Rate of Liquid Membrane-Forming Compounds: Compound shall restrict the loss of water to not more than 0.055 g/cm^2 of surface in 72 hours when tested in accordance with ASTM C156 at the coverage rate recommended by the manufacturer.
   1. Submit letter from manufacturer stating coverage rate of liquid membrane-forming compound and liquid membrane-forming and sealing compound to meet this restriction in loss of water.

3.12 SEALING OF EXPOSED CONCRETE SURFACES

A. Preparation: Clean surface of all graffiti, dirt, grease, and other bonding restrictive materials using sand-blasting or other methods approved by the Project Manager. Vacuum surface to remove all dust particles.

B. Apply penetrating sealer in strict accordance with the manufacturer's instructions for applications to all above grade, upper and vertical exposed concrete surfaces except those receiving alternate surface treatments or toppings as shown on the Contract Drawings.

3.13 FIELD QUALITY CONTROL

A. Testing and Inspection:
   1. During the entire period when concrete is being placed, provide testing services by an independent testing laboratory as specified in Article 1.04.D.
   2. The Project Manager reserves the right to make any and all tests as the Project Manager deems necessary during the progress of the work.
   3. Failure of the independent testing laboratory or the Project Manager to detect defective work will not prevent rejection when defect is discovered, nor will it obligate the Project Manager for final acceptance.
   4. The Independent Testing Laboratory shall:
      a. Secure composite samples in accordance with ASTM C172.
      b. Mold and cure six test specimens for each strength test in accordance with ASTM C31 and as follows:
         (1) Concrete compression test: Use standard 150 mm x 300 mm cylinders.
         (2) Identify each test by number, mix, amount of admixture, origin of sample in the structure, the date the test specimen was made, the date the test specimen was tested, the amount slump determined, and the compressive strength test results.

(3) Test Methods:

(a) Compressive strength test: ASTM C39.

(b) Make one group of six test cylinders for each 76 m^3 of concrete poured or not less than six test cylinders for any amount of concrete less than 76 m^3 poured in each structure, or one days pour.

(c) Test two specimens at 7 days for information and test three specimens at 28 days for acceptance.

c. Make slump tests for each strength test and whenever consistency of concrete appears to vary in accordance with ASTM C143.

d. Make air content tests for each strength test in accordance with ASTM C231 or ASTM C173.

e. Prepare and submit all reports required in the various standards and specifications referenced herein.

(1) Distribution of reports shall be:

(a) Two copies to the Project Manager.

(b) One or more copies, as required, to the Contractor.

f. Immediately notify the Contractor and the Project Manager of any test results which do not conform to the Specification requirements.

B. Evaluation and Acceptance:

1. The strength level of the concrete will be considered satisfactory so long as the averages of all sets of three consecutive strength tests results equal or exceed specified strength and no individual test result is below specified strength by more than 3.45 MPa.

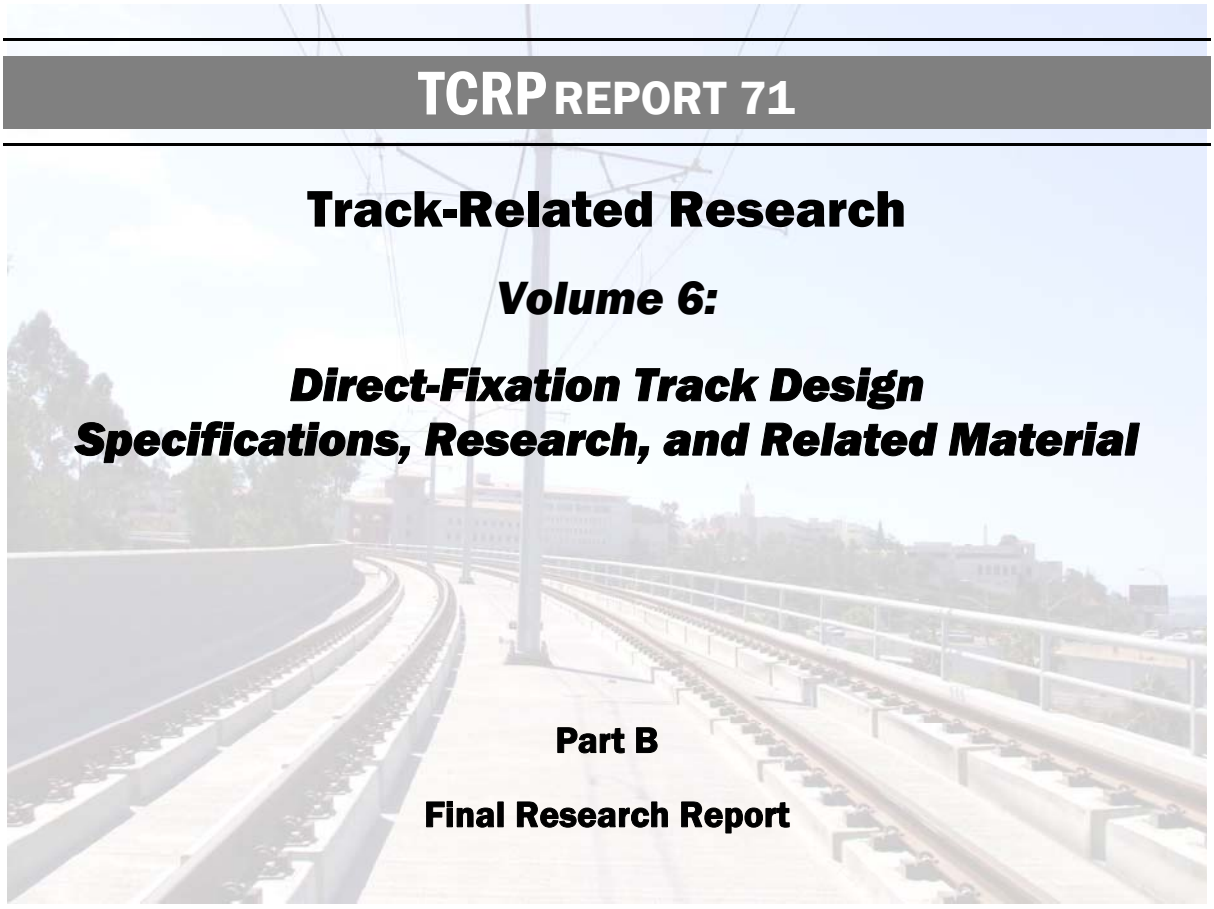
2. If the strength of cylinders falls below specified compressive strengths, the Project Manager shall have the right to order a change in the mix proportions for the remaining concrete being poured.

3. The Project Manager, at his discretion, will obtain the test core specimens from hardened concrete in accordance with ASTM C42.

4. If the strength of cylinders fall below specified compressive strengths, at the Contractor's expense, the Project Manager will require tests on the in-place concrete, using any appropriate method including the core method. Defective concrete shall be removed and replaced by the Contractor at no additional cost to SEPTA.

END OF SECTION

TRANSIT COOPERATIVE RESEARCH PROGRAM



TCRP REPORT 71

Track-Related Research

Volume 6:

Direct-Fixation Track Design Specifications, Research, and Related Material

Part B

Final Research Report

James M. Tuten III
Consultant
8708 Lockerly Court
North Charleston, SC 29420

Editor: L.E Daniels , P.E.
L.E. Daniels Transportation Engineering
4222 Curragh Oaks Lane
Fair Oaks, CA 95628-6604

TRANSPORTATION RESEARCH BOARD

May 2005

Abstract

This report presents results of field reviews and laboratory investigations of direct fixation (DF) fastener systems.

As prelude to the laboratory investigations, transit agency observations are presented to define Direct Fixation fastener service performance and issues as of 1995.

The report then presents the results of laboratory testing and analysis on a number of different types of Direct Fixation Fasteners. The laboratory testing measured individual fastener component characteristics and those of fully assembled fasteners, including dynamic and static stiffness, and longitudinal rail restraint. The testing measured static and dynamic responses of fastener assemblies under a range of loads from transit loading through heavy axle loading on fasteners with designs appropriate for the load regimen. Some tests were conducted under variation in conditions representative of field conditions. The battery of investigations included Direct Fixation fastener fatigue testing and ground-borne vibration isolation testing.

The Report includes a review of analytical evaluation tools (computer models) for Direct Fixation track analysis and interaction between track and vehicle.

PART B: FINAL RESEARCH REPORT

TABLE OF CONTENTS

1. Introduction and Overview

This Report contains data, evaluations, field reviews, and analysis on Direct Fixation fasteners from:

- An earlier Transit Cooperative Research Program (TCRP) project[1],
- Direct Fixation evaluation for heavy axle load service sponsored by the Kowloon-Canton Railway Corporation,
- Direct Fixation evaluation sponsored by the Frankford Elevated Reconstruction Project (FERP).

Direct Fixation (DF) fasteners attach the rails to supporting structures such as bridge decks, aerial structures, and tunnel floors. The principal purposes in specifying Direct Fixation track are: (a) to reduce the track envelope in tunnels and locations with restricted clearances, and (b) reduce dead load on aerial structures. Both purposes aim to reduce the cost of structures.

While the concept is not new, modern Direct Fixation fasteners are designed to allow rail flexure and impact attenuation similar to, but within a much smaller physical envelope, the more traditional track structures such as wood cross ties in ballast, concrete-embedded wood half-ties, or wood ties on steel stringers. Modern Direct Fixation fasteners also improve on electrical isolation of traditional track types. Some industry specialists promote Direct Fixation fasteners to control ground borne vibrations.

Direct Fixation track has grown in acceptance over the past 20 years, finding different uses than the above purposes. Direct Fixation track is favored in train washes, freight loading areas for caustic cargo, station areas, and locations with ground vibration concerns.

The growth in acceptance is not without problems. Transit system experience with different fastener designs has shown that Direct Fixation track has problems that fall into one of two specific categories: (1) functional failures of one or more components of the fastener itself, and (2) indirect (contributory) problems. Functional failures are due to design deficiencies under the given service loads and other environmental stresses. An Urban Mass Transportation Administration study[2] showed that most problems with DF fastener systems were related to

- Failure of anchorage systems (anchor bolts, invert concrete, etc.) or
- Corrosion of components (fasteners, anchors, and rail).

[1] TCRP Project D-5, "Performance of Direct Fixation Track Structure."

[2] Phillips, C., "Wheel/Rail Force Measurements at the Washington Metropolitan Area Transit Authority", ***Proceedings: Direct Fixation Fastener Workshop***, UMTA-MA-06-0153-85-3, June 1985, pp 143-157.

The study reported failure of insulating elements, loosening of clip bolts, failure of clips and/or clip bolts, loosening of anchor bolts, failure of fastener base plates or grout pads, and electrical breakdown due to build-up of debris (rail wear particles).

Because the study is from 1985, there is a need to reassess Direct Fixation service performance in context of more mature experience with original fastener designs and installations, improved designs and materials since 1985, and much broader installation base since 1985 that permits a more considered evaluation of the available experience.

There is a large absence in data on Direct Fixation fasteners characteristics and what those mean to performance, and, as a result, there are fundamental questions on track mechanics that arise from this lack of basic engineering data. Important discourse on technical benefits, construction costs and long-term maintenance benefits have been unsatisfactory raw arguments between agencies and specialists with questions on one side and unsubstantiated opinions on the other.

Tolerances in manufacturing and construction are the key to success or failure of Direct Fixation track performance expectations. Direct Fixation track can meet or exceed proponent's expectations only if tolerances are met. However, there is not a reasonable basis of understanding the manufacturing tolerances, e.g. fastener stiffness, damping and geometry, in the three planes.

With Direct Fixation designs and material technology improving since the 1985 UMTA study, an update on Direct Fixation service performance was needed to guide these laboratory tests. Also modern Direct Fixation installations were approaching maturity with 20 years of service in 1995, and there were more installations in service. This report summarizes site visits and interviews with transit professionals across the United States in 1995.

The report presents the results of laboratory testing and analysis on a number of different types of Direct Fixation Fasteners. The laboratory testing measured individual fastener component characteristics and those of fully assembled fasteners, including dynamic and static stiffness, and longitudinal rail restraint. The testing measured static and dynamic responses of fastener assemblies under a range of loads from transit loading through heavy axle loading on fasteners with designs appropriate for the load regimen. Some tests were conducted under variation in conditions representative of field conditions. The battery of investigations included Direct Fixation fastener fatigue testing and ground-borne vibration isolation testing DF track requires precision in manufacturing and construction to meet expected performance. Direct fixation track is a system that requires precision in construction and, installed properly, maintains its geometry and properties with much less maintenance attention than conventional tie and ballast track. Where tie and ballast track is easily adjusted for surface, line and gauge, Direct Fixation track has small, finite, adjustment limits. Direct Fixation stiffness and support conditions are fixed by a fastener's design and by installation quality, with no available adjustment short of replacing the fastener.

However, a clear basis for practical Direct Fixation construction tolerances is not available. This report provides data on the effects of construction tolerances on important track parameters.

In parallel, the industry has no data showing how fastener characteristics, such as stiffness, vary from manufacturing for a given fastener. The stiffness curve for many Direct Fixation fasteners is non-linear[3], and the industry has no comprehensive data showing how or whether different fasteners have different characteristics at expected loads.

[3] Non-linear stiffness curves means that the stiffness is load dependent.

The report documents characteristic data on numerous different fasteners to show the difference in manufacturing for a single fastener model, and the differences of those characteristics between different fastener designs.

A number of analytical and experimental investigations have been conducted over the past two decades to define and understand the mechanisms of vehicle/track interaction. In the context of rail transit systems, these studies have concentrated in particular on vehicle/track curving behavior and the generation of rail corrugations. These studies have highlighted the importance of fastener stiffness, vehicle suspension stiffness, wheel profiles, track geometry, environmental factors, and operating conditions in vehicle/track performance. As a result of these studies, a substantial database characterizing the track load environment is available, and a number of detailed, validated computer simulation models have been developed. These analytical approaches are reviewed in this report.[4]

[4] Please see *Part A: Direct Fixation Track Design and Example Specifications* for track design methods and analysis.

2. Transit Direct Fixation Experience

2.1 General

In order to improve the performance of direct fixation fastener performance it is useful to understand fastener experiences under service.

The service environment is obviously an important influence on fastener performance. Direct Fixation track deployment (by types of DF track) throughout the industry and the deployment of DF fasteners, as of 1994 when the data was collected, is presented in Figure 2-1. The same data are shown in Figure 2-2 with the DF track types combined.

Figure 2-3 shows the coincidence of the different DF track systems on the types of superstructures existing in transit. Figure 2-4 shows the same data in a percentage format of DF track system for each.

From these figures, Direct Fixation track has become the preferred track design for aerial structures and tunnels.

2.2 Direct Fixation Track Structure Performance

2.2.1 Reporting Agencies

During 1995 and 1996, representative information on North American experience with Direct Fixation track performance was gathered from the following agencies and firms through site visits and interviews. (listed alphabetically):

- BART (Bay Area Rapid Transit)
- CTA (Chicago Transit Authority)
- MARTA (Metropolitan Atlanta Rapid Transit Authority)
- MBTA (Massachusetts Bay Transportation Authority)
- LACMTA (Los Angeles County Metropolitan Transportation Authority)
- MTA (Mass Transit Administration of Maryland, or Baltimore Metro)
- NYCT (New York City Transit)
- PATCO (Port Authority Transit Corporation)
- SEPTA (Southeastern Pennsylvania Transportation Authority)
- WMATA (Washington Metropolitan Area Transit Authority)
- Wilson-Ihrig & Associates.

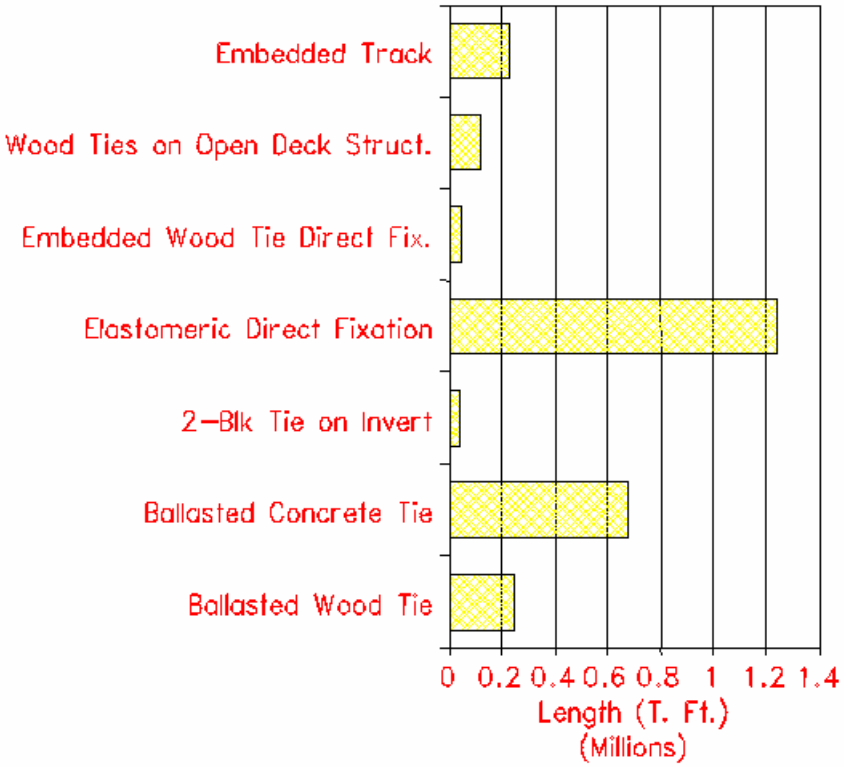


Figure 2-1. Occurrence of all track types in transit

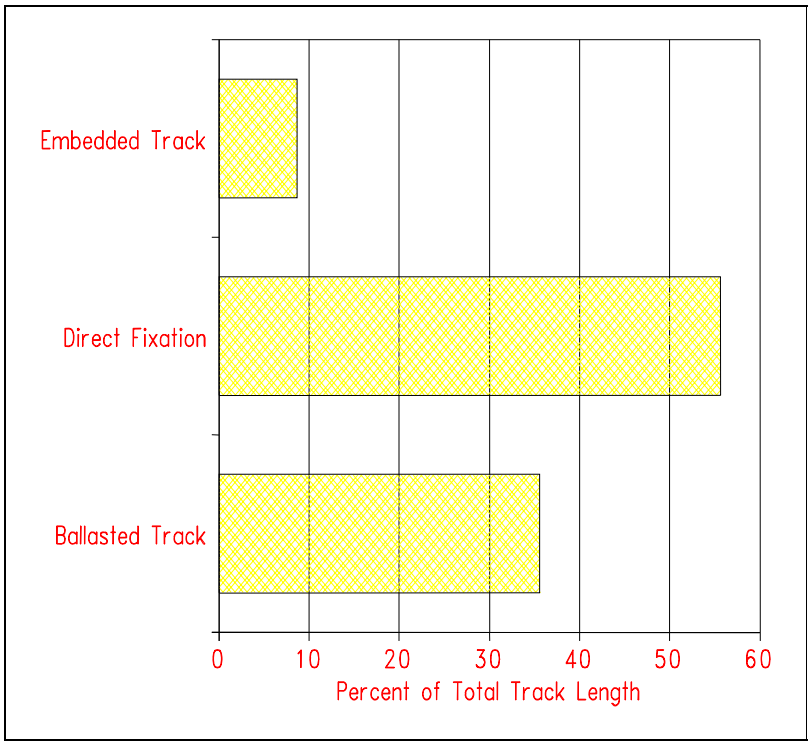


Figure 2-2. Distribution of track types in transit by major track categories

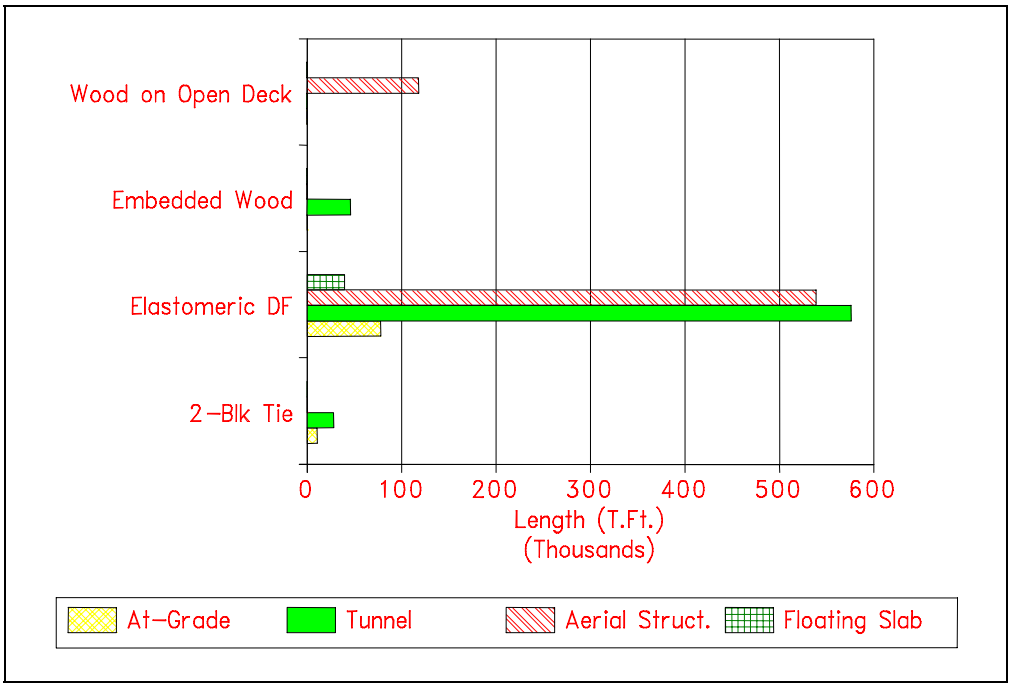


Figure 2-3. Occurrence of DF track types on superstructure types

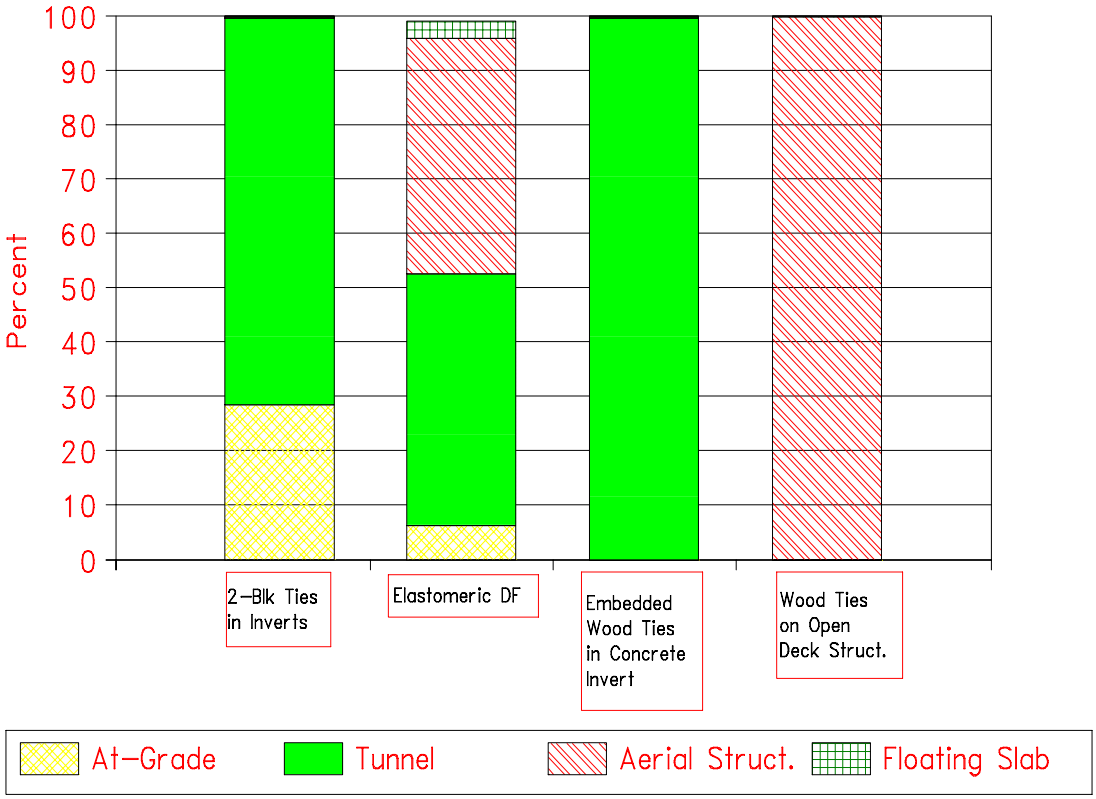


Figure 2-4. Relative occurrence (%) of DF track types on superstructure types

The following is a summary of DF fastener performance obtained during site visits at transit agencies listed in Appendix C, and interviews of maintenance and engineering managers at those agencies. The site visits where conducted during the Spring-Summer, 1995.

The information should be viewed within the context of evolving Direct Fixation technology from the 1920's through 1995 when this survey was performed. "Modern" fasteners are those installed since 1975 when the bonded fastener technology was developed and the boltless rail clip gained in acceptance.

2.2.1.1 BART (Bay Area Rapid Transit) DF Problems

- Anchor bolt failures (88 failures in 23 years; 704,000 bolts in service)
- Failures of "fastener bodies" (elastomeric plates) from high impact loads at approaches
- Fastener loosening due to vertical misalignment from non-uniform track settlement of aerial structures
- Fastener clip bolt loosening in curves.

2.2.1.2 CTA (Chicago Transit Authority) DF Problems

- Failure of fastener-to-invert hold-down bolts (loose bolts, seized/worn threads, broken bolts), particularly in curves and sometimes associated with water collected at bolt head
- Degraded grout pads
- Movement of shims out from under fasteners

Several locations on the Chicago Transit Authority urban transit lines were visited on May 25, 1995, to examine the type of track structure on which Direct Fixation fasteners are used. Six distinct sites were examined during this visit. The following notes describe the fasteners and conditions at each of these locations:

1. **O'Hare Line (Line 24 OH) Approaching O'Hare Terminal** (Figure 2-6).

   - Failure of hold-down bolts. (Figures 2-7, 2-8)
   - Bolts loose or seized
   - Base concrete deterioration with exposed rebar (Figure 2-10)
   - Associated movement of the support concrete under trains.

   The fasteners have been in place since 1984.

Figure 2-6. O'Hare Line approaching subway portal to airport

Figure 2-7. Bolt failure on O'Hare Line DF fastener

Figure 2-8. Bolt failure on O'Hare Line DF fastener

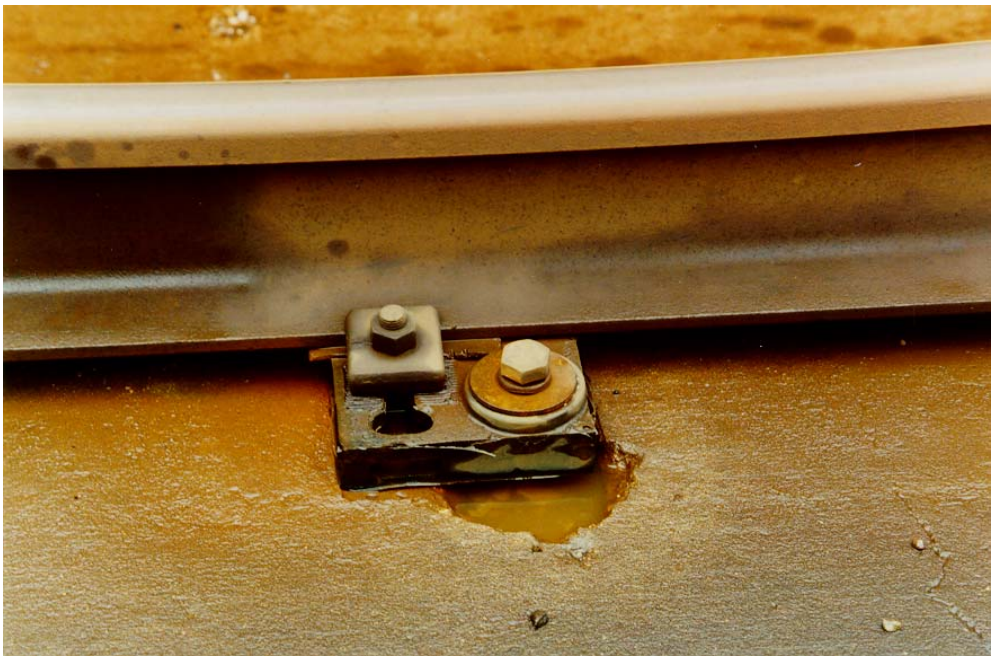


Figure 2-9. Repair "Pocket" in invert near DF fastener insert, O'Hare Line

Figure 2-10. Deteriorated base concrete with exposed rebar

2. O'Hare Line (Line 24 OH) at Irving Park (Pulaski) Station

This location consists of a steel deck over Pulaski Road with concrete two-block ties on a nominal 30-inch spacing resting on a (roughly) 1/2-inch thick composition pad, stiff rail clips, a chevron cross-hatched rail seat pad about 3/16-inch thick, and a U-shaped hold-down clamp to the deck (Figure 2-11). Problems at this location included broken tie bars (Figure 2-12), pads skewing out from under the blocks and the rail seats, and rail corrugations. Noticeable short-wavelength (1-1/4 to 1-1/2 inch) corrugations were seen both on the two-block tie section (about 200 ft in length) and the adjacent wood-tie, ballasted track. Some longer wavelength (3-inch) corrugations were also noted in places. No rail clip or U-clamp failures were seen or mentioned.

Figure 2-11. Two-block ties near Irving Park Station, O'Hare Line

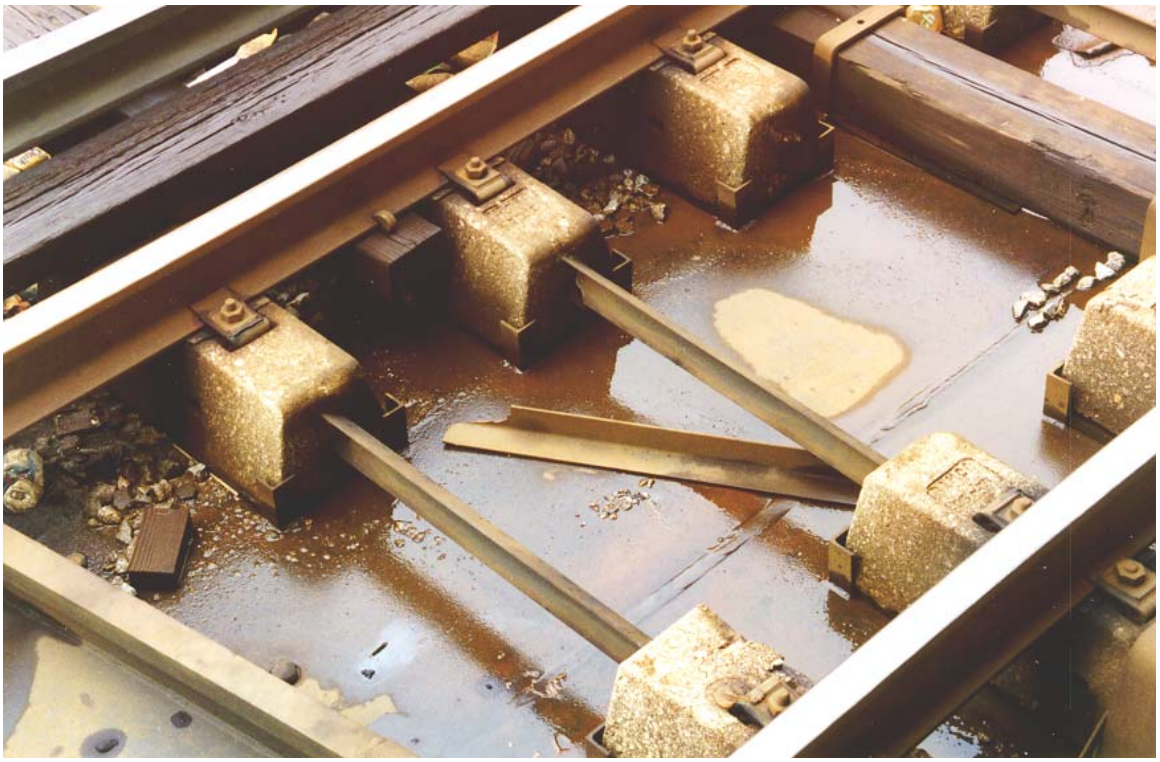


Figure 2-12. Two-block tie bar failure, Irving Park Station, O'Hare Line

3. North Main Line (Line 11 NM) at Addison Street Station

The station has been extensively rebuilt with Direct Fixation track on slab for elevated structures. There were surface elevation problems on the pour; grout on the second pour is spalling, although the site is only about a year old (Figure 2-13). Shims tend to work their way out from under the fasteners, and once again there are hold-down bolt failures: loosened (Figure 2-14) or broken (Figure 2-15). It was not known whether the loosened bolts were binding the same as Location #1. Although the hold-down bolt well has a drain notch (see Figures 2-14 and 2-15), water was seen to collect at the bolt head in at least several of the fasteners.

Figure 2-13. Invert spalling, shim movement at Addison Street Station, North Main Line

Figure 2-14. Bolt failure with DF fastener, Addison Street Station, North Main Line

Figure 2-15. Bolt failure with DF fastener, Addison Street Station, North Main Line

4. Loop (Line 41 LP) at Adams/Wabash Station

This location is typical of sites where additional vertical clearance was attained by removing the wood ties, raising the supporting I-beams, and using DF fasteners between rail and beams. At this location, plate type DF fasteners are used, with the hold-down bolts fastened through the beam flange (Figure 2-16). This particular installation has been in service for three years with no apparent problems.

5. State Subway (Line 12 SS) between Washington and Grand

This track dips under the Chicago River in the subway. It consists of wood half-ties imbedded in the concrete invert. Spring clips and tie plates on a composition pad with lag bolt hold-downs have been in service about two years as replacements. There is some clip breakage. The invert slab has failed at the low spot (Figure 2-17) where water collects. This has been grouted, but the grout is failing now.

6. Dearborn Subway (Line 26 DS) at Washington Station

The track uses a plate with four lag bolts, sleeved, with a pad under the plate. The lag bolts are fastened to wood half-ties imbedded into the concrete invert (Figure 2-18). There are clip failures, and the lag bolts tend to loosen. This is the original (1960s) fastening system.

Figure 2-16. Typical DF fastener installation on cross beams, Loop Elevated Line

Figure 2-17. Failed slab and grout in State Subway under Chicago River

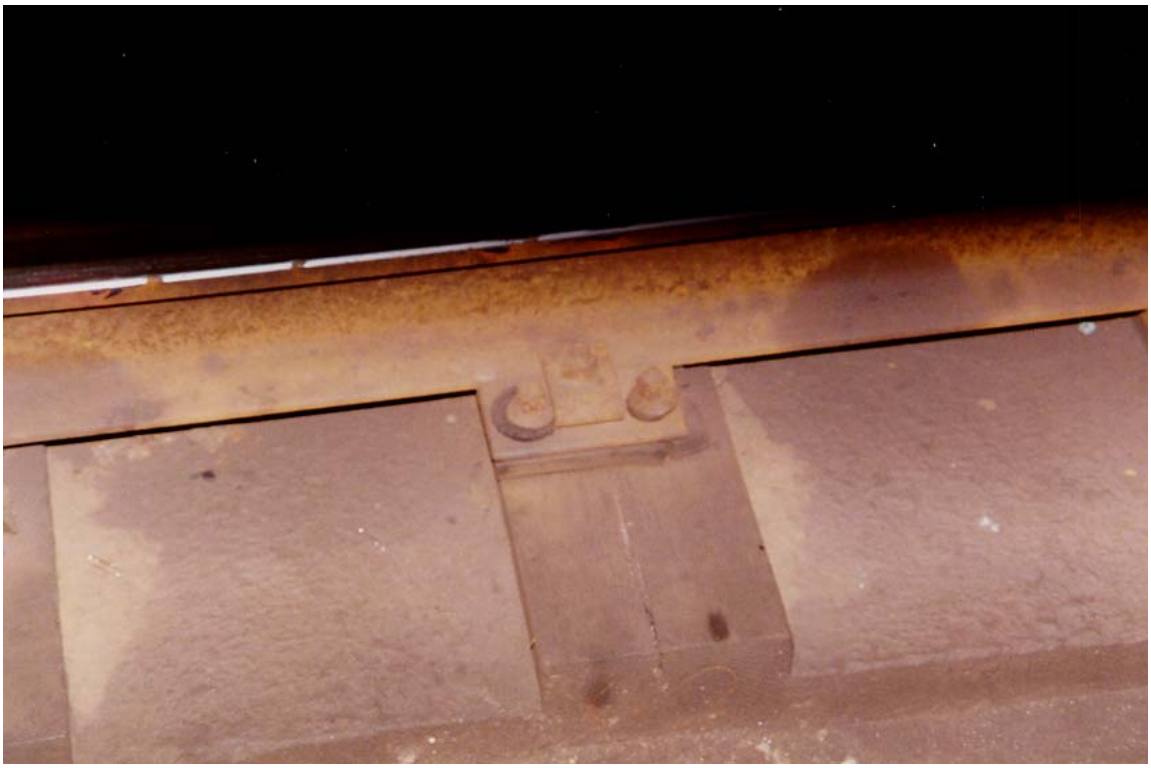


Figure 2-18. Original fastening system, Dearborn Subway

2.2.1.3 MARTA (Metropolitan Atlanta Rapid Transit Authority) DF Problems

- Anchor bolt failures due to corrosion and electrolysis (when insulator sleeve breaks due to shear failure and corrosion), within a few months of installation
- Rail clip fall-outs ("rare")
- Loosening of rail spring clips due to overstress
- Corroded anchor bolt may cause nut to freeze, and can disable gage adjustment feature of DF fastener

2.2.1.4 MBTA (Massachusetts Bay Transportation Authority) DF Problems

- Rail clip breakage due to overdriving of clips
- Rail clip fallout as a result of insulator failure/fall-out
- Rail base corrosion due to water entrapment in one DF fastener design

Figures 2-19 through 2-22 show features seen at MBTA.

Figure 2-19. Spring clip showing excessive debris accumulation

Figure 2-20. Spring clip

Figure 2-21. Broken clip

Figure 2-22. Broken clip with surface concrete spalling

LACMTA (Los Angeles Metropolitan Transportation Authority) DF Problems

- Corrosion in tunnels due to water leaks on Red Line
- Lateral adjustment problems in special trackwork, where there is no adjustment capability in DF fasteners
- Inconsistent measurements of crosslevel and vertical profile between track geometry car and manual methods, which may be due to relatively low stiffness of DF track and dynamic coupling with track geometry vehicle

MTA (Mass Transit Administration of Maryland) DF Problems

- Failure of fastener to concrete hold-down (due to anchor bolt corrosion, grout pad degradation, and/or anchor bolt mechanical fatigue)
- Delamination near bottom of elastomer in and around the anchorage assembly
- Round-off of square bolt set in concrete (due to stray current)
- Loosening/fall-out of rail clips.

In Figure 2-23 a broken hold-down bolt is shown in a pour-in-place fastener. This design places a bending load on the bolt. Bolts were failing in large numbers, apparently from bending fatigue. This particular application was on a floating slab where the rail was prone to corrugation, which is clearly evident in Figure 2-24. An application of a DF fastener to special trackwork is shown in Figure 2-25.

Figure 2-23. Broken holddown bolt on pour-in-place fastener

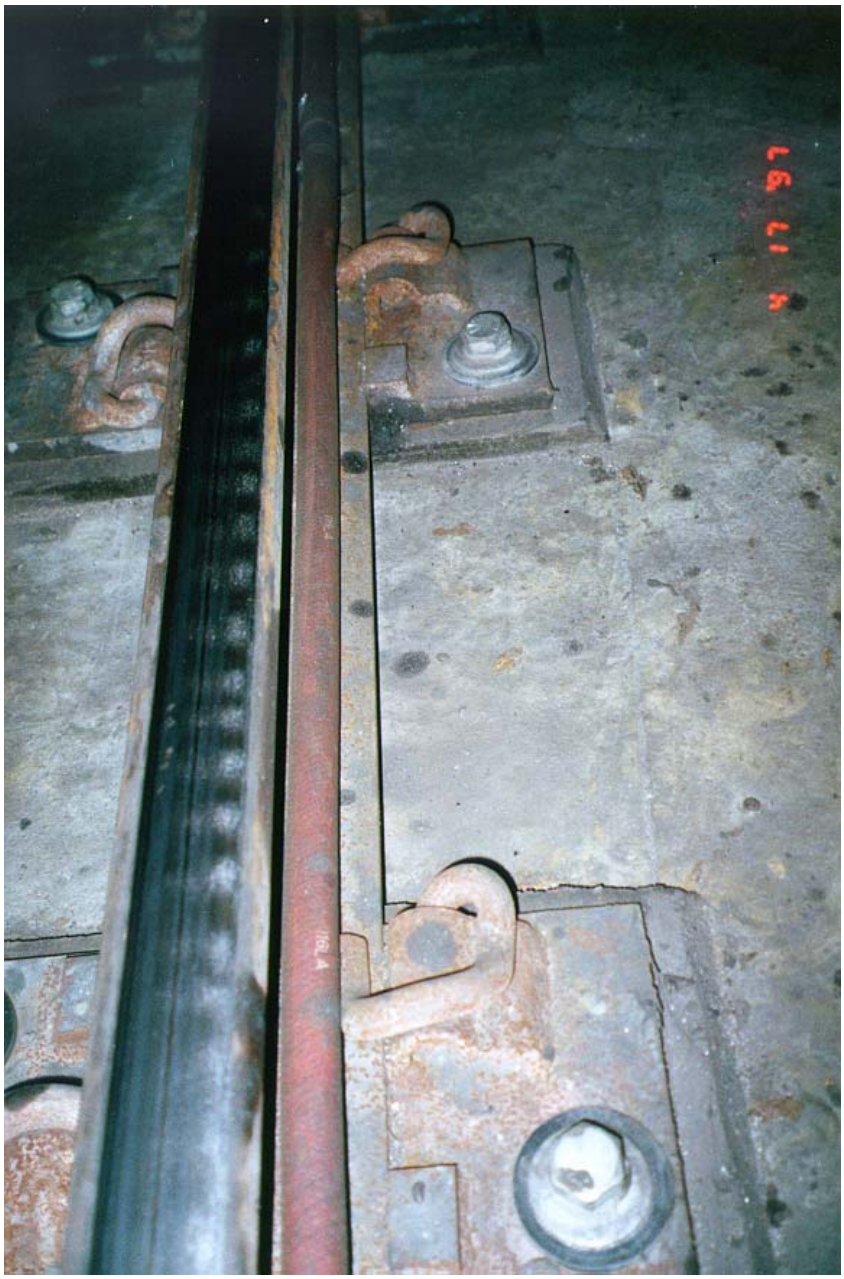


Figure 2-24. Corrugation exhibited on floating slab track section

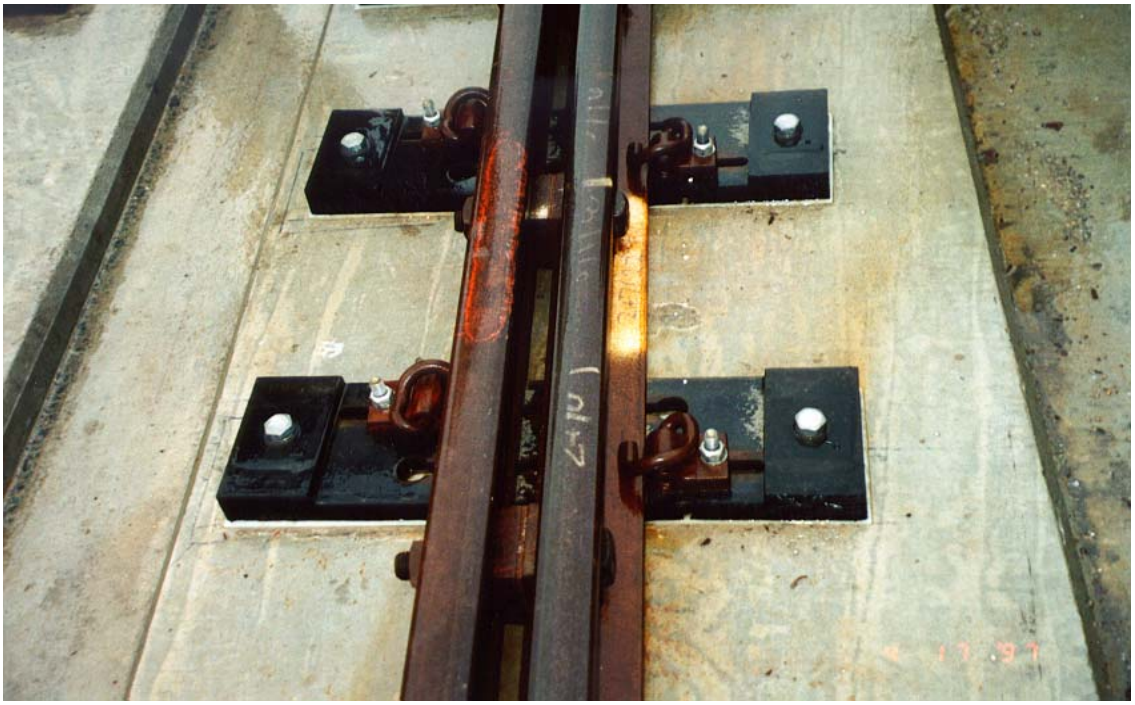


Figure 2-25. Special trackwork application of DF fastener

NYCT (New York City Transit) DF Problems

- DF fastener plate and bolt corrosion due to entrapped water in rubber encasement boot
- Shear failure of bolts caused by electrolysis/corrosion
- Deterioration of concrete paddy due to poor quality mix, weak bond between pours, or stray current

PATCO (Port Authority Transit Corporation) DF Problems

- Corrosion of hold-down for rail clips (makes it difficult to change out the rail)
- Creation of voids between elastomer pad and concrete and/or between pad and plate, caused by deterioration of grout paddies
- Insulation failures, accelerated by stray currents
- Anchor bolt failures, due primarily to corrosion, which in turn is a result of failure of insulating washers

SEPTA (Southeastern Pennsylvania Transportation Authority) DF Problems

- Loose rail clips
- Fastener corrosion in subway
- Clip breakage in sharp curves
- Anchor bolt failures due to inadequate insulation and poor bolt quality
- Loss of anchor bolt hold-down in special trackwork
- Separation/delamination between shim and structure (“minor problem”)

A number of different problems were encountered in various sections with the direct fixation fasteners installed during the 1988–89 time frame on the Market Frankfort Elevated Line. In particular an excessive number of spring clips were breaking and the fastener nuts were working loose. Figures 2-26 through 2-29 show some of the problems. An independent study was conducted to determine some of the causes of the failures. In this study the track was found to have poor vertical alignment and shimming. The supplemental static loads imparted to the fasteners and components were believed to be a major cause of the component failures. In a simultaneous effort to remedy the fastener failures a retrofit spring clip shoulder was developed for use with the existing direct fixation fasteners and a standard spring clip. An example of this arrangement in a full restraint configuration is shown in Figure 2-30. Additional photos of this retrofit are included as Figures 2-31 and 2-32. This retrofit was developed in both a full restraint configuration and a Zero Longitudinal Restraint (ZLR) configuration. While these new clips are easier to install and maintain due to their boltless nature, they have also been exhibiting premature failures, which are believed due to poor vertical track alignment.

Figures 2-33 through 2-38 show additional fastener features seen at SEPTA.

Figure 2-26. Plate type fastener with 2 inch steel shim

Figure 2-27. Temporary wooden shims

Figure 2-28. Missing rail clip and hold-down

Figure 2-29. Broken rail clip

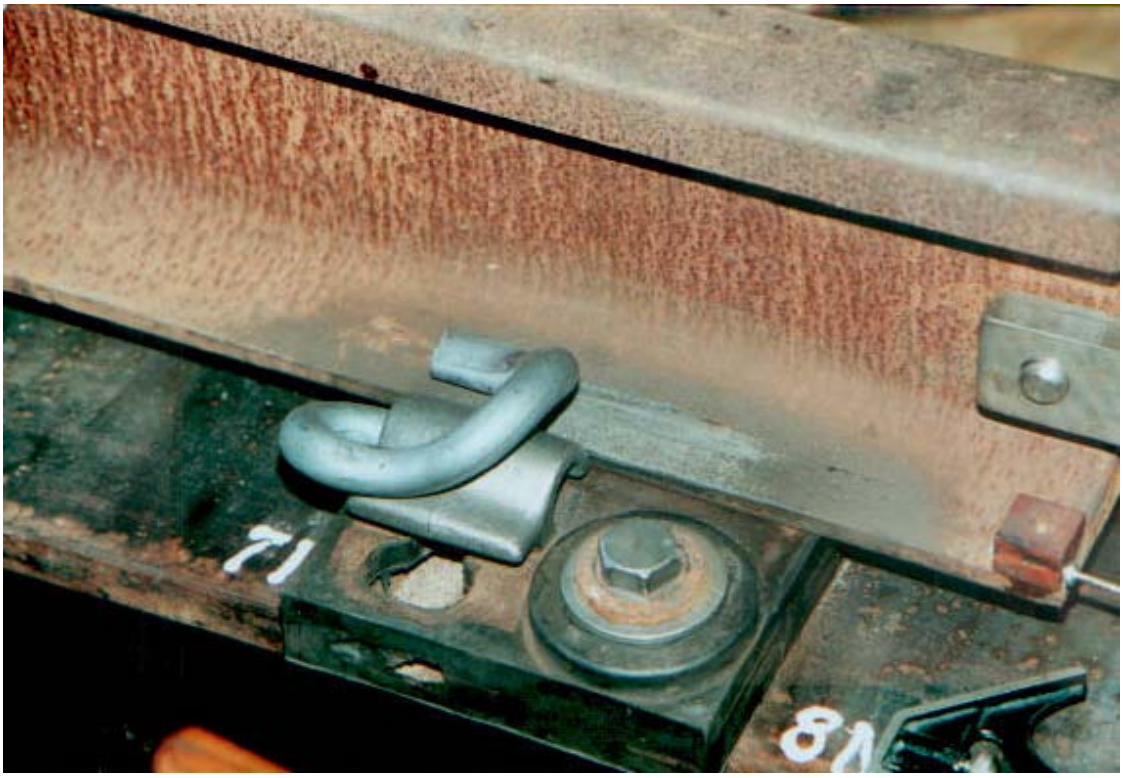


Figure 2-30. Alternate Rail clip retrofit to DF fastener replacing bolted clip

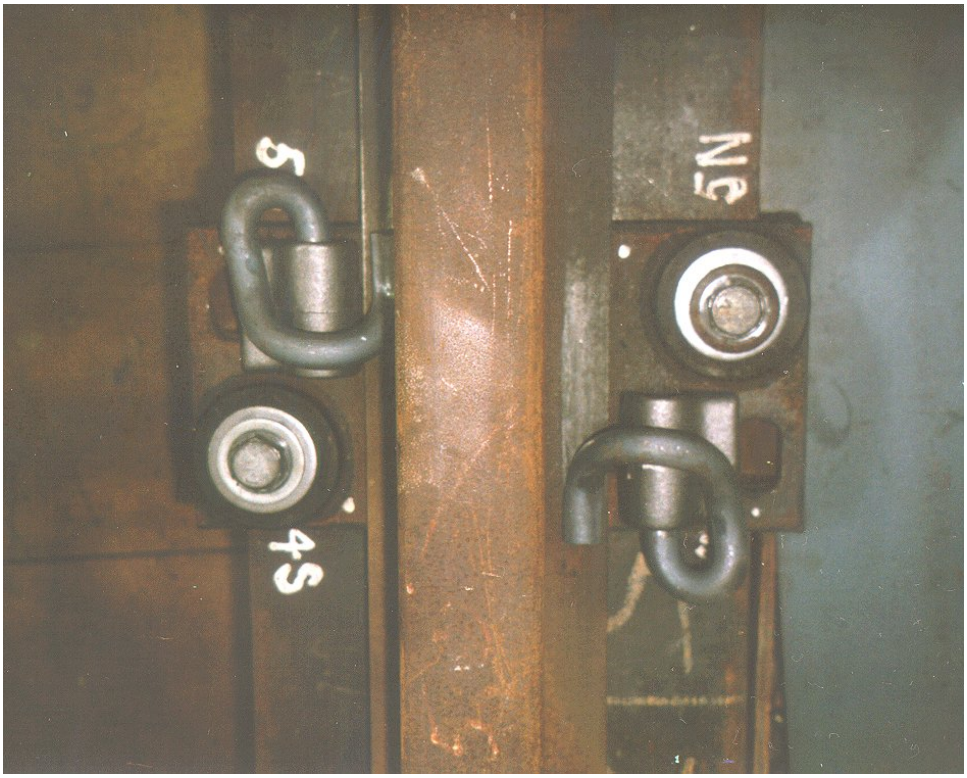


Figure 2-31. Retrofit to DF fastener: top view

Figure 2-32. Retrofit to DF fastener: side view

Figure 2-33. SEPTA in-house design showing rubber bolt covers on hold-down

Figure 2-34. In-house design, spring clips, spring loaded hold-down

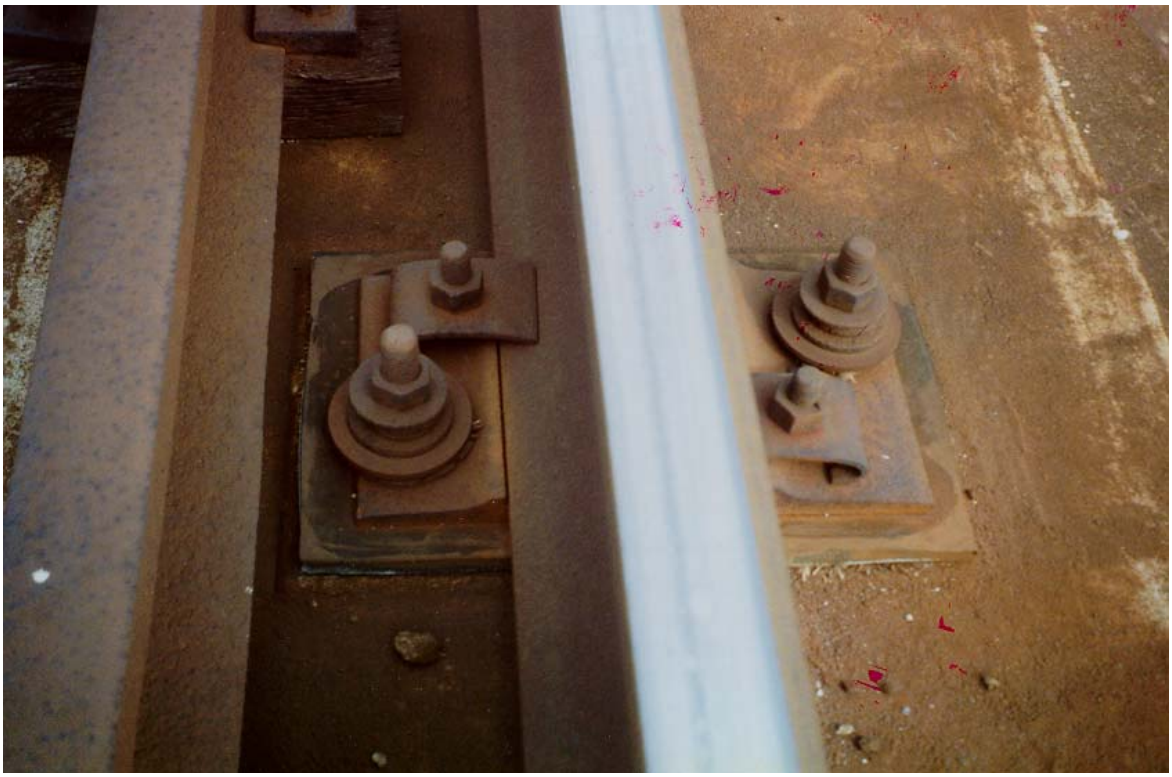


Figure 2-35. Bolted plate design

Figure 2-36. Excessive corrosion and Bolted Plate hold-down

Figure 2-37. Bolted Plate showing fastener pullout

Figure 2-38. Excessive corrosion of bolted Plate

2.2.1.5 WMATA (Washington Metropolitan Area Transit Authority) DF Problems

- Elastomer separation at grout pad/bottom of fastener plate
- Shear failure of pin connecting top and bottom plates of fastener (old design), leading to elastomer separation and damaged bottom plates, especially in curves
- Loose bolted clips, attributed to thermally induced rail stresses
- Corrugation in curves where there are high fastener deflections
- Rail clip breakage and fall-outs

2.2.1.6 GCRTA (Greater Cleveland Regional Transit Authority)

The GCRTA installed its Waterfront line in 1992 - 1994 with zero longitudinal restraint rail fasteners. The fasteners are used on a flyover loop and bridge to control thermal forces into the structure. An example of this installation is shown in Figures 2-39 and 2-40. The fastener in Figure 2-39 is located in a tangent and uses two hold-down bolts, while the one in Figure 2-40 is located in the curve and uses a slightly different design with four hold-down bolts.

Figure 2-39. Two-bolt DF fastener with zero longitudinal restraint rail clip.

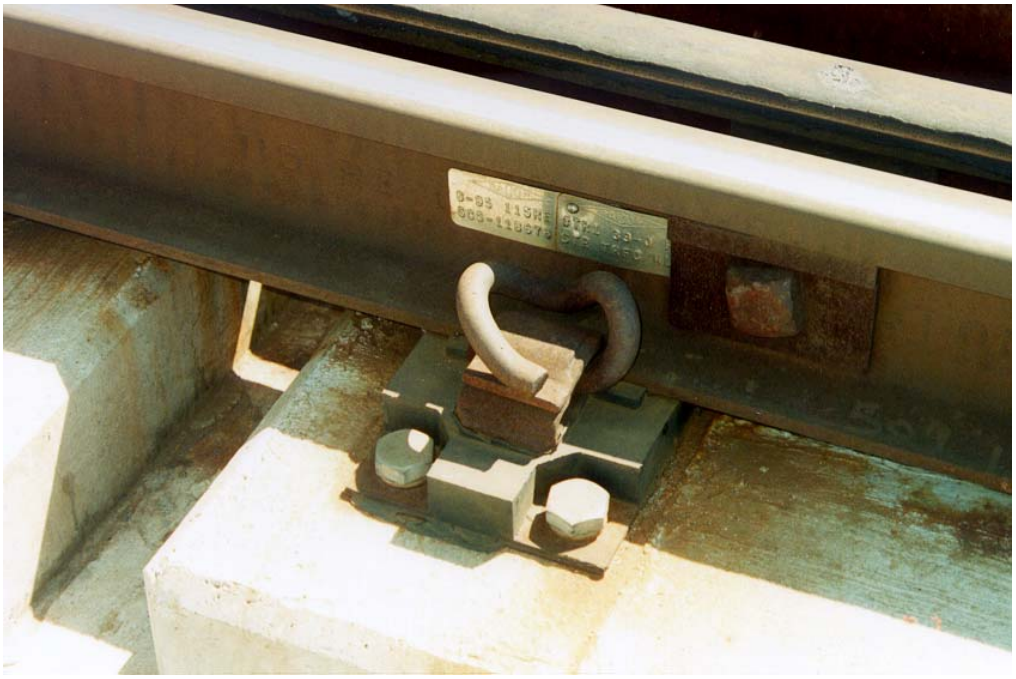


Figure 2-40. Four-bolt DF fastener with ZLR implemented

2.2.2 Summary of Information Gathered During Site Visits

The vertical stiffness that is specified by different agencies is shown in Table 2-1. Lateral values are rarely specified.

Table 2-1. Specified fastener properties

Agency	Fastener	Vertical Stiffness (lb/in)	Lateral Stiffness (lb/in)
Frankford Elevated Reconstruction Project (FERP)/SEPTA	Plate, Low and High Restraint Fasteners	300,000	35,000
Los Angeles Red Line	Plate	51,000+/- 20%	Between 32,000 and 64,000
	non-bonded plate and elastomer	900,000 at 1,800 lb; 1,900,000 at 2,800 lb	
	Continuous (Cork Rubber)	est. 750,000 to 1,000,000	
BART	Plate, rigid toe clamp, Neoprene Bonded	125,000 mean	
NYCT,PATCO, CTA PATH, SEPTA, WMATA	Plate, Spring Clip, Neoprene bonded	125,000 mean	
Toronto TTC, SEPTA,PATH	Bolted spring clip, non-bonded neoprene pad	est. 500,000	
MARTA, WMATA	Plate, Screw type rigid toe clamp, bonded neoprene rubber	125,000	
LACMTA, WMATA	Plate, Boltless flat leaf spring, bonded neoprene	150,000	

Agency	Fastener	Vertical Stiffness (lb/in)	Lateral Stiffness (lb/in)
NYCT	Bolted, non-bonded butyl elastomer	est. 250,000 to 500,000	
LACMTA, WMATA	Plate, various rail clip configurations, bonded neoprene	generally in the range of 125,000	
	Frame type, spring clip, bonded	70,000 (static), 90,000 (dynamic)	

A summary of problems reported by the interviewed transit properties is provided in Table 2-2. This table also presents the percentage of properties with the problem. This is done on a simple number of occurrences basis. No weighting for track miles has been performed.

Among the most common DF track problems were various problems associated with poor drainage and loss of electrical insulation, or improper installation.

The following are common transit agency recommendations:

- For the hold-down system, use female threaded inserts in the concrete rather than threaded rod.
- Minimize threaded fastener components, using high strength bolts where required.
- Minimize corrosion through isolation of metal components and use of corrosion resistant metal components.
- For ease of maintenance, use spring clips instead of “compression” or bolted rail clips
- Develop more realistic fastener test procedures

It is noteworthy that there were differences of opinion on if/how the DF fastener should provide a position adjustment feature. For example, one system recommends additional adjustment capability for DF fastener systems, while another recommends no adjustment capability. Further, preferences for DF design characteristics ranged from “simple” to tailoring the characteristics for each application in a transit system.

The combined experience and opinions of the transit properties have identified methodologies with good performance and those with mixed or poor performance.

Table 2-2. Summary of transit agency interviews

	Consequences	Balt MTA	BART	CTA	LA METRO	MARTA	MBTA	NYCT	PATCO	SEPTA	WMATA	Percent
Anchor Bolt Deterioration - Corrosion & Electrolysis	-Loss of Adjustability/Removability of DF fastener -Accelerated Fatigue Failure of Bolt	X		X	X	X		X	X			60
Anchor Bolt Breakage	-Loss of Hold-Down Capability	X	X	X		X				X		50
Grout Pad Deterioration	-Water Entrapment Leading to Corrosion -Loss of Anchor Bolt/Insert Pull-out Strength -Track Misalignment	X		X				X	X			40
Elastomer Delamination & Separation	-Loss of Direct Fixation fastener Stiffness/Damping Properties	X	X							X		30
Rail Clip Loosening	-Reduction/Loss of Hold-Down Capability	X	X			X				X	X	50
Rail Clip Fallout	-Loss of Hold-Down Capability	X				X	X				X	40
Rail Clip Breakage	-Loss of Hold-Down Capability						X			X	X	30
Fastener Hardware Deterioration - Corrosion	-Loss of DF fastener Stiffness/Damping Properties -Loss of Adjustability -Track Misalignment		X		X		X	X		X	X	60
Fastener Plate Deterioration - Impact Damage	"		X									10
Fastener Loosening - Track Settlement	-Reduction/Loss of Hold-Down Capability -Track Misalignment		X									10
DF fastener Shim Movement & Fallout	"			X								10
Short Wavelength Corrugations	-Excessive Noise -High Rates of Rail Wear	X	X	X	X		X	X		X	X	80
Profile Deviation at Transition Zones	-Track Settlement at Bridge/Aerial Structure Platform Approaches -Poor Ride Quality, Increased Tamping								X			10

Table 2-2. Summary of transit agency interviews (continued)

	Consequences	Balt MTA	BART	CTA	LA METRO	MARTA	MBTA	NYCT	PATCO	SEPTA	WMATA	Percent*
Weld Failure on Clips at Base	-No Toe Load									X		10
Insulation Failure/Stray Current Due to Electroysis	-Track Circuit Shunts -Premature Failure of Hold-Down Bolts						X	X	X	X		40
Poor Drainage, Leading to Accelerated Concrete Deterioration, Leading to Poor DF Base Plate Load Distribution	-Poor Surface (Gage/Crosslevel) -Excessive Rail Wear -Concrete Chipping, Spalling -Clip Rotation/Loss of Restraint							X	X	X		30
Lack of Standards for Bolt Torquing	-Excessive Tightening Causes High Pull-out Force on Bolt -Insufficient Torque Causes Rail Rotation	X				X				X		30
Avoid Ordering Direct Fixation Components from a Company Which has Little Demonstrated Experience or Commitment	-No Ability to Procure Replacement Parts If/When Company leaves Business	X					X					20
Avoid use of Adjustable Fasteners in New Construction	-Bolts Corrode/Loosen -Unnecessary Expense					X						10
Avoid Purchase of Too Many Different Types of DF Fasteners (Inventory and Training Problem)	-Poor Installation -Poor Maintenance						X					10
Difficulty in Achieving Construction Tolerances/Use of Shims	-High Maintenance -Poor Track Geometry due to Shim Fallouts	X				X						20
Difficulty in Using Track Geometry Car Due to Car/Track Dynamics	-Excessive Time and Cost to Ensure Accurate Geometry Measurements				X							

3. Fastener and Fastener Component Static Stiffness Measurements

3.1 Objective

One of the key parameters used to characterize a DF fastener is the static stiffness. The objective for the fastener static stiffnesses tests was to determine reliable, realistic stiffness measurements for a number of different DF fasteners representing a wide range of design types. Since the stiffness in the vertical and lateral directions are always coupled, this is a complex measurement. Additionally, the roll stiffness of the fastener will affect the lateral displacement of the railhead under typical operating scenarios, which further complicates this measurement. Over the years standardized criteria have been developed to define the testing methodology for measuring rail support stiffness. The important criterion is that the stiffness should be that perceived by a wheel, the only perspective that truly matters in operation. A laboratory stiffness is only partially useful if it cannot be correlated back to field experiences. The testing performed by Battelle made use of a number of specialized loading fixtures and instrumentation to provide a complete overview of fastener stiffness under a series of conditions for a number of different types of fasteners. The approach, procedures, and results for these tests will be presented in this Section. Specifically, stiffness was measured under quasi-static vertical loading, quasi-static vertical and lateral loading, and dynamic vertical loading were performed.

3.2 Test Overview

A number of different rail fasteners were tested. The types of fastener and the number of fasteners tested are shown in Table 3-1. The test set-up is shown in Figures 3-1 and 3-2. The fastener to be tested is installed in a test frame that is mounted into a 50 kip MTS[5] testing frame. A short piece of rail is mounted onto the fastener under test using whatever method is standard for that fastener. A specially designed loading head with integral load cells constructed from a wheel rim of an AAR profiled wheel is then installed between the rail head and the vertical ram of the MTS machine. The vertical ram is connected with a long loading column to allow lateral movement of the railhead while minimizing the lateral force error due to column loading. The MTS machine is used then to provide the vertical force for testing. A separate, hand actuated lateral hydraulic cylinder is used to provide lateral force to the railhead fixture through a load cell. The fastener and rail are instrumented with displacement transducers to measure rail displacement in the vertical and lateral directions, and rotation and yaw of the rail. The following data were taken continuously for each experiment using a PC driven data acquisition program: vertical load, vertical actuator displacement, vertical displacement at the east end of the rail, vertical displacement at the west end of the rail, lateral load, lateral displacement at the foot of the rail, and lateral displacement at the top of the rail.

[5] MTS is a test control system that can be programmed to control multiple hydraulic load cylinders within a load frame.

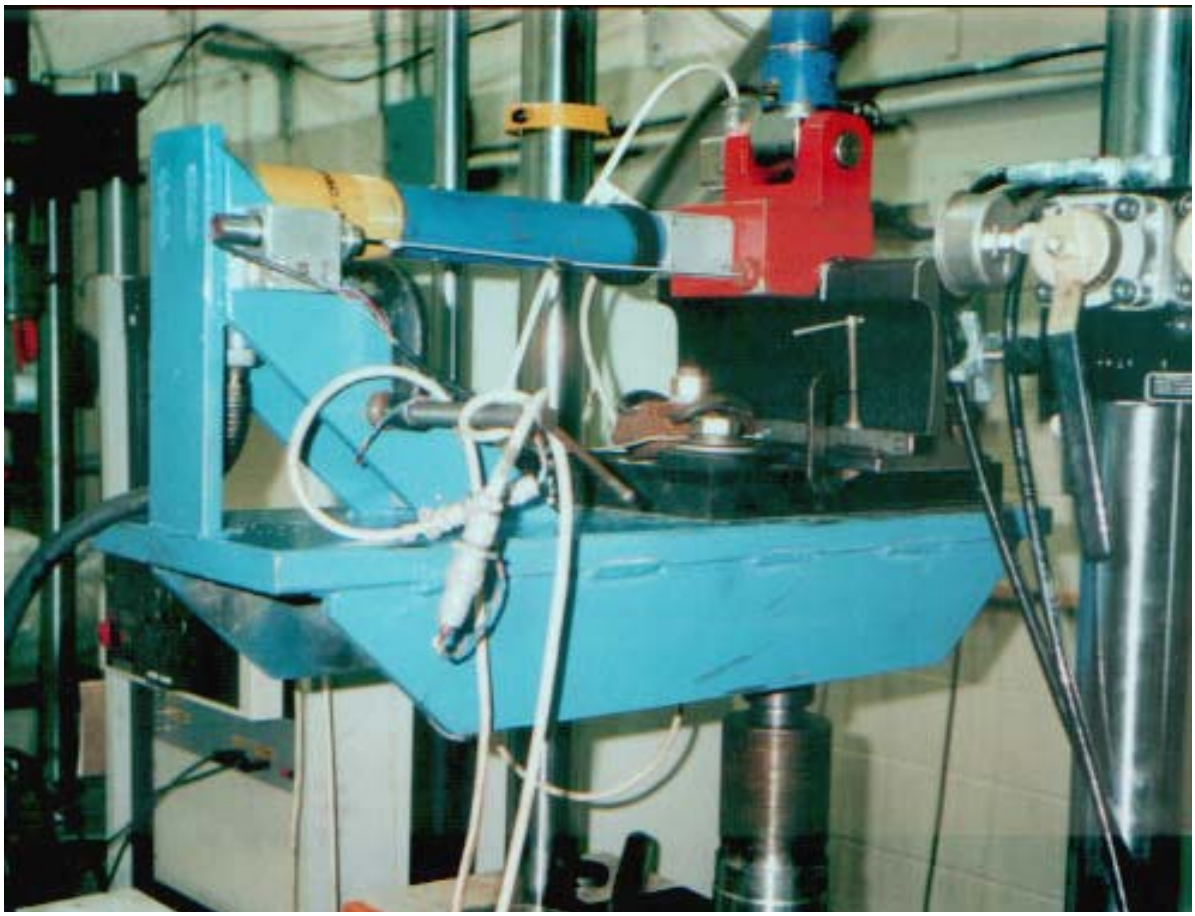


Figure 3-1. Angle view of fastener stiffness test setup

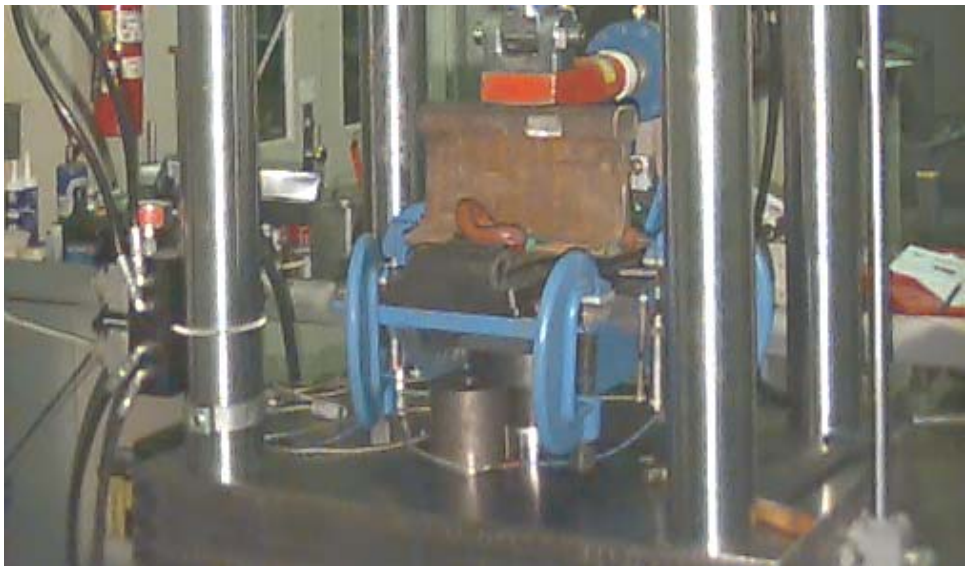


Figure 3-2. Overall view of fastener stiffness test setup

A total of 16 different DF fasteners and several embedded block components were examined in detail. These fasteners represent nine different DF systems. These are listed in Table 3-1 and pictured in Figure 3-3. There are no particular preferences to this selection except availability and an attempt to include DF fasteners of each major type. These samples are representative of the majority of DF fastener designs on the market.

Table 3-1. Single fastener test matrix

Fastener Name	Number Tested–Designation
Frame Fastener 1	5–A, B, C, D, E
Frame Fastener 2	3–F, G, H
Frame Fastener 3	3–I, J, K
Bonded Plate 3	1–L
Bonded Plate 2	1–M
Bonded Plate 1	1–N
Unbonded Plate–2 pad	1–O
Unbonded Plate–3 pad	1–P
Embedded Block	2- as components only Q, R
Bonded Plate 4	2–Past test data

Values represented in the study were representative to give a range of nominal values of components in use today. They are not to be considered as recommendations for use.

3.2.1 Quasi-Static Vertical Loading

Each set of tests started when the fastener was loaded with a vertical load in load control[6] at a rate of 1 minute to maximum load. Each fastener was loaded in load control 5 times with maximum loads of 44.5 kN (10 kip), 89.0 kN (20 kip), 133.4 kN (30 kip), 177.9 kN (40 kip) and 222.4 kN (50 kip). The load was maintained on the specimen for 30 seconds, and then the load was removed at the same rate that it was applied. This slow rate of application was necessary to achieve a true "quasi-static" stiffness. If the load rate was increased, it began to alter the stiffness measurement. The results for the first fastener, Frame Fastener 1A are shown in Figure 3-4. The results for the remainder of the Frame Fastener 1 samples are very similar in characteristics, although there is significant difference in the values. In addition, the basic characteristics of each type fastener are different. Some are linear; some have a more pronounced non-linear stiffening characteristic. In addition the variance between fasteners of the same type at a given load may vary 20% or more. The raw data results for each can be found in Appendix D. A summary of the vertical stiffness results for each of the fasteners is shown below in Table 3-2.

[6] "Load control" means that force feedback is used to control the test system. Alternative test controls could be "deflection control" or other parameter.

Figure 3-3. Views of several representative fasteners

Table 3-2. Quasi-static vertical fastener stiffness results[7]

Fastener	Quasi-Static Fastener Stiffness, kN/mm		
	44.8 kN (10 kip)	88.9 kN (20 kip)	133.4 kN (30 kip)
Frame Fastener 1A	24.6	74.9	151.8
Frame Fastener 1B	23.9	79.3	177.1
Frame Fastener 1C	23.3	80.5	152.9
Frame Fastener 1D	24.1	92.4	154.0
Frame Fastener 1E	26.3	81.8	132.8
Frame Fastener 2F	12.2	29.3	66.2
Frame Fastener 2G	13.5	24.7	53.1
Frame Fastener 2H	12.4	26.4	60.4
Frame Fastener 3I	22.1	31.8	50.2
Frame Fastener 3J	27.8	33.6	48.5
Frame Fastener 3K	27.0	32.1	48.2
Bonded Plate 3 L	48.9	59.0	81.4
Bonded Plate 2M	29.8	35.0	48.5
Bonded Plate 1N	24.9	30.6	43.7
UnBonded Plate-2 pad O	5.8	19.6	42.7
UnBonded Plate-3 pad P	9.3	42.5	78.9

[7] Stiffness is defined as the tangent slope to the load-deflection curve at the stated load (i.e. 44.8 kN, 88.9 kN, 133.4 kN). This stiffness is called the "tangent stiffness" to differentiate it from other methods of characterizing stiffness.

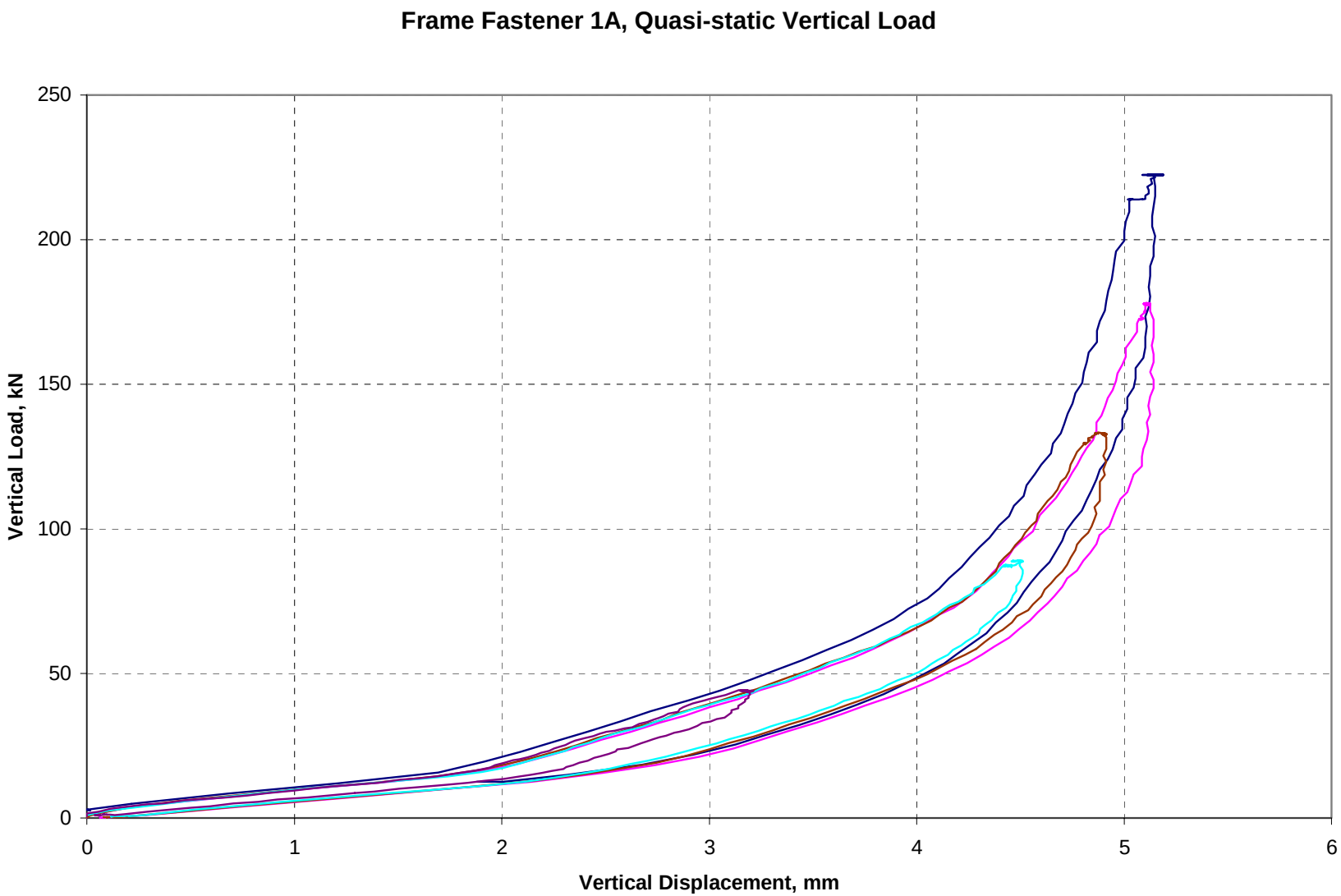


Figure 3-4 Frame fastener 1A Railhead Vertical Displacement Versus Quasi-Static Vertical Load

3.2.2 Lateral Load Test

There were several objectives to this test. The first objective of this activity was to experimentally determine the lateral static stiffness for a rail and fastener combination. Secondly the test would allow determination of the loads experienced by elastic rail clips in transit service and identify any limits that might be encountered by monitoring the rail clip deflection and setting a maximum allowed deflection criteria. Third, the tests were designed to evaluate the permanent deformation of elastic clips after a series of lateral loading events.

3.2.2.1 Lateral Load Procedure

The task first reviewed documented rail loads (principally L/V ratios) as part of an effort to define general design parameters. A maximum L/V of 0.8 was defined because this is the maximum nominal L/V used for design studies, and it is also the typical lower Nadal derailment limit. Because the example evaluation is a design study for mixed passenger and heavy freight, vertical loads up to 50 kips were evaluated. A single fastener does not encounter this load except under wheel impact, but the evaluation was looking for design and failure limits. Single fastener tests were performed using the fasteners listed in Table 3.1. Test loads were programmed to sweep from innocuous loading through a rail rollover (deflection) limited value (required by the inherent test configuration but intended to test extreme values of loading occurring in service). A maximum rail clip deflection limit of 0.1 inch was also implemented to prevent failure of a set of rail clips on every load cycle.

The test loads and unloads the rail laterally for each vertical incremental load value, measuring load and deflection continuously as each load increment is loaded and unloaded. The results are presented as plots of vertical load versus deflection, lateral railhead deflection versus load, lateral rail base deflection versus load, rail rotation versus load, and vertical displacement versus dynamic vertical load. The plotted results are presented in Appendix D for a total of 16 different fasteners. In a number of the cases, rail clip deflections were limited to 0.10 inch to prevent destruction of the retaining clips on each load cycle. A sample plot of lateral railhead deflection versus load is shown in Figure 3.5. This plot illustrates that vertical load has an effect on lateral stiffness. In a like manner the deflection of the rail base is also measured and an example is shown in Figure 3-6. Measured rail rotation is of up to three degrees, a value that will affect the location of the wheel-rail contact point.

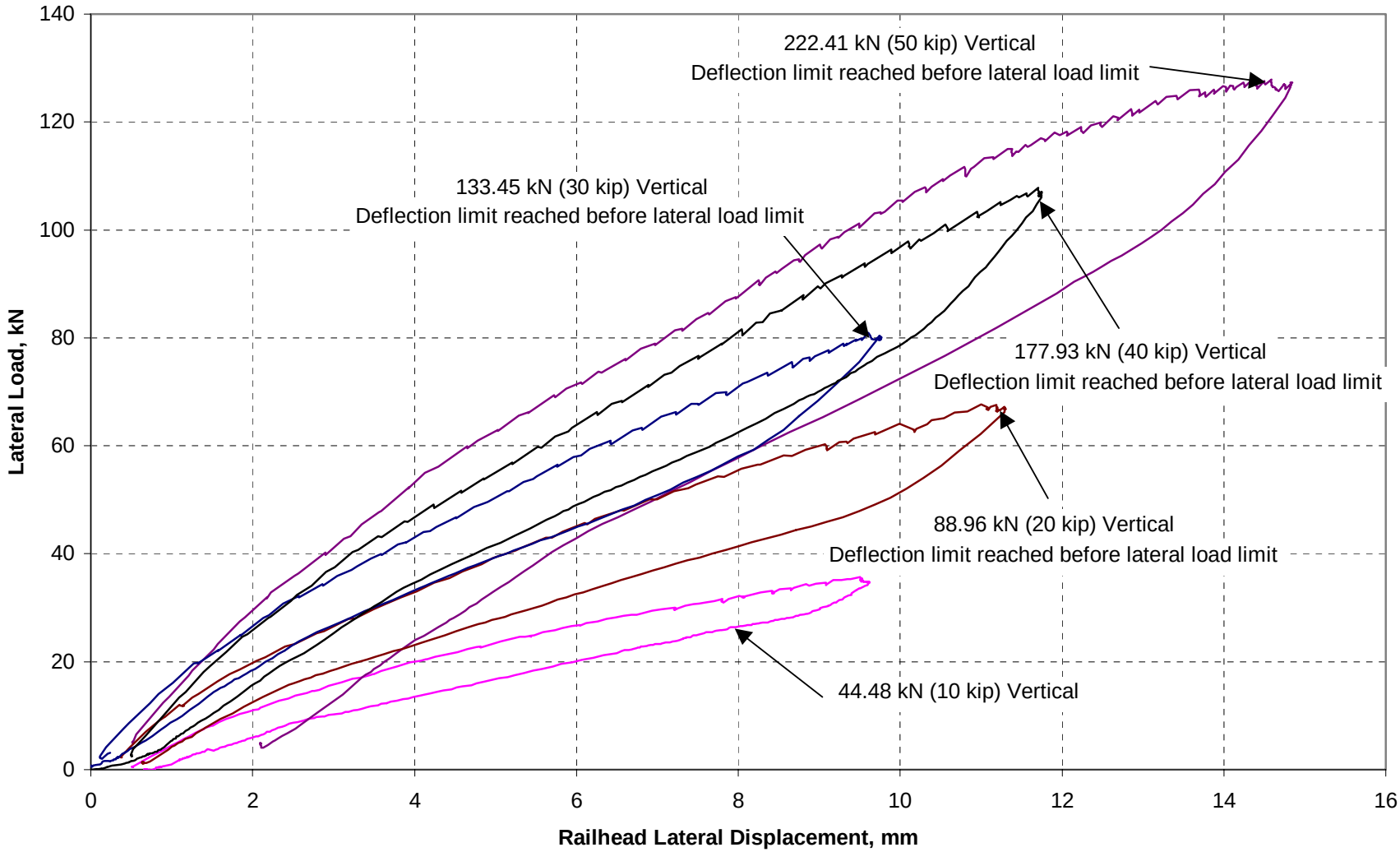


Figure 3-5 Frame fastener 1A Railhead Lateral Displacement Versus Quasi-Static Vertical and Lateral Load

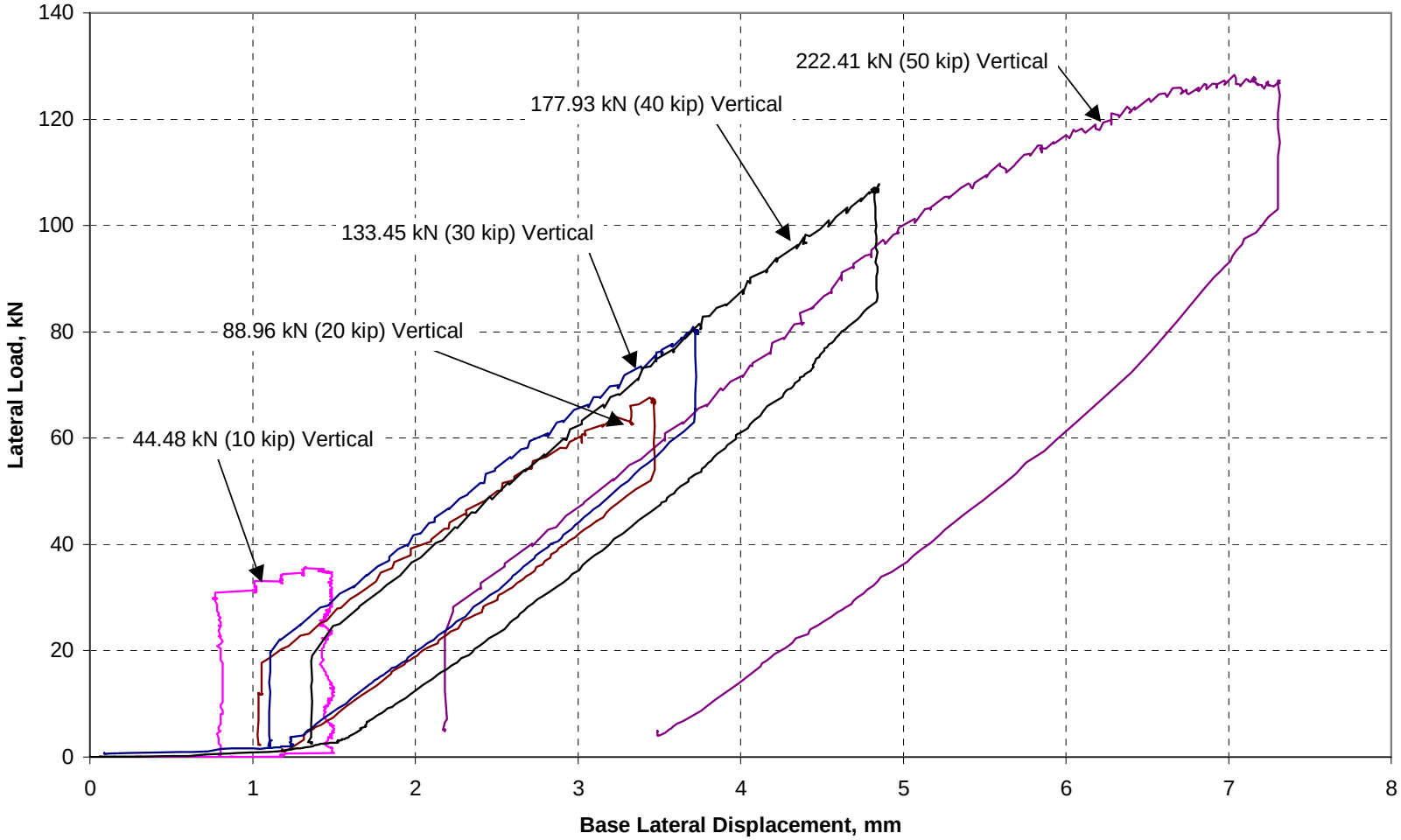


Figure 3-6 Frame fastener 1A Railbase Lateral Displacement Versus Quasi-Static Vertical and Lateral Load

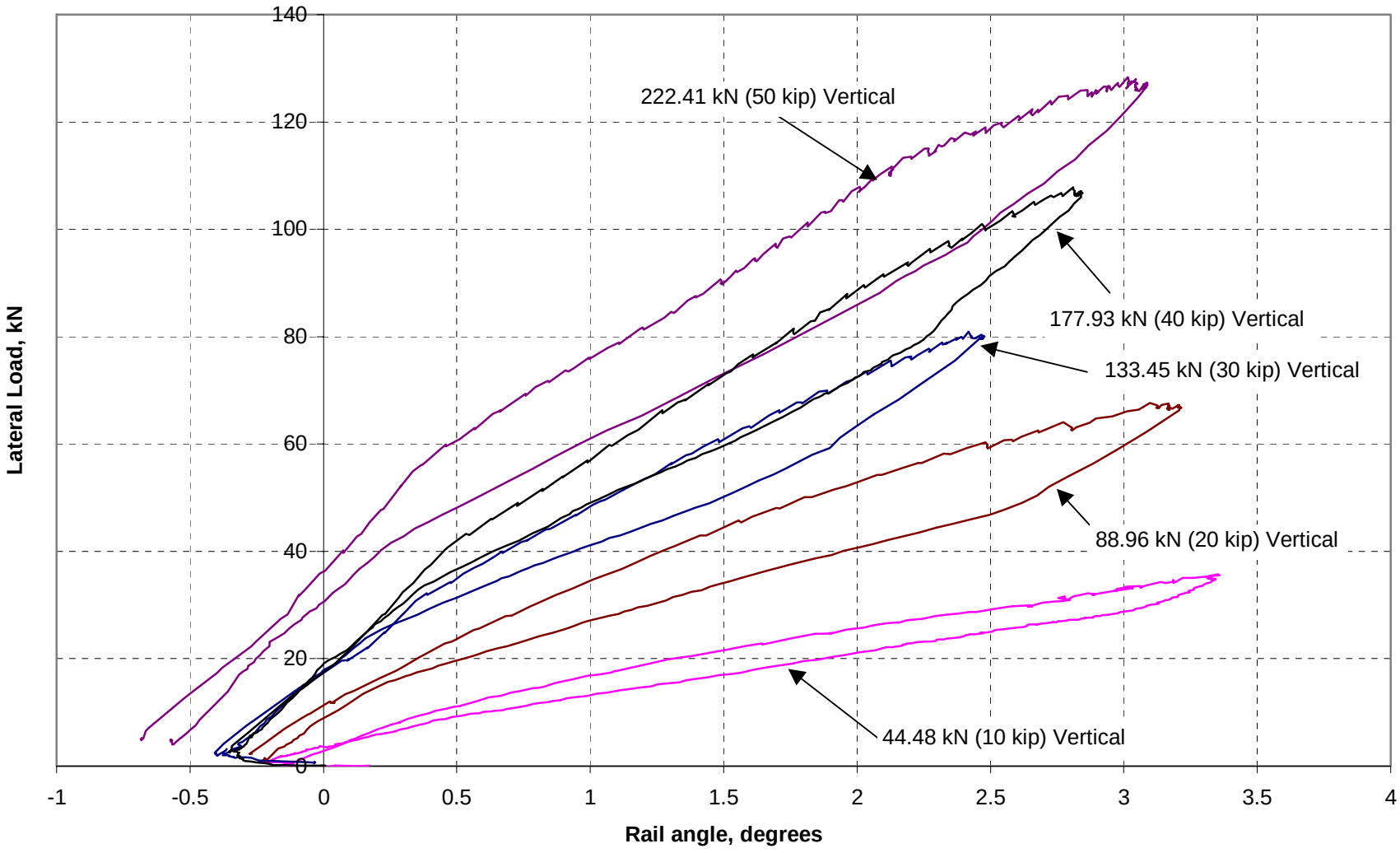


Figure 3-7 Frame fastener 1A Rail Rotation Angle Versus Quasi-Static Vertical and Lateral Load

3.2.3 Toe Load Testing

The rail clip toe load was measured on each test setup as a part of the pre-test documentation. This measurement was made prior to performing any of the static tests. A post test measurement was made for several sets where the rail clips were not destroyed during testing.

The rail clip toe load was determined by vertically unloading the rail clip and measuring the force. The toe load was measured for each clip of the fastener. The results were averaged for each fastener. To begin the testing, a shim was placed between the rail clip toe and the rail. A clamp grasped the toe of the rail clip and a jackscrew applied the vertical load while a force transducer measured the tension load. As the toe load was reduced to zero, the shim was removed. The load and time were recorded on a computer data acquisition system. The testing was completed a minimum of four times with each toe and the values were averaged. Figure 3-8 shows one complete loading cycle.

Table 3-3 shows the average toe load for the rail clips. All fasteners used a common elastic rail clip.

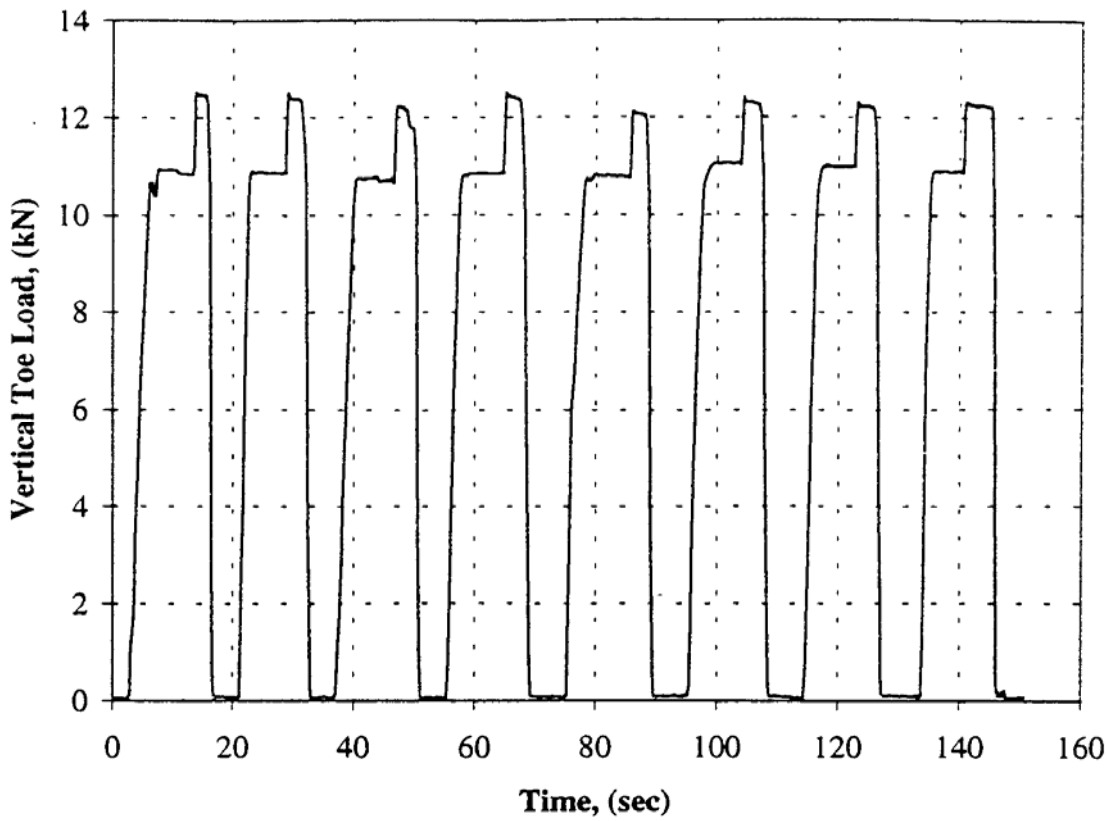


Figure 3-8. One completed toe load test cycle

Table 3-3. Baseline average toe load for Frame Fastener 1 series

Fastener	Average Toe Load kN (kips)
Fastener A - Clip A	10.3 (2.3)
Fastener A - Clip B	9.7 (2.2)
Fastener B - Clip A	10.9 (2.4)
Fastener B - Clip B	10.3 (2.3)
Fastener C - Clip A	10.9 (2.4)
Fastener C - Clip B	10.0 (2.3)
Fastener D - Clip A	9.9 (2.2)
Fastener D - Clip B	11.1 (2.5)
Average	10.5 (2.4)

3.3 Static Fastener Test Results

Examination of the test data presented in the section above, and in Appendix D, lead to a number of observations and conclusions. Some of the more salient are:

- Fasteners are available in a wide range of vertical stiffnesses and the stiffness may be tailored.
- The linearity and characteristics of various fastener designs are different. To some extent the designs are tailored to address different design issues and performance characteristics and envelopes.
- The vertical stiffness of a fastener is dependant upon the load it carries.
- The lateral stiffness of a fastener is dependant upon both the vertical and lateral load it carries.
- The variability of fastener stiffness from fastener to fastener of the same type may be greater than the difference between different types with the same “spec”.
- Vertical loads play an important part in restraining a rail against lateral loads and preventing the failure of spring type rail clips.
- Properly installed spring clips provide the spring toe load as designed, but the clips are susceptible to overloading due to lateral loads. Once overloaded, the clip may lose all functionality.

3.4 Characterization of Components, Force vs. Deflection

In this series of tests, each component of two track forms[8] selected for the fatigue evaluation of Section 8 was subjected to individual force vs. deflection characterizations. These tests were performed on up to five different samples of each test article.

3.4.1 Pad Stiffness Test Matrix

Table 3-4 shows the test matrix for the quasi-static and dynamic stiffness characterization for the embedded block rail pads, microcellular pads and boots.

Table 3-4. Number of railroad boot and pad experiments

Test Article	Quasi-Static		Dynamic			
	600 sec	Repeatability	1 Hz	5 Hz	10 Hz	20 Hz
Microcellular Pad	3	1	2	2	2	2
Embedded Block Rail Pad 1	3	1	2	2	2	2
Rail Pad 3-7031	2	1	2	2	2	2
Boot Sidewall	2	2	2	2	2	2
Boot End	2	2	2	2	2	2
Boot Bottom	3	1	2	2	2	2
Boot Bottom + Block Pad	3	1	2	2	2	2
Totals	21	12	17	17	17	17

3.4.2 Quasi-Static 600 Second Test

These tests were quasi-static load-controlled experiments. Each pad was centered between two platens in the 222 kN (50 kip) servo hydraulic test machine, and the load was increased using a ramp waveform to a maximum load of 222 kN (50 kip) in 600 seconds. The load was then held for 30 seconds and then returned to zero. Figure 3-9 shows a photograph of the experimental setup.

To eliminate excessive bending loads on the test fixture, the ends and sidewalls of the boots were removed from the boot and tested individually. Figure 3-10 shows an example of the load deflection behavior for the embedded block microcellular pad. The plots for the remainder of the component experiments can be found in Appendix E.

For these experiments, the tangent stiffness for each of the specimens was calculated at loads of 22.2 kN (5kip), 44.5 kN (10kip), 89.0 kN (20kip), and 133.4 kN (30 kip). Table 3-5 shows the measured tangent stiffness for each specimen.

[8] The track form is embedded dual block ties. The articles tested are rubber boots, and block pads (also "microcellular pad") between the concrete blocks and the support concrete, and pads between the rail and the concrete block.

Figure 3-9. Photograph of embedded block system component test setup

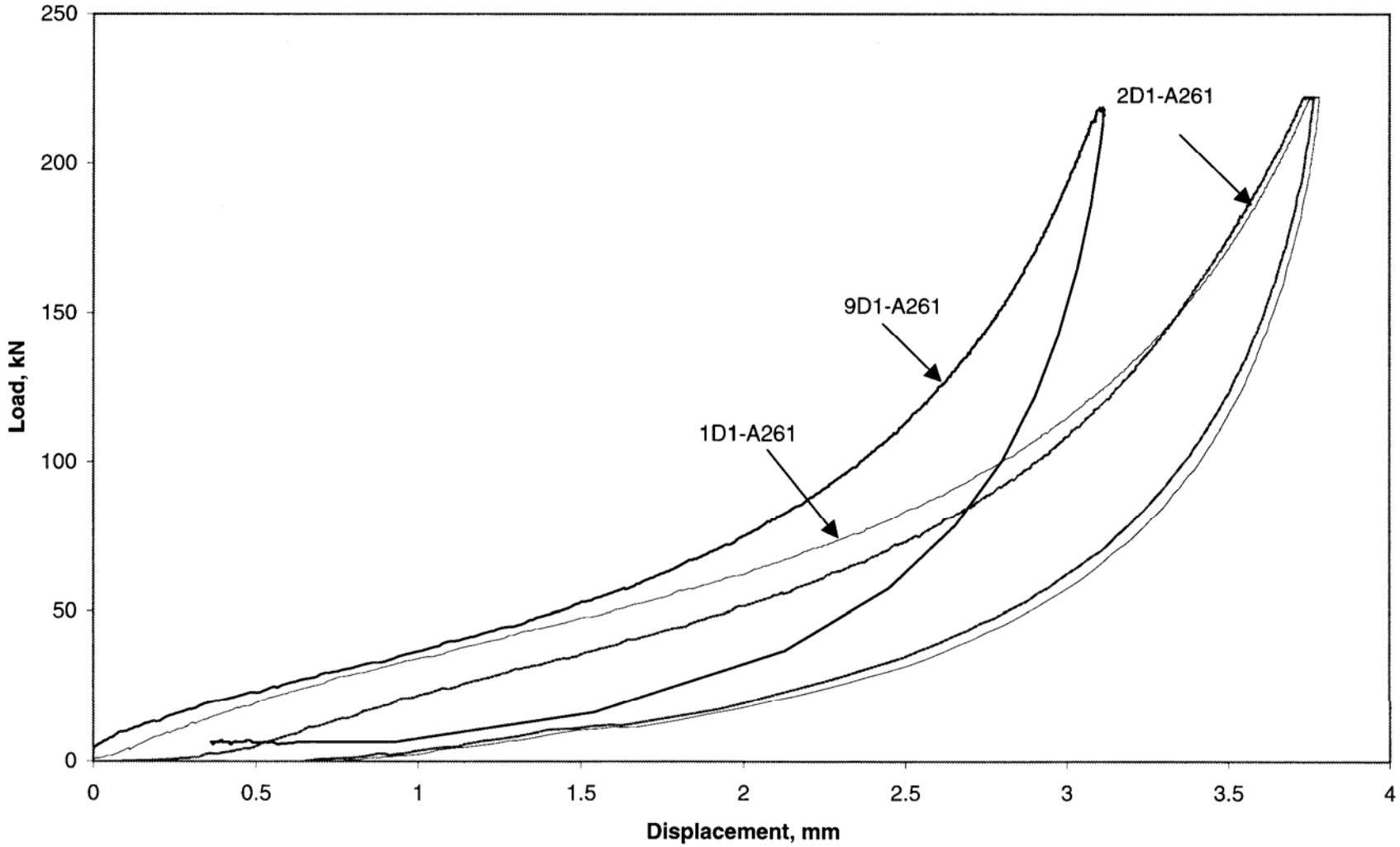


Figure 3-10. Embedded block pad quasi-static load deflection behavior

Table 3-5. Quasi-static tangent stiffness results

Specimen Type	Specimen Number	Tangent Stiffness, kN/mm			
		22.2 kN (5 kip)	44.5 kN (10 kip)	89.0 kN (20 kip)	133.4 kN (30 kip)
Microcellular Pad	1D1-A261	31.4	29.70	71.1	136.0
	9D1-A261	26.8	24.6	52.0	101.3
	2D1-A261	28.6	29.6	60.4	131.5
Embedded Block Rail Pad 1	1D1-A262	216.9	494.4	717.2	717.2
	9D1-A262	147.8	463.0	546.9	546.8
	2D1-A262	237.0	364.2	448.7	405.1
Rail Pad 3	7031A	29.6	74.3	78.0	98.2
	7031B	29.6	68.3	78.0	98.2
Boot Sidewall	1D1-A263A	111.2	111.8	115.1	145.0
	1D1-A263B	94.1	101.5	113.8	158.3
Boot Endwall	1D1-A264A	118.4	123.2	598.2	598.0
	1D1-A264B	93.4	93.4	274.6	2294.5
Boot Bottom	1D1-A265	374.0	567.7	567.7	567.7
	9D1-A265	338.2	516.3	516.3	516.3
	2D1-A265	269.0	565.5	639.0	639.0
Boot Block Pad	1D1-A266	24.7	31.4	70.6	128.9
	9D1-A266	26.7	35.7	71.0	125.0
	2D1-A266	23.1	31.1	66.2	117.2

3.4.3 Repeatability

These experiments were very similar to the 600-second tests except the load was increased to 222 kN in 60 seconds, held for 30 seconds, and unloaded in 60 seconds. This process was repeated for each specimen three times without removing the specimen or any instrumentation. An example of the load-displacement behavior of the embedded block pad is shown in Figure 3-11. The repeatability figures for each experiment can be found in Appendix F. The figures show that the results are consistent between loadings.

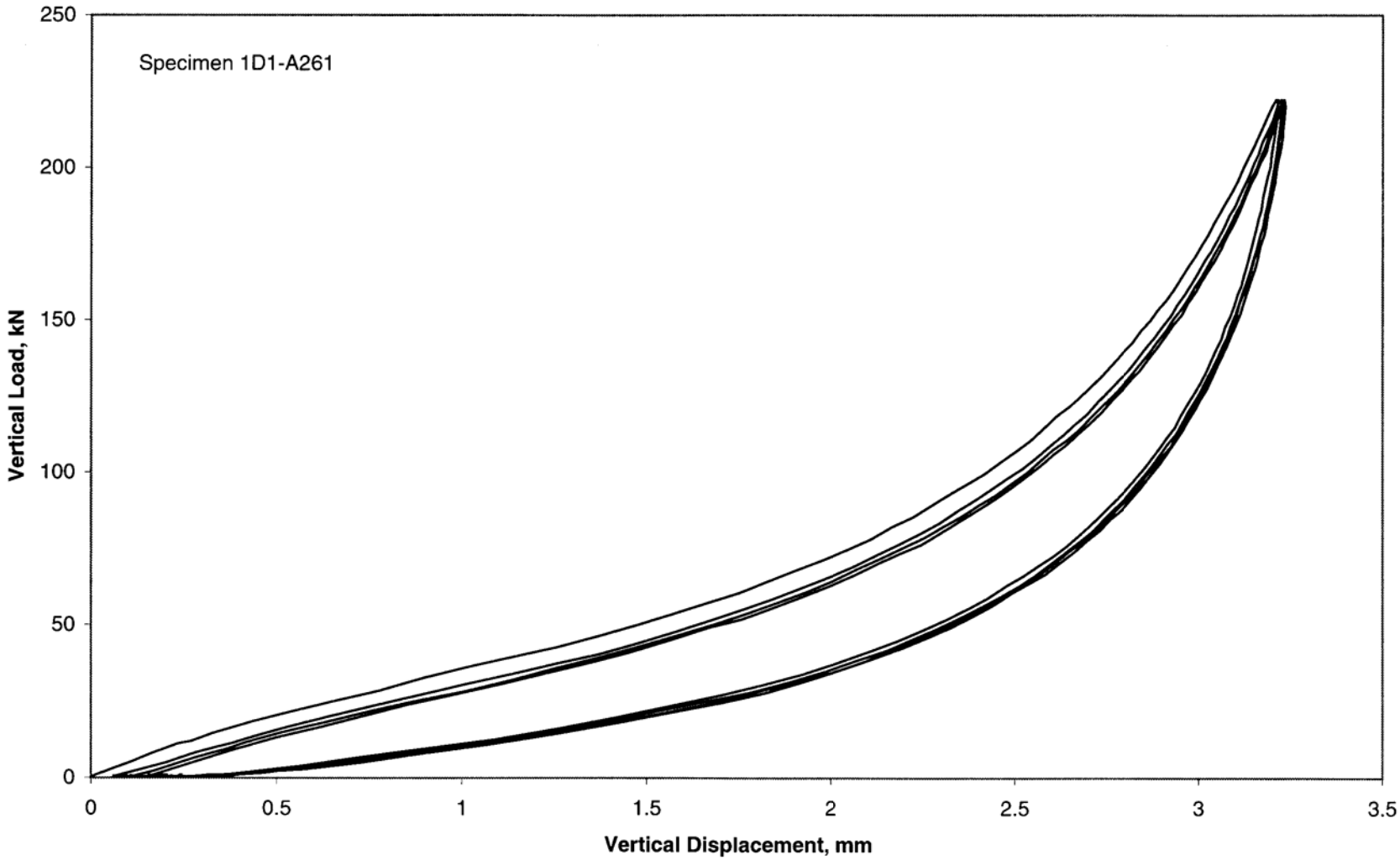


Figure 3-11. Embedded block pad repeatability behavior

3.5 Component Static Stiffness Test Results

Examination of the test data presented in the section above, and in Appendix E, F, and G lead to a number of observations and conclusions. Some of the more salient are:

- Fastener components are available in a wide range of stiffnesses and the stiffness may be tailored.
- The linearity and characteristics of various fastener components are different. To some extent the designs are tailored to address different design issues and performance characteristics and envelopes.
- By examining individual components it is possible to calculate the stiffness and therefore the performance of the assembled system, to some degree, depending on the geometry and other factors.
- The repeatability of assembled fastener systems will represent the sum of the variation of the individual components. With more components, more variability in the performance will be encountered and consistency against test behavior will be diminished.

4. Critical Assessment of Fastener Dynamic Stiffness and Fastener Transfer Function Testing

4.1 Fastener Dynamic Stiffness

The objective of this research activity is to determine the dynamic stiffness of selected DF fasteners and to determine the effectiveness of Direct Fixation fasteners in mitigating vibration frequency through transfer function testing of fasteners. Vibrations of interest are in two frequency ranges. The first range is sub-audible ground borne vibrations due to the wheel pass frequency, typically 1-15 Hz. The second is audible noise due to rail vibrations induced by rolling contact and surface roughness, typically 20 to 1000 Hz. The first frequency range is best determined using conventional hydraulic test methods, while the second is better suited to test with electro-dynamic shaker testing.

4.1.1 Dynamic Vertical Stiffness for Complete Fastener

After the completion of the quasi-static tests in Section 3 a series of dynamic tests were run for each fastener. In these tests the servo-hydraulic capability of the MTS testing frame was used to apply a cyclic dynamic load overlay to the basic vertical load. The final series of dynamic tests were designed to fully characterize the performance of the fasteners for events and loading in the frequency range corresponding to wheel passage. Dynamic single fastener tests were completed using the 50 kip (222 kN) MTS load frame with the same test set-up as for the vertical stiffness measurements. These tests were performed in a manner similar to the vertical stiffness measurements except that an added dynamic component was added to the load. The load response was mapped for a four different loading frequencies to enable calculation of the static to dynamic stiffness ratio.

In these experiments, the vertical load was cycled without the presence of the lateral load. Each fastener was tested at vertical loads of 44.5 ± 22.2 kN, 89.0 ± 44.5 kN, and 133.4 ± 44.5 kN, and at frequencies of 1, 5, 10, and 20 Hz. Each experiment consisted of 25 cycles. A plot showing an example of the dynamic vertical load experiments can be seen in Figure 3-9. The remainder of the raw data plots is available in Appendix D. A summary of the static fastener stiffness was given in Table 3-2 and the dynamic fastener stiffness for each of the fasteners tested is given in Table 4-1. For each of the experiments conducted, a tangent stiffness was measured at load levels of 44.8 kN (10 kip), 88.9 kN (20 kip), and 133.4 kN (30 kip).

Table 4-1 shows the dynamic fastener stiffness while Table 4-2 shows the dynamic-to-quasi-static fastener stiffness ratio for the various fasteners. Note that the increased scatter between the duplicate experiments at the higher mean loads is due to the low signal-to-noise ratio in the displacement transducers at the high mean loads. This problem makes the selection of the tangent stiffness difficult and increases the scatter in the results.

Table 4-1. Dynamic fastener stiffness

Fastener	Dynamic Fastener Stiffness, kN/mm											
	44.8 kN (10 kip) Mean Load				88.9 kN (20 kip) Mean Load				133.4kN (30 kip) Mean Load			
	1 Hz	5 Hz	10 Hz	20 Hz	1 Hz	5 Hz	10 Hz	20 Hz	1 Hz	5 Hz	10 Hz	20 Hz
Frame fastener 1A	34.8	34.8	37.5	45.2	143.4	143.4	143.4	143.4	416.5	416.5	416.5	416.5
Frame fastener 1B	31.3	31.7	30.8	29.1	133.6	133.5	132.6	116.9	270.3	290.7	290.7	290.7
Frame fastener 1C	28.4	45.8	52.2	77.2	100.0	169.8	206.2	287.3	471.7	526.0	526.0	579.3
Frame fastener 1D	28.5	35.8	37.0	59.3	135.6	161.3	161.3	320.0	600.5	600.5	600.5	600.5
Frame fastener 3I	34.4	34.4	35.4	34.4	44.2	48.2	48.2	47.8	77.1	77.5	77.5	81.7
Frame fastener 3J	31.0	30.5	33.8	50.8	41.0	50.5	50.5	66.8				
Frame fastener 3K	30.0	30.5	31.1	32.2	43.7	49.9	51.2	51.2	89.4	91.0	93.1	93.1
Bonded plate 3L	57.1	57.1	57.1	57.1	76.2	76.2	76.2	76.2	104	104	104	104
Bonded plate 2M	44	44	44	44	50	50	50	50	71.4	71.4	71.4	71.4
Bonded plate 1N	33	33	33	33	40	40	40	40	56.7	56.7	56.7	56.7
Unbonded plate-2pad O	12	12	12	12	41.3	41.3	41.3	41.3	75.8	75.8	75.8	75.8
Unbonded plate-3pad P	20.4	20.4	20.4	20.4	78	78	78	78	–	–	–	–

Table 4-2. Fastener dynamic-to-quasi-static stiffness ratio

Fastener	Dynamic/Quasi-Static fastener stiffness ratio											
	44.8 kN (10 kip) Mean Load				88.9 kN (20 kip) Mean Load				133.4kN (30 kip) Mean Load			
	1 Hz	5 Hz	10 Hz	20 Hz	1 Hz	5 Hz	10 Hz	20 Hz	1 Hz	5 Hz	10 Hz	20 Hz
Frame fastener 1A	1.41	1.41	1.51	1.85	1.92	1.92	1.92	1.92	2.78	2.78	2.78	2.78
Frame fastener 1B	1.32	1.33	1.28	1.22	1.69	1.69	1.67	1.47	1.52	1.64	1.64	1.64
Frame fastener 1C	1.22	1.96	2.22	3.33	1.25	2.13	2.56	3.57	3.12	3.45	3.45	3.85
Frame fastener 1D	1.18	1.49	1.54	2.44	1.47	1.75	1.75	3.45	3.85	3.85	3.85	3.85
Frame fastener 1E	1.27	1.27	1.30	1.30	1.47	1.67	1.67	1.79	4.00	4.00	4.00	4.00
Frame fastener 2F	1.36	1.39	1.49	1.30	1.66	1.68	1.66	1.92	1.82	2.14	2.14	2.56
Frame fastener 2G	1.19	1.26	1.31	1.35	1.23	1.53	1.53	1.65	1.99	1.99	1.99	2.05
Frame fastener 2H	1.13	1.17	1.17	1.14	1.26	1.50	1.50	2.13	2.07	2.07	2.07	2.3
Frame fastener 3 K	1.24	1.24	1.27	1.24	1.32	1.43	1.43	1.42	1.59	1.6	1.6	1.68
Frame fastener 3 L	1.40	1.38	1.53	2.30	1.29	1.59	1.59	2.1	2.62	3.29	3.29	3.29
Frame fastener 3 K	1.11	1.13	1.13	1.15	1.62	1.55	1.59	1.59	1.85	1.89	1.93	1.93
Bonded plate 3L	1.17	1.17	1.17	1.17	1.29	1.29	1.29	1.29	1.28	1.28	1.28	1.28
Bonded plate 2M	1.48	1.48	1.48	1.48	1.43	1.43	1.43	1.43	1.47	1.47	1.47	1.47
Bonded plate 1N	1.33	1.33	1.33	1.33	1.31	1.31	1.31	1.31	1.30	1.30	1.30	1.30
Unbonded plate-2pad O	2.07	2.07	2.07	2.07	2.11	2.11	2.11	2.11	1.78	1.78	1.78	1.78
Unbonded plate-3pad P	2.19	2.19	2.19	2.19	1.84	1.84	1.84	1.84	–	–	–	–

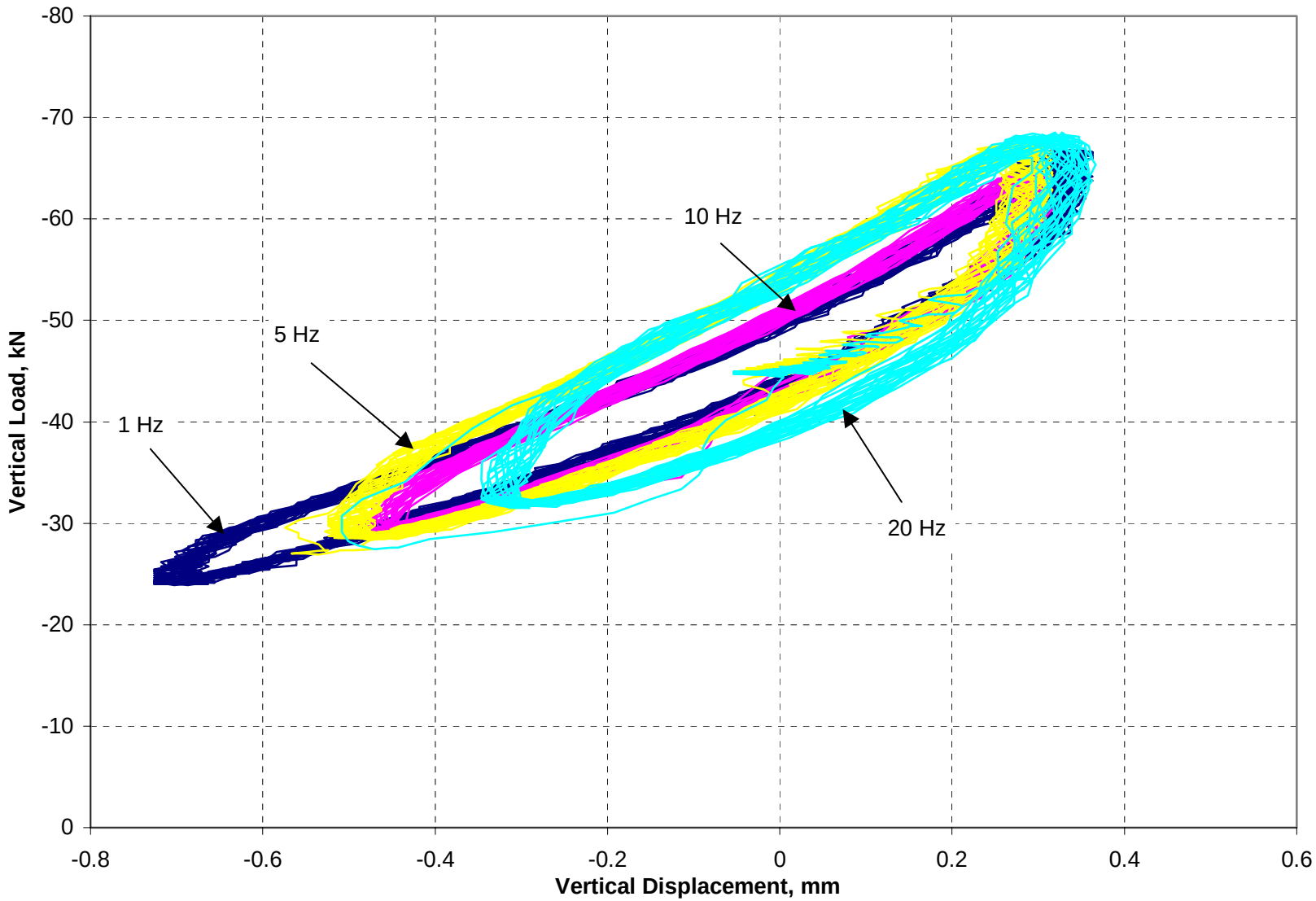


Figure 4-1 Frame fastener 1A Vertical Displacement Versus Dynamic Vertical Load

The repeatability of the results in Table 4-2 shows a dependency on the vertical load, especially for those fasteners which are designed to be non-linear in their characteristics (Frame fastener 1 as an example). Tables 4-1 and 4-2 seem to show some unexplained inconsistencies between the duplicate Frame fastener 1 fasteners. First, in some cases the dynamic stiffness appears to be independent of frequency. However, in the case of the Frame fastener 1C, the dynamic stiffness is highly dependent on frequency at both the 44.8 kN and 88.9 kN mean loads. Also, the range of the data between fasteners is relatively large. For instance, at 20 Hz the stiffness ratio range between 1.22 and 3.33 for a 44.8 kN mean load and between 1.64 and 4.00 for a 133.4 kN mean load. It is possible that the differences lie in the variability in the components of the fastener and the dimensional tolerances of the fastener. In addition, if the setup and assembly of the fasteners are not identical, differences in the results can occur due to seating effects.

4.1.2 Dynamic Stiffness of Components

These experiments were dynamic, cyclic experiments conducted with a mean load of 133.45 kN (30 kip) and an alternating load of ± 44.5 kN (10 kip). The setup and data acquired were identical to the other experiments. Only two of each specimen type were tested with these loads at frequencies of 1, 5, 10, and 20 Hz for a total of approximately 25 cycles per test per frequency. An example of the dynamic experimental results for the embedded block pad is shown in Figure 4-2.

The tangent stiffness for each dynamic experiment was calculated at the mean load and plotted as a function of frequency. Figure 4-3 shows an example of these data. The complete set of the data plots can be found in Appendix G. The summarized data from these plots can be found in Table 4-3.

Table 4-3. Dynamic stiffness at 133.4 kN (30 kip)

Test Article	Tangent stiffness at 133.4 kN (30 kip), kN/mm				
	QS	1 Hz	5 Hz	10 Hz	20 Hz
Microcellular Pad	136.0	345.4	340.7	369.5	304.6
		298.8	403.5	412.1	344.7
Rail Pad 1	717.2	1484.1	1716.9	1805.4	1805.4
		1787.0	1990.1	2109.9	2109.9
Bottom of Boot	567.73	2575.4	3304.3	3304.3	3019.4
		2968.2	3574.0	3574.0	2968.2
Boot Sidewall	145.0	358.1	443.4	465.8	453.7
		442.2	527.5	561.3	542. 2
Boot Endwall	598.2	1636.7	1636.7	1636.7	1278.3
Boot+Block Pad	128.9	326.1	393.5	427.1	465.7
		306.7	393.5	427.1	447.9

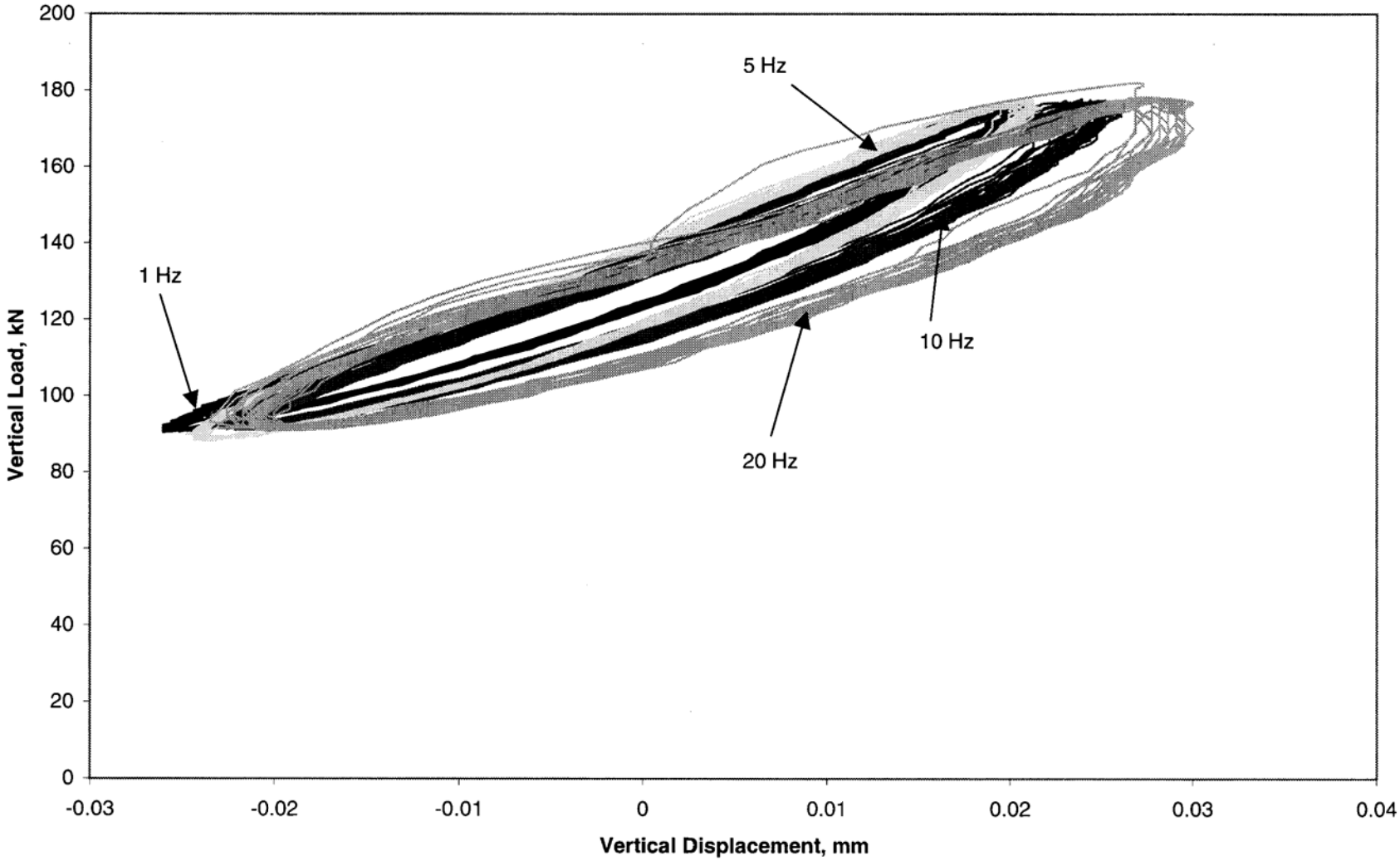


Figure 4-2. Embedded block pad dynamic load-deflection behavior

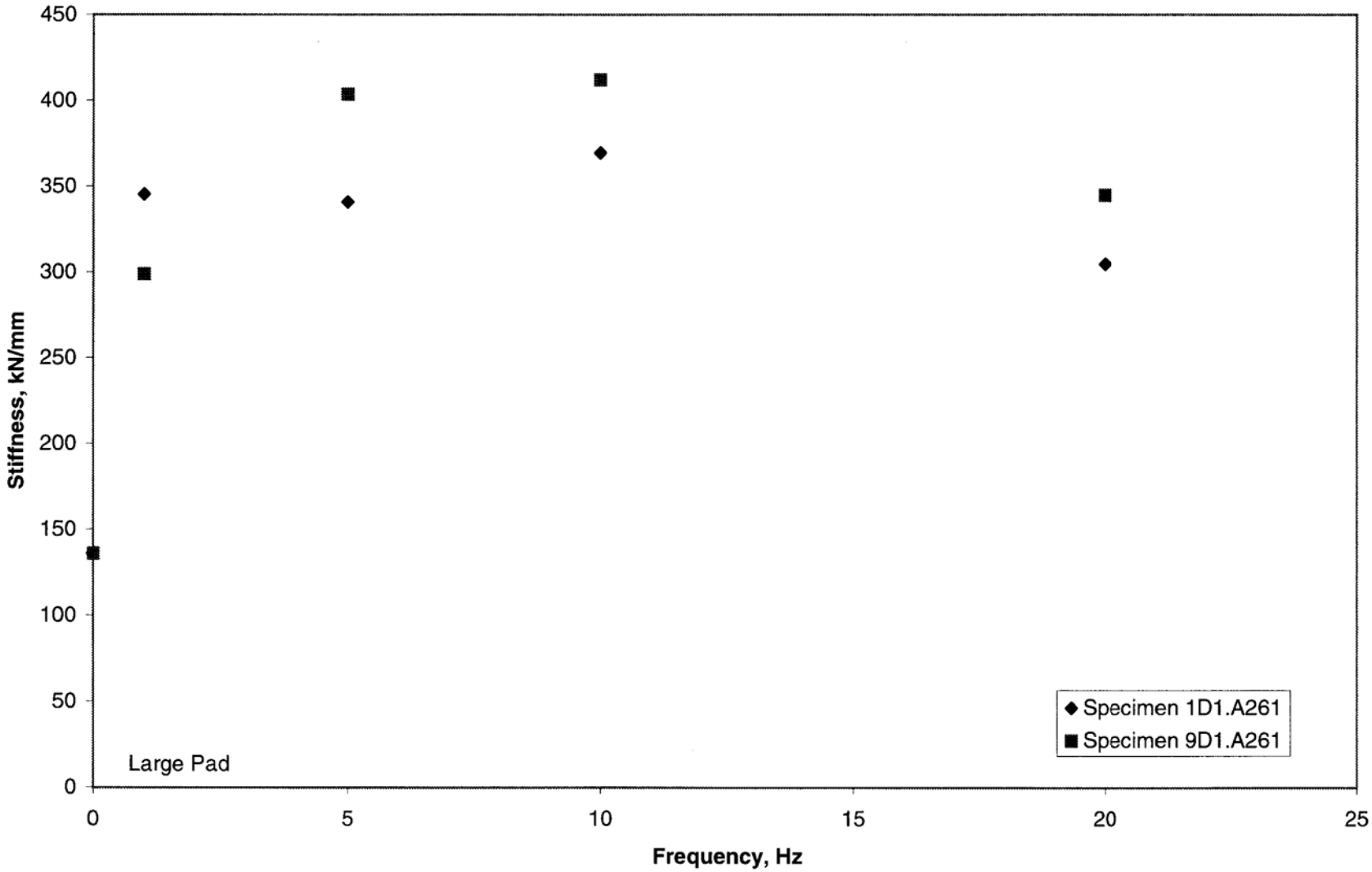


Figure 4-3. Block pad stiffness as a function of frequency

4.2 Fastener Transfer Functions

The objective of this activity was to measure the transfer function[9] of different DF fasteners in the laboratory to determine the potential of the fastener for attenuating ground-borne vibration frequencies. The testing included transfer function curves which also present the performance and attenuation of the low end of the noise spectrum.

4.2.1 Experimental Procedures

Calculations to determine the forcing frequency for various conditions were performed. In general, wheel pass frequencies fall between 4 and 15 Hz while surface roughness induced vibrations may reach several kilohertz. The primary interest in these tests was to determine the transfer function for the primary energy of wheel passing (between 1 and 15 Hz, depending on train speed). In order to include frequencies that are important to air borne acoustic vibrations the analysis will focus on frequencies between 1 and 1000 Hz. The transfer function describes how energy is attenuated across the fastener (loss of vibration amplitude) and whether there are any resonant responses across the frequencies of interest.

The issue of satisfying noise and vibration requirements is a major concern with any chosen track design. The selection of a direct fixation fastener will be strongly influenced by the ability of the fastener and track form to mitigate noise and vibration transmission to the supporting structure. The major fastener parameter at issue is the fastener transfer function with respect to vertical and lateral dynamic loads and vibrations. This parameter is not usually specified, but can be analytically derived based upon the fastener stiffness and mass. Previous work has been done using an impact loading approach to characterize the performance of various track components. A problem with this approach is that the track is not sufficiently pre-loaded prior to the loading impact. The non-linear nature of track and track structures leaves much room for error and uncertainty regarding the validity of this approach.

Battelle developed equipment necessary to measure track form transfer functions directly, under full wheel loads. This equipment was used previously to characterize rail seat pads under dynamic loading. Photographs of this equipment in vertical and lateral test configurations are shown in Figures 4-4 and 4-5, respectively.

The vertical configuration involves a softly sprung hydraulic cylinder to apply the static wheel loads, while dynamic loading is supplied in parallel by a 4,000 lb. (17.8 kn.) electrodynamic shaker. The dynamic loading is used to determine the transfer function for the fastener installed on the 3,000 lb. (13.3 kN.) reaction block by mounting a series of accelerometers on the rail, the intermediate block or base plate member, and the reaction block. To measure lateral transfer functions, the vertical hydraulic cylinder is used to maintain simulated wheel loading while the lateral dynamic excitation is applied with the electrodynamic shaker. These vertical and lateral tests are separate and require a reconfiguration of the test stand between each series of tests. A significant effort is required for each reconfiguration.

The Q system[10] was tested first vertically since it was already set up in the test system as a result of previous testing. The R embedded block track system was then tested vertically. The system was then reconfigured and the R embedded block was tested laterally. The R embedded block was then removed and a series of mounting inserts were cast into the reaction mass with high-strength concrete to allow testing of the various types of fasteners. All vertical runs were made and then the system reconfigured for

[9] Transfer function: In mechanical dynamics, the transfer function is the ratio of response motion at one end of a spring or spring-like component (such as elastomer) to motion applied at the other end of the component. The applied motion is varied over a range of frequencies. The results show the range of frequencies that the component will and will not filter applied the motion.

[10] Please refer to Table 4-4 for identification of the systems tested.

the lateral tests. Most of the effort in performing these tests is in the configuration of the test specimens. Different mounting methods, hold down anchor bolt patterns, and spacings require significant effort between tests to mount the different fasteners onto the reaction block. In the case of the second embedded block system, a retrofit and concrete recast was necessary. (Essentially the effort replicated the repair/replacement of a block in service.)

Five channels of instrumentation were used. In all cases, Channel 1 was used to measure the rail acceleration. Channel 2 was used to measure either the embedded block acceleration or the acceleration of the rail mounting plate of the plate and frame fasteners. Channel 3 was used to measure the acceleration of the 3,000 lb. (13.3 kn.) reaction mass. Channel 4 was used to measure the dynamic force input from the load cell between the shaker and the rail. The fifth channel was connected to a load cell and was used to measure the static force exerted by the hydraulic cylinder. It was also possible to measure the dynamic force in the cylinder as it was affected by the dynamic load. These channel designations are important when reviewing the data plots.

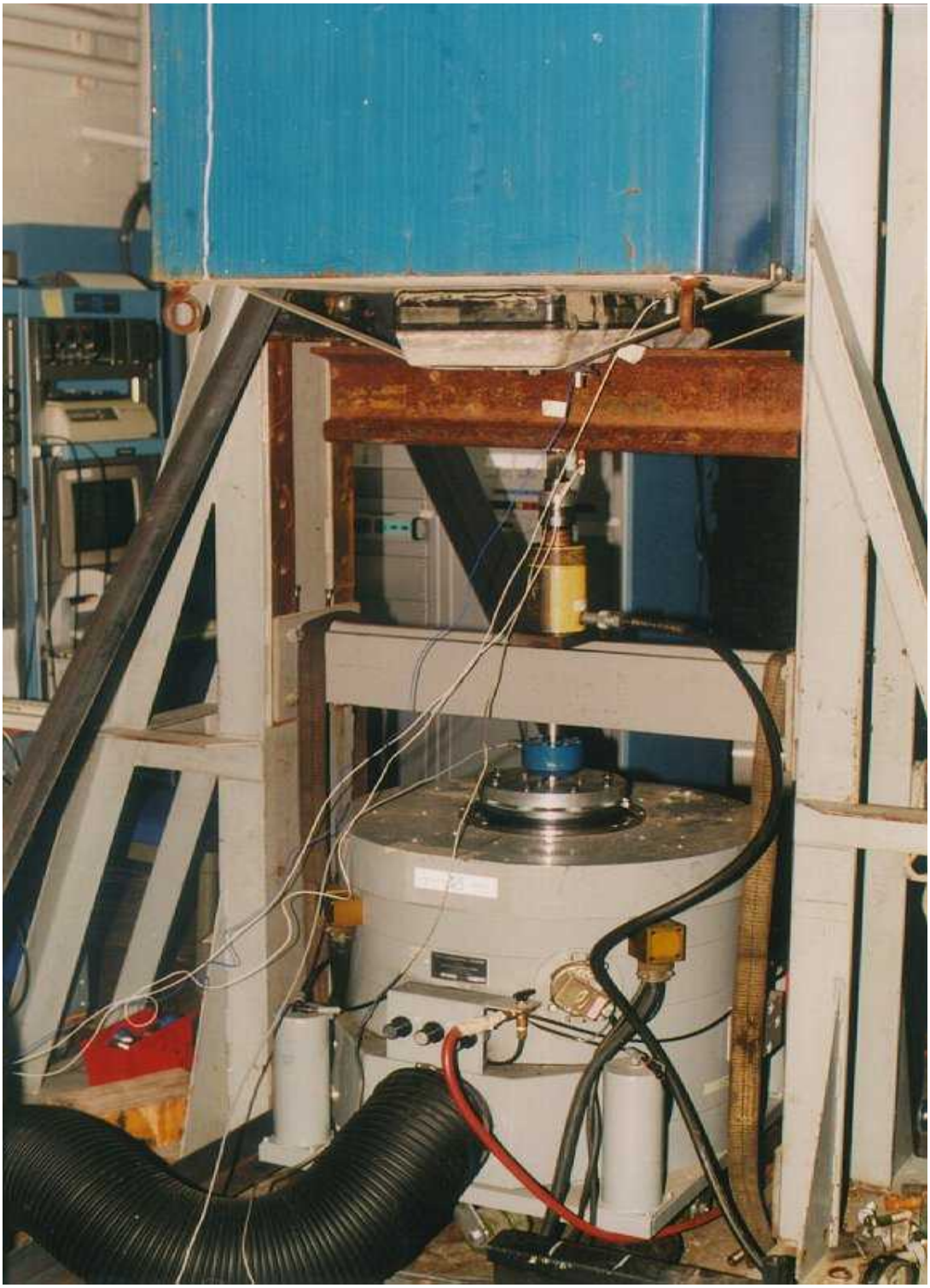


Figure 4-4. Transfer function test setup, vertical

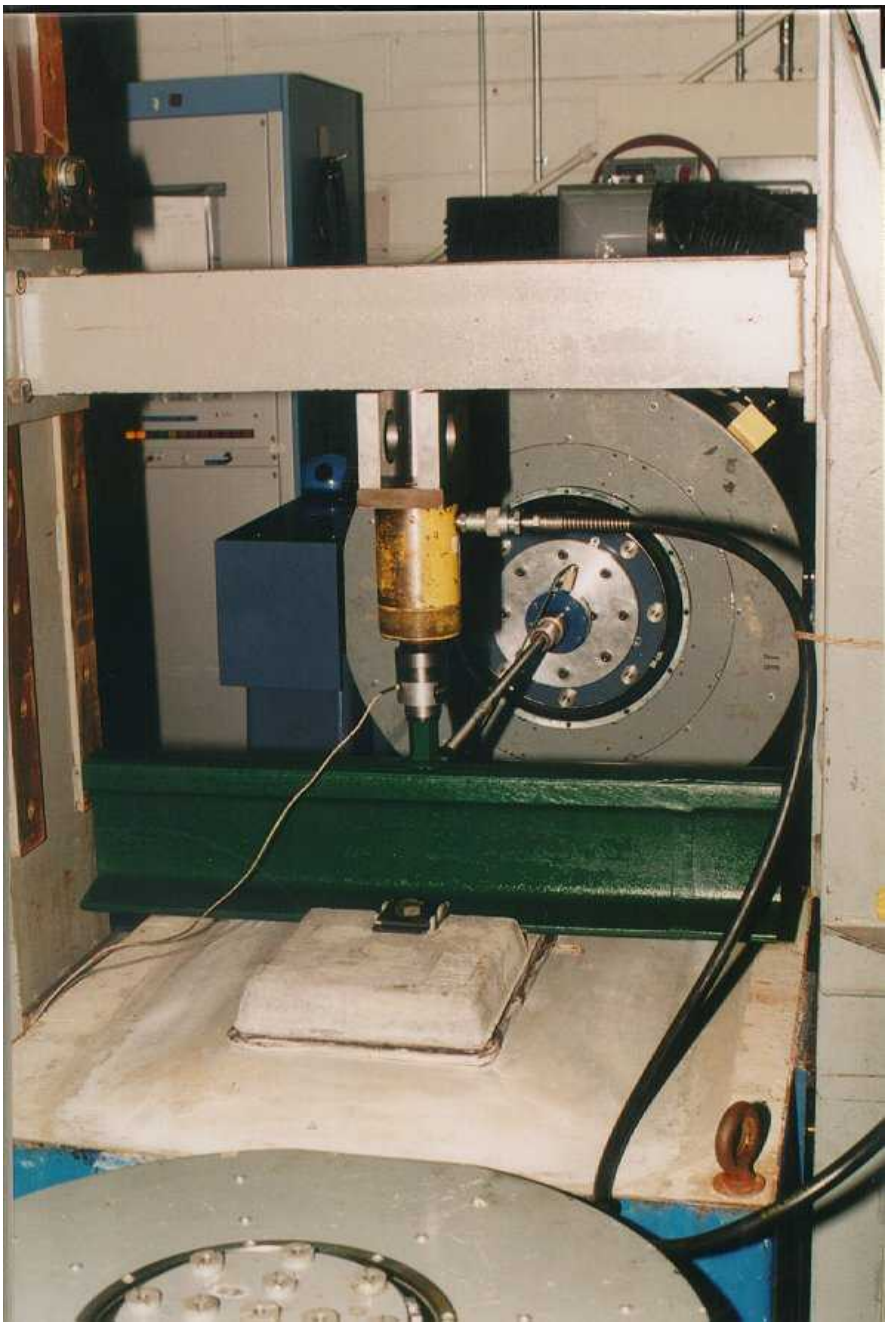


Figure 4-5. Transfer function test setup, lateral

Table 4-4. Fastener systems tested

Fastener Type	Use	Comments
Embedded block Q	Transit	Fastener originally cast in reaction block. Use as known baseline.
Embedded block R	Heavy Transit	Prototype dual stiffness boot used with existing embedded block design. Show effects of added mass between rail and invert. A test with double microcellular pads showed predicted decrease in natural frequency and transmission.
Frame fastener 1	Heavy Transit	A large dual stiffness design for passenger and heavy locomotive use.
Frame fastener 2	Transit	Soft fastener for noise reduction,
Unbonded plate with spring preload 2-pad O	Transit	Very soft fastener using microcellular pads and preload spring.
Unbonded plate with spring preload 3-pad P	Transit	Very soft fastener using microcellular pads and preload spring.

Testing was on the fasteners listed in Table 4-4 was performed using two methods. These are described below.

4.2.1.1 Method 1

A pseudo-random forcing function was used to drive the shakers to provide broadband excitation to the rail. A 500 lb. (2.22 kn.) rms. force was applied. A SD390 dynamic analyzer was used to capture the resultant accelerations and forces in the test system. These data were collected for each test system at several levels of vertical preloads. A minimal preload was tested first, followed by tests with vertical preloads of from 3,000 lb. to 18,000 lb., in 3,000 lb. increments (13.3 to 79.8 kN. in 13.3 kN. increments). Data were collected for each channel for each preload and stored. Example plots of data from the R embedded block tests are shown in Figures 4-6 to 4-12 for the lightly loaded case.

Data for a 9,000 lb. (40 kn.) preload are shown in Figures 4-13 to 4-18, and data for a 18,000 lb. (80 kN.) preload are shown in Figures 4-19 to 4-24. The data are very consistent between data sets except for a shift in frequency of the first resonant peak. This peak shifts with the vertical stiffness of the R embedded block system, from a low of 57 Hz to a high of just over 100 Hz (see Figures 4-9, 4-16, and 4-22). The frequency of the first resonant peak is associated with the mass of the rail, embedded block, and shaker armature oscillating vertically on the compliance of the fasteners. An additional confirmation was provided by inserting a second microcellular pad under the R embedded block. The stiffness was measured and had decreased to 63% of the single pad. The transfer function test on this modified system showed a resonant frequency of 45 Hz, which agrees with the calculated value for the lowered stiffness. A lateral dataset is shown in Figures 4-25 to 4-45. This dataset is representative of the lateral performance of the R embedded block system. Similar data were collected for the Frame fastener 1, Frame fastener 2, and unbonded plate designs and are presented as Figures 4-31 to 4-45.

4.2.1.2 Method 2

The test set-up for Method 2 was very similar to Method 1 except that the transfer function was developed using swept sine testing. The SD390 analyser was set to capture data in a peak hold mode and the shaker controller was programmed to automatically control the sinusoidal excitation. The same test cases were run and the same types of data were collected. Method 2 was found to work better with the Frame fastener 1, Frame fastener 2, and unbonded plate designs.

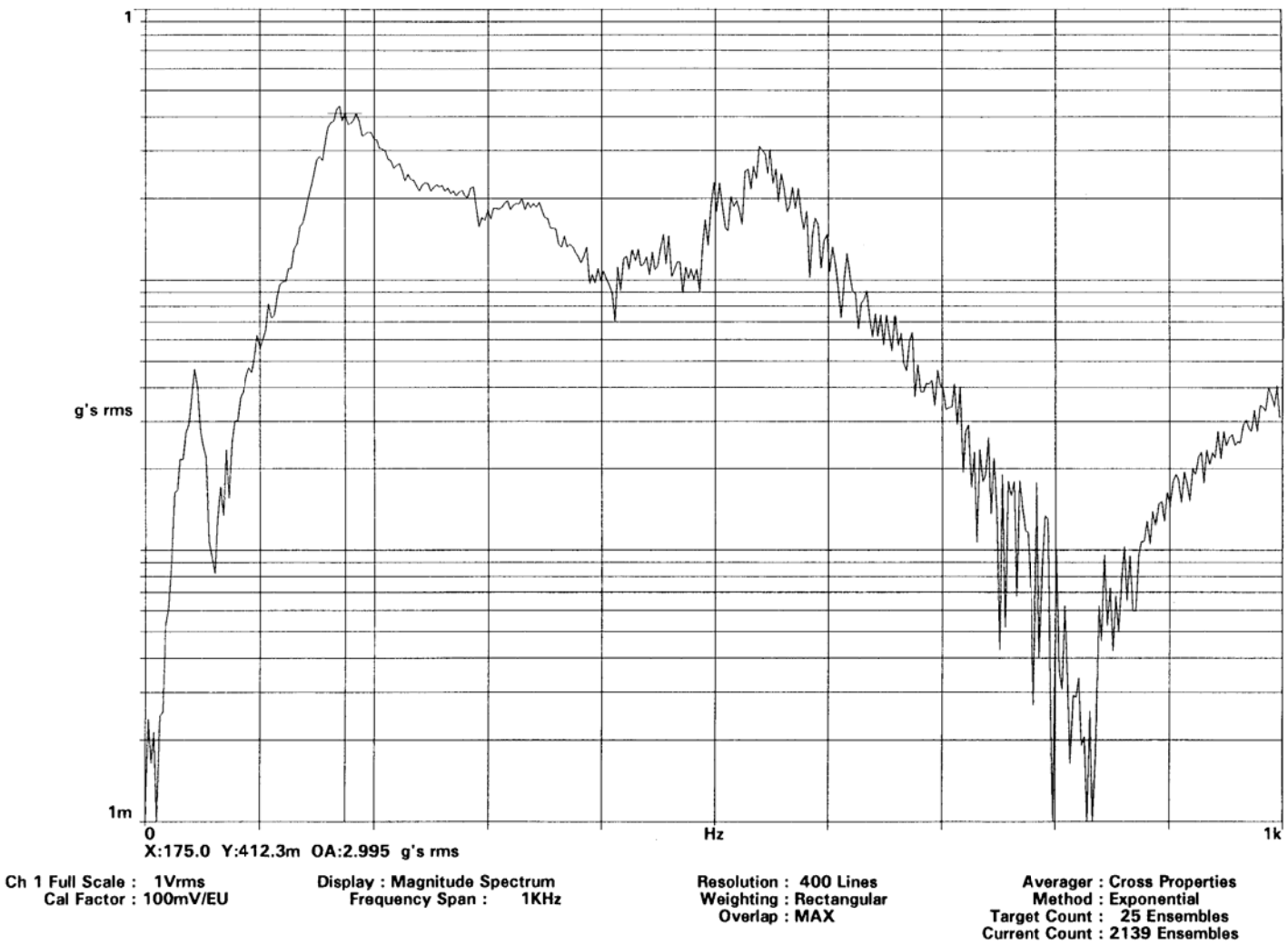


Figure 4-6. R1k-19 A, vertical rail acceleration with R embedded block system, 750 lb preload

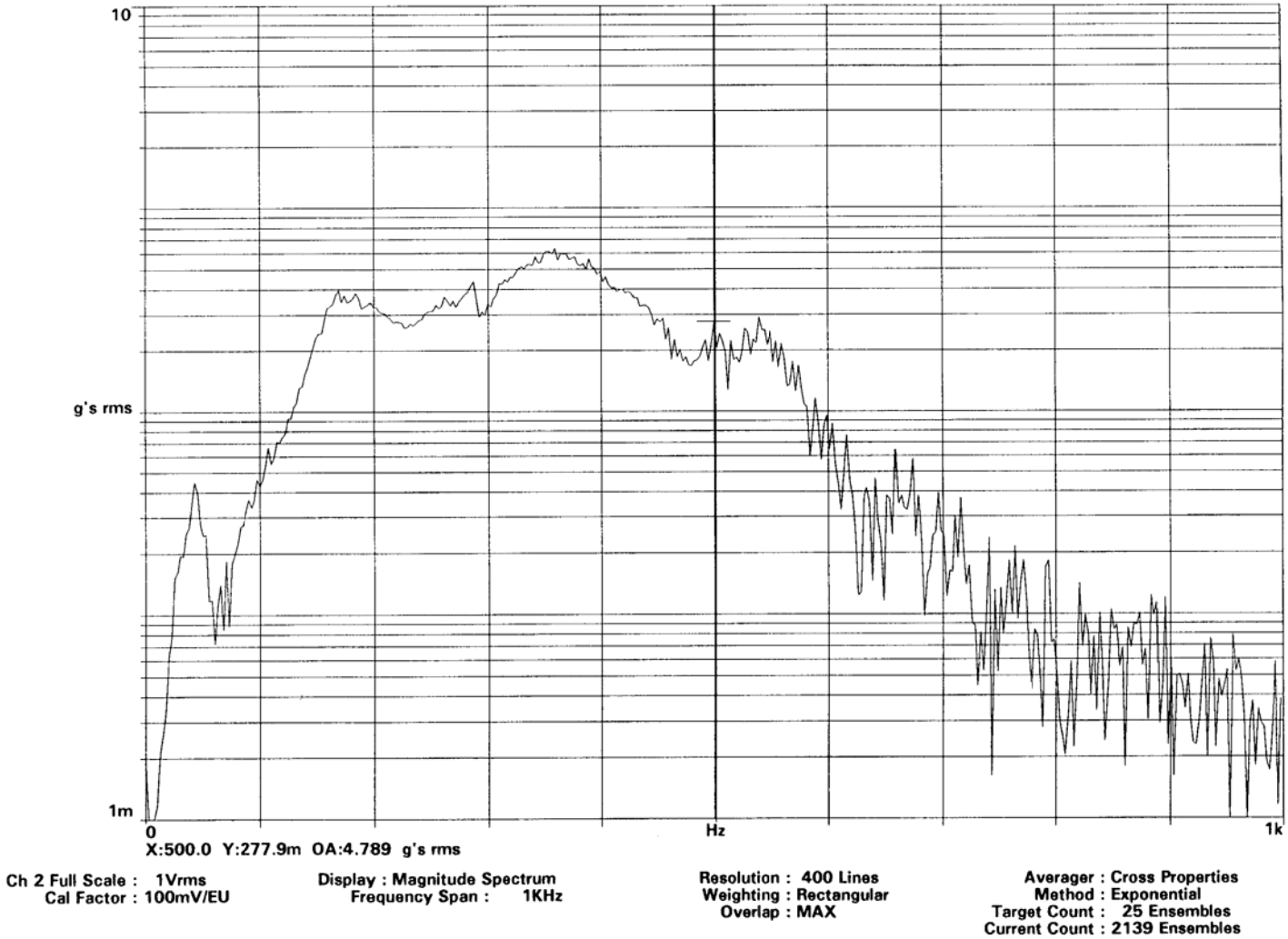


Figure 4-7. R1k-19 B, vertical R embedded block acceleration, 750 lb. preload

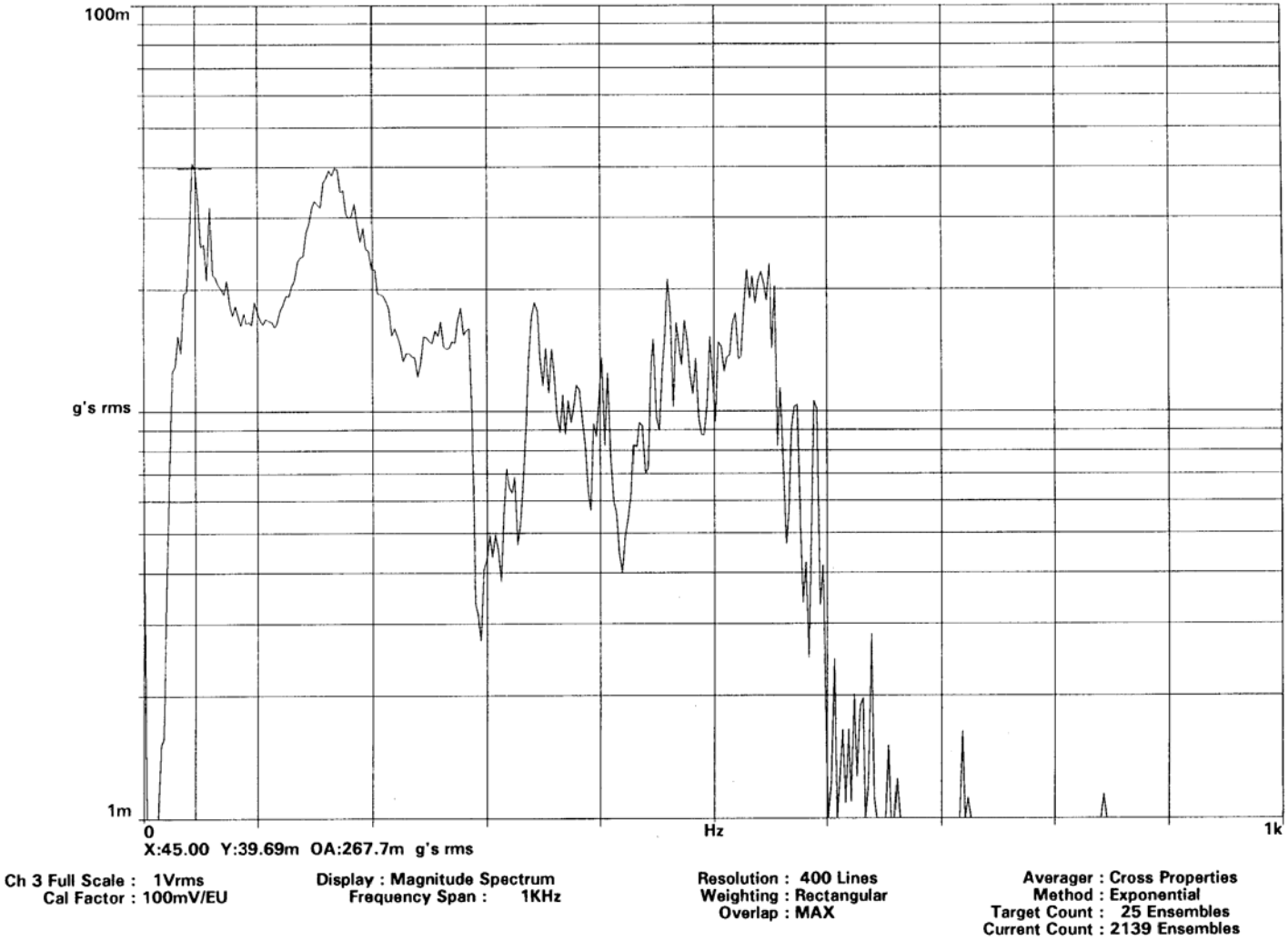


Figure 4-8. R1k-19 C, vertical reaction mass acceleration with R embedded block system, 750 lb. preload

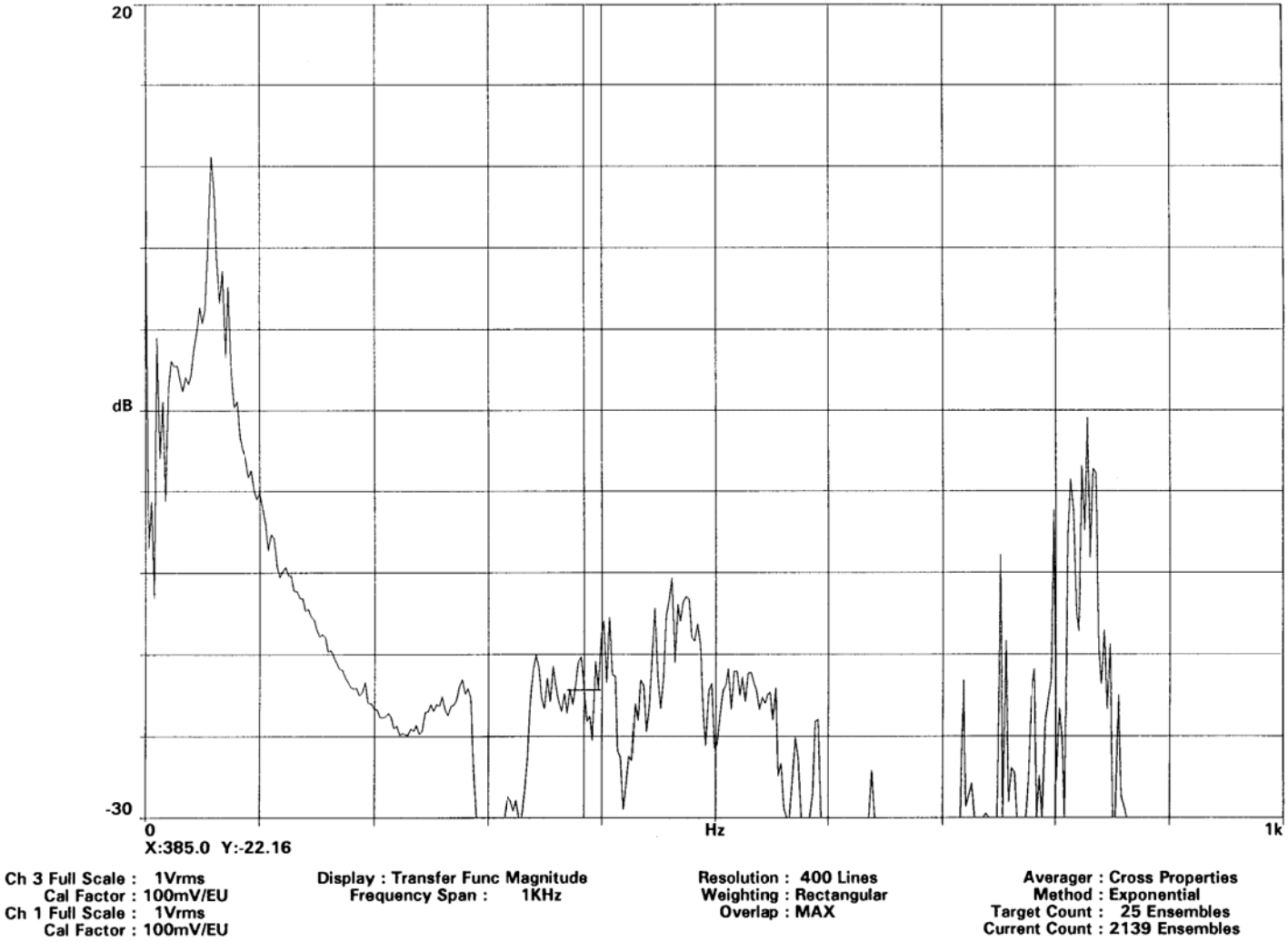


Figure 4-9. R1k-19 D, vertical transfer function for R embedded block system, 750 lb. preload

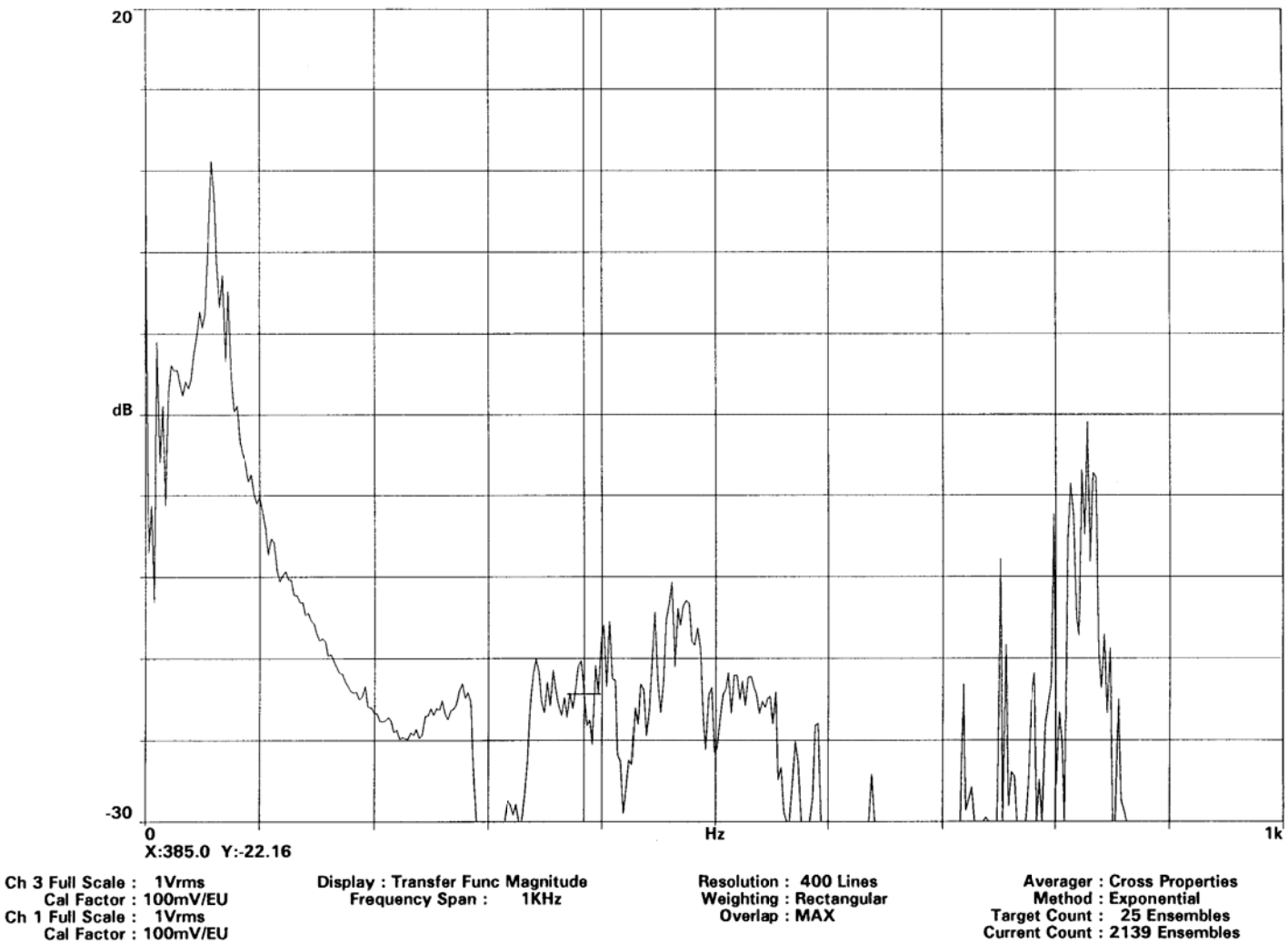


Figure 4-10. R1k-19 E, vertical force input for R embedded block system, 750 lb. preload

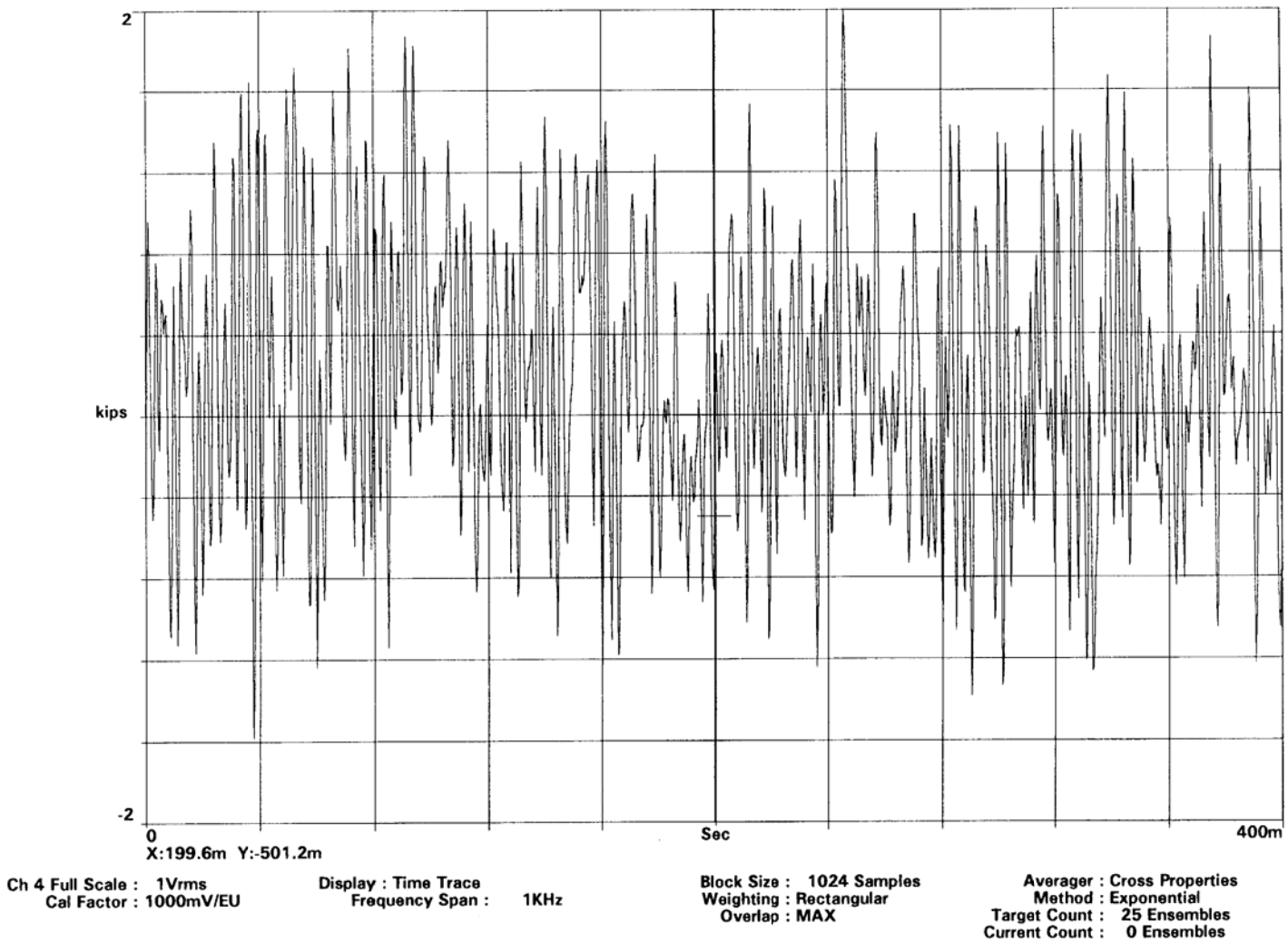
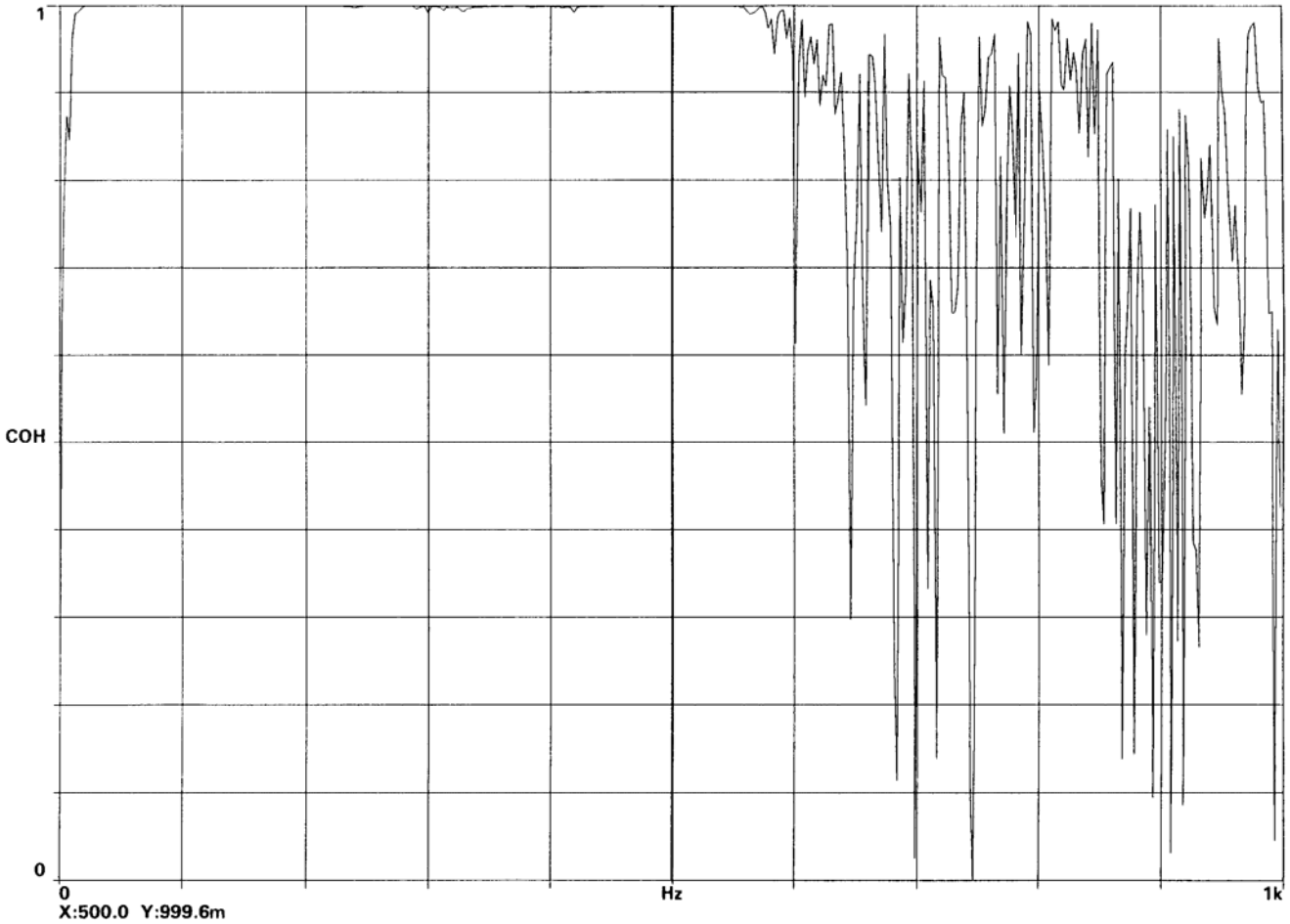


Figure 4-11. R1k-19 F, vertical force input time history with R embedded block , 750 lb. preload



Ch 3 Full Scale : 1Vrms
Cal Factor : 100mV/EU
Ch 1 Full Scale : 1Vrms
Cal Factor : 100mV/EU

Display : Transfer Func Coherence
Frequency Span : 1KHz

Resolution : 400 Lines
Weighting : Rectangular
Overlap : MAX

Averager : Cross Properties
Method : Exponential
Target Count : 25 Ensembles
Current Count : 2139 Ensembles

Figure 4-12. R1k-19 G, vertical transfer function coherence for R embedded block system, 750 lb. preload

The vertical transfer function for the Frame fastener 1 at various preloads is shown in Figures 4-46 to 4-51. The lateral transfer function for the Frame fastener 1 at 6,000 lb. (26.5 kN), 12,000 lb. (53 kN.), and 18,000 lb. (79.5 kN) preload is shown in Figures 4-52 to 4-54. The vertical transfer function for the Frame fastener 2 is shown in Figures 4-55 to 4-60, while the lateral transfer function is shown in Figure 4-61. These fasteners did not exhibit a frequency shift like that for the R embedded block system. This is believed to be because of the linear nature of the fastener at these loads.

The testing of these fasteners provides data necessary to perform evaluations on the noise and vibration isolation effectiveness of the different fasteners. The actual measured values for transmissibility and forced response should prove useful to project noise consultants. Typically, calculated or assumed values have been used for such noise evaluations.

4.3 Results

A limited set of testing results is provided in this report due to the volume of data collected. The results are consistent and believed to be valid for frequencies below 500 Hz. Above that frequency resonances in the test stand affect results. One issue of possible contention is the questions as to how much of the wheelset and/or vehicle mass should be included when performing a calculation of the system resonant frequency. The authors believe the spring rate used in the calculation should be based upon the load provided by the weight of the vehicle, but that the mass used for calculating track resonance should be based upon the actual mass of the rail and fastener system. No mass associated with the wheelset should be included, except when detailed high frequency dynamic modeling of the track is under study. This would include modeling for corrugation susceptibility and prevention.

Most of the vibration of the track occurs as the wheel approaches and leaves the fastener (on a time-based percentage). During these times the mass of the wheel certainly can't be included in track vibration calculations. In fact, the rail and fasteners may be bridged due to uplift and free to vibrate with little damping. When the wheel is over the fastener, the wheelset mass may be included for dynamic calculations, recognizing that the wheel/rail interface provides a biased load that is limited by the inability of the interface to provide tension. There is also added mass and friction damping provided when the wheel is over the fastener.

The testing showed surprising agreement with analytical results. In all cases the predicted natural frequency of the track and the measured frequency were within a few percent based upon measured weights and stiffnesses. This was true when modeling the track fastener system as a simple mass-on-spring system. Important factors in this calculation:

- It is important to use the tangent (dynamic) stiffness of the fastener system at the appropriate preload. (% of wheel load shared by a single fastener) If the fastener stiffness is nonlinear, like the R embedded block and Frame fastener 1, the resonant frequency is dependent upon the load. See Figures 4-62 and 4-63. The load values presented in the example data are midrange, greater than the fastener loads of a transit vehicle but less than a locomotive.

- The added mass of the R embedded block system serves to provide a lower resonant frequency of the track system than the lighter plate and frame DF fastener systems.

- All the fastener systems provided no virtually attenuation of vibration below their natural frequency. This is consistent with theory. Since the natural frequency of these systems is in the 40 to 150 Hz range they have virtually no ability to affect long-wavelength ground-borne vibrations.

- All the systems exhibited the vertical resonant peak consistent with a single-order spring-mass system. At the resonant frequency the systems actually amplify any vibration input. In some cases the amplification could be as much as 6 to 10 dB.

- The systems attenuated vibration above their natural frequency consistent with the single order model. Attenuation of 20 to 30 dB was measured as a noise floor above the natural frequency. This is clearly shown in Figures 4-31, 4-42, 4-48, and 4-57.

The information presented in the following acceleration plots and transfer functions is of use mainly to those experienced in system dynamics and vibrations. These plots provide data useful for system modeling as might be performed by noise consultants. There is no reliable, simple way of providing direct comparisons of fastener performance with this data since results depend on a large number of system parameters including rail weight, support structure characteristics, fastening methodology, and design stiffness, to name a few.

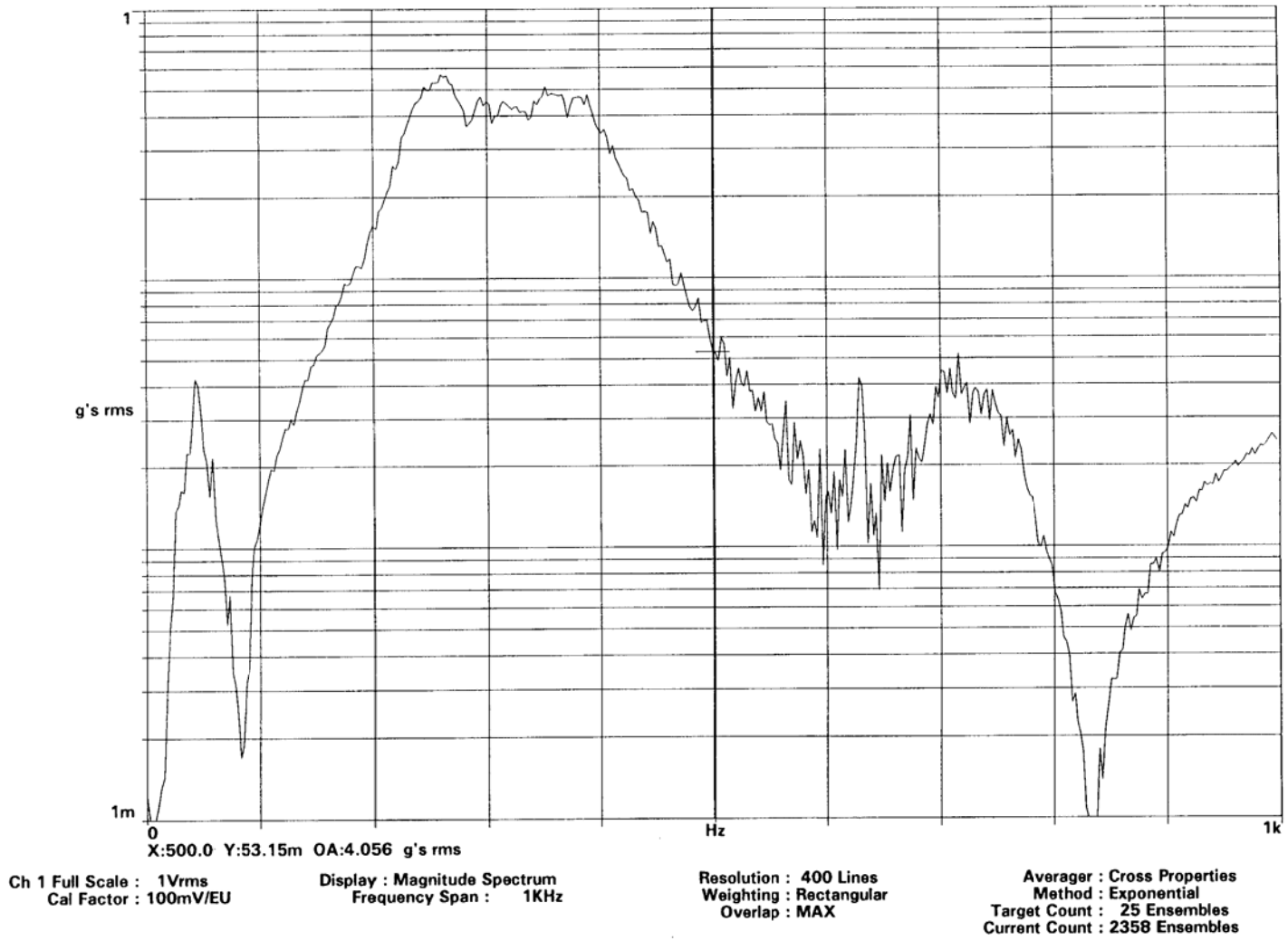


Figure 4-13. R1k-16 A, vertical rail acceleration with R embedded block system, 9000 lb. preload

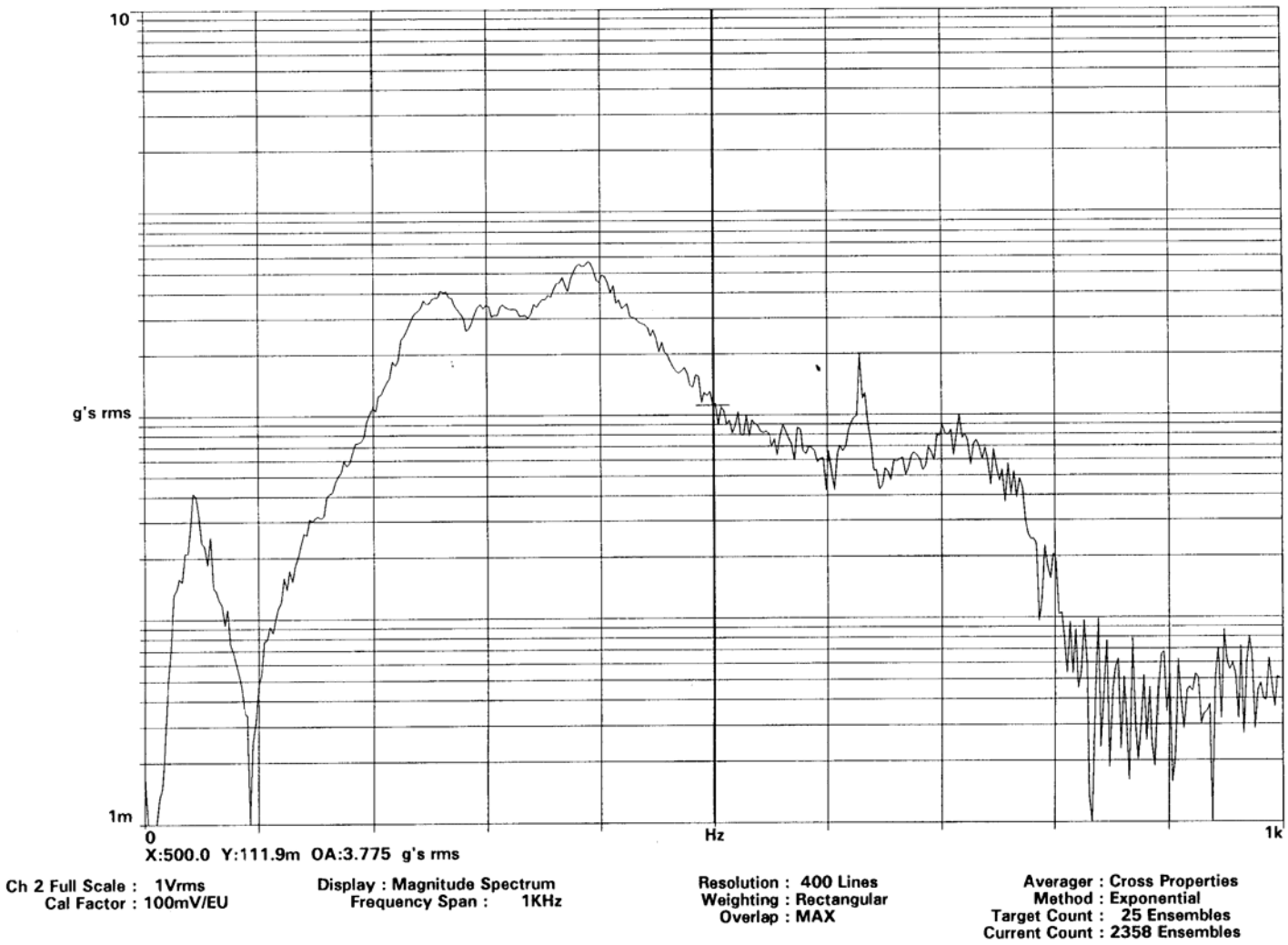


Figure 4-14. R1k-16 B, vertical R embedded block block acceleration, 9,000 lb. preload

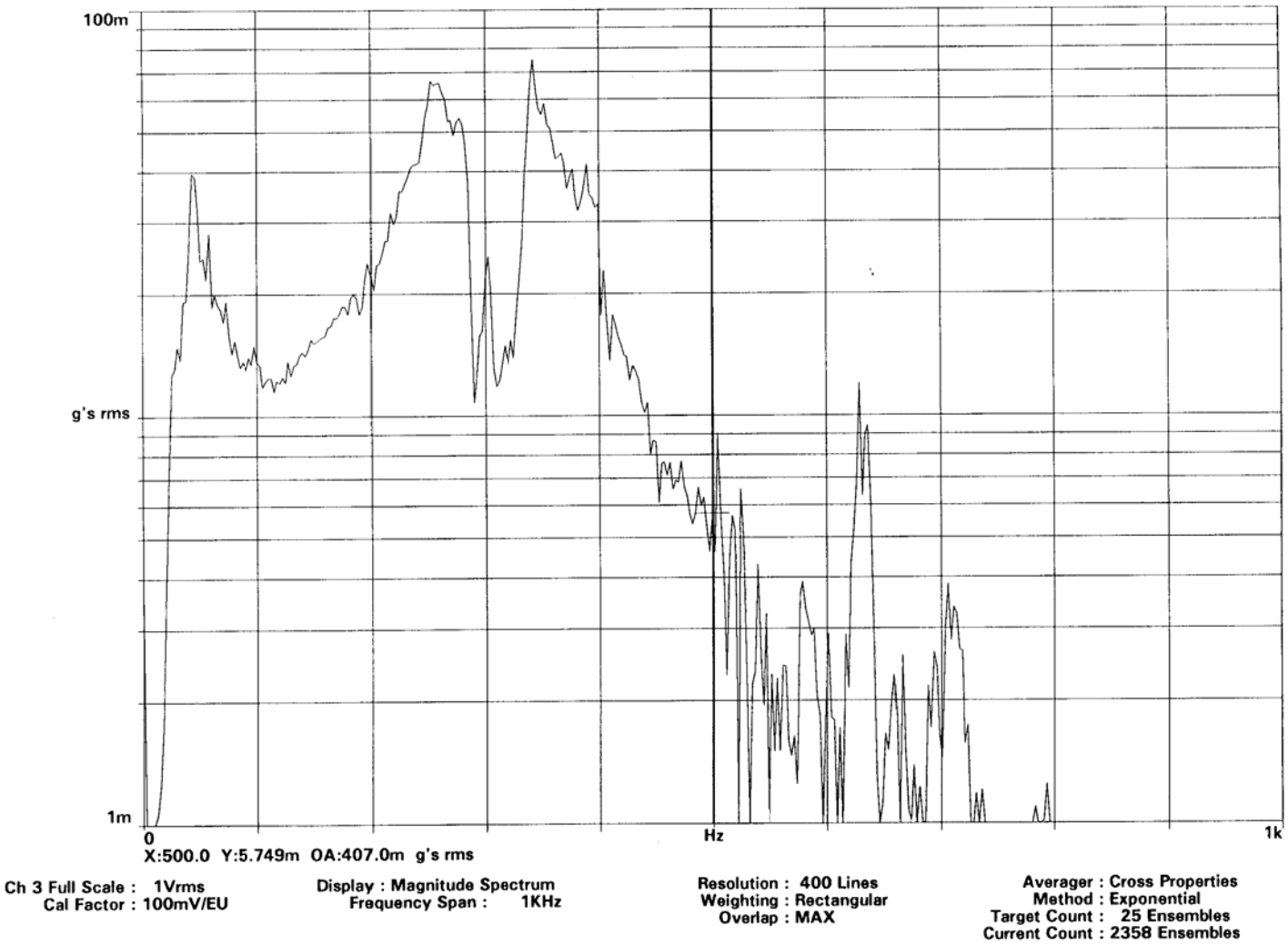


Figure 4-15. R1k-16 C, vertical reaction mass acceleration with R embedded block system, 9,000 lb preload

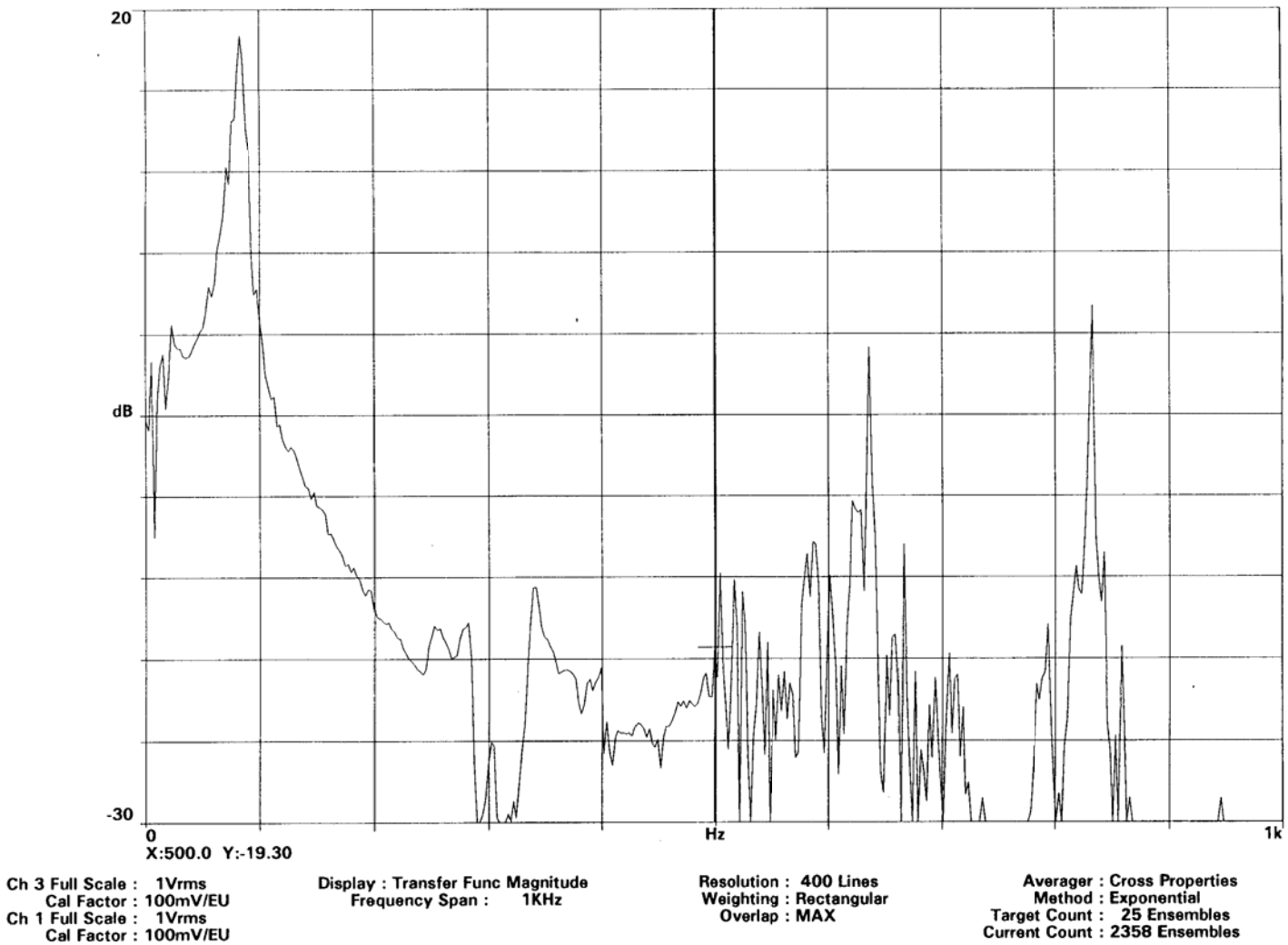


Figure 4-16. R1k-16 D, vertical transfer function for R embedded block system, 9,000 lb. preload

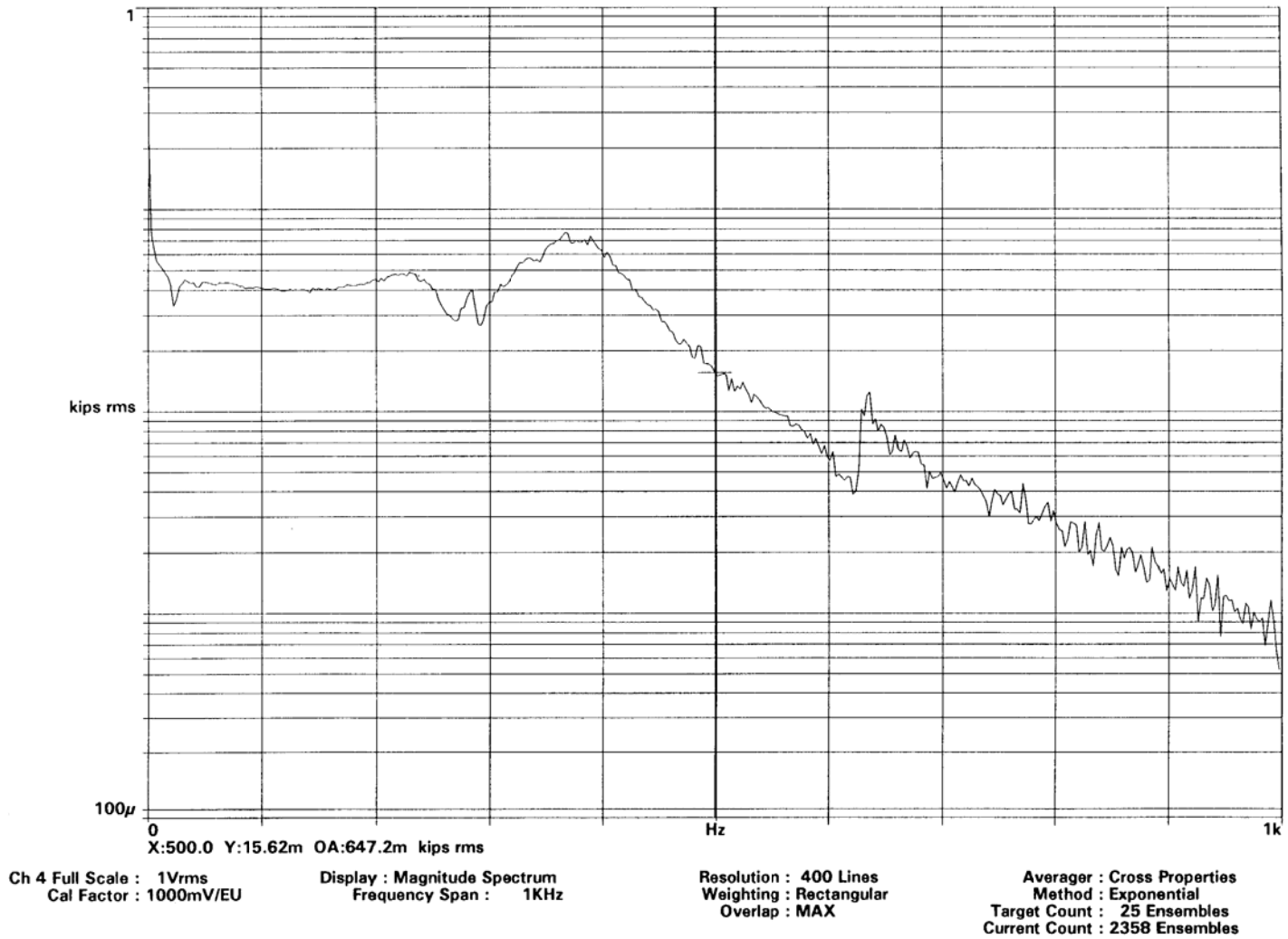


Figure 4-17. R1k-16 E, vertical force input for R embedded block system, 9,000 lb. preload

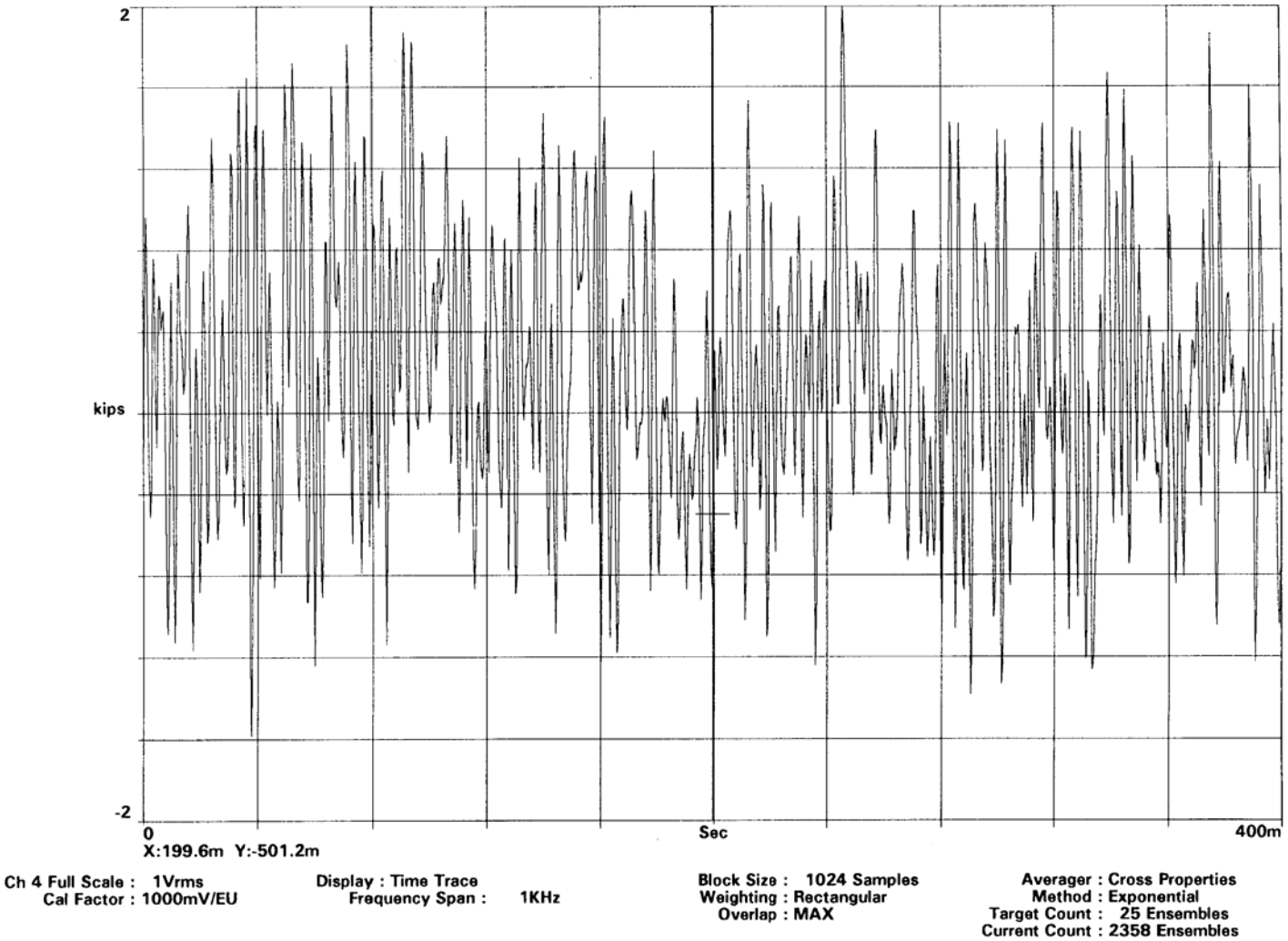


Figure 4-18. R1k-16 F, vertical force input time history with R embedded block system, 9,000 lb. preload

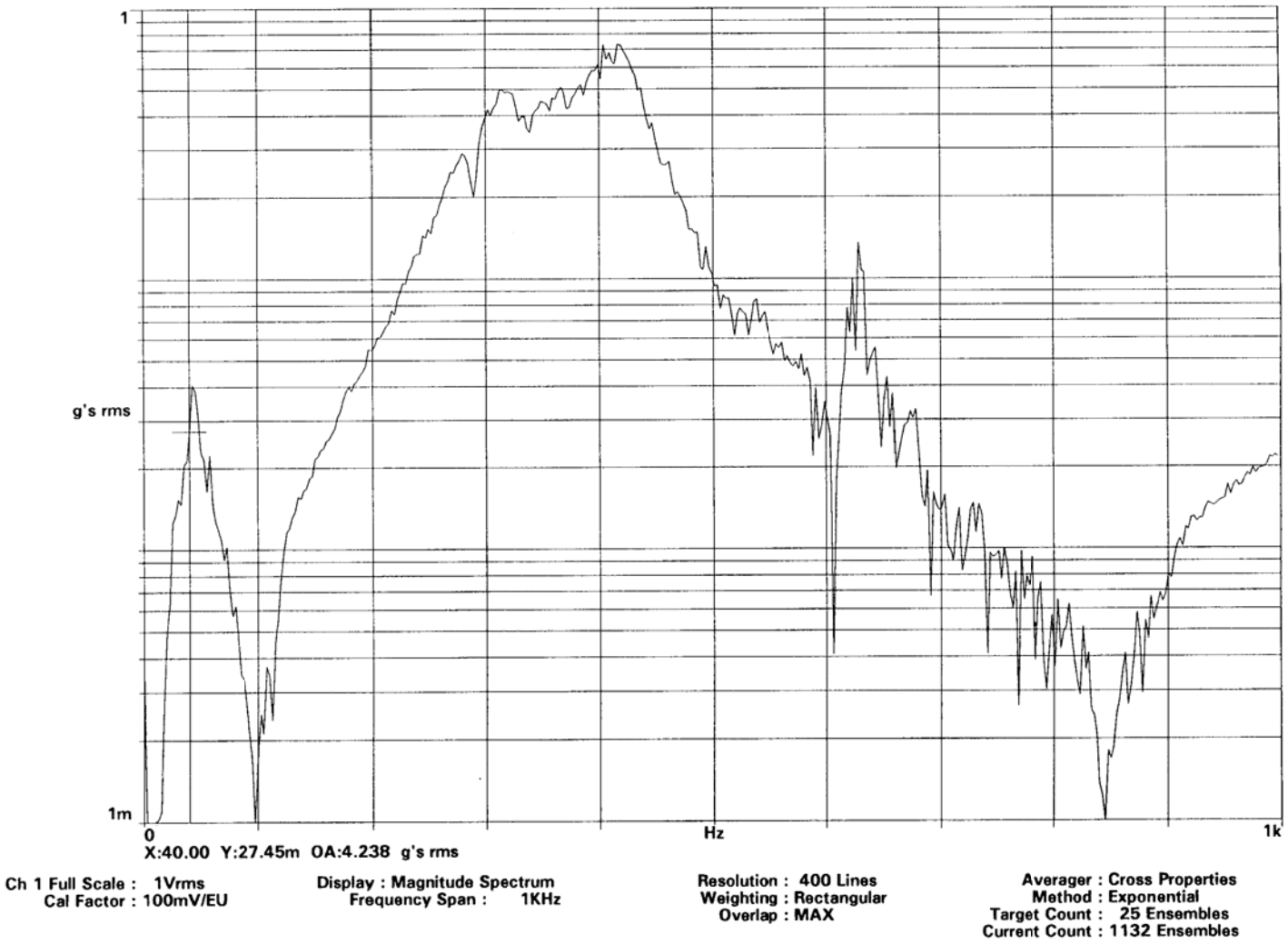


Figure 4-19. R1k-17 A, vertical rail acceleration with R embedded block system, 15,000 lb. preload

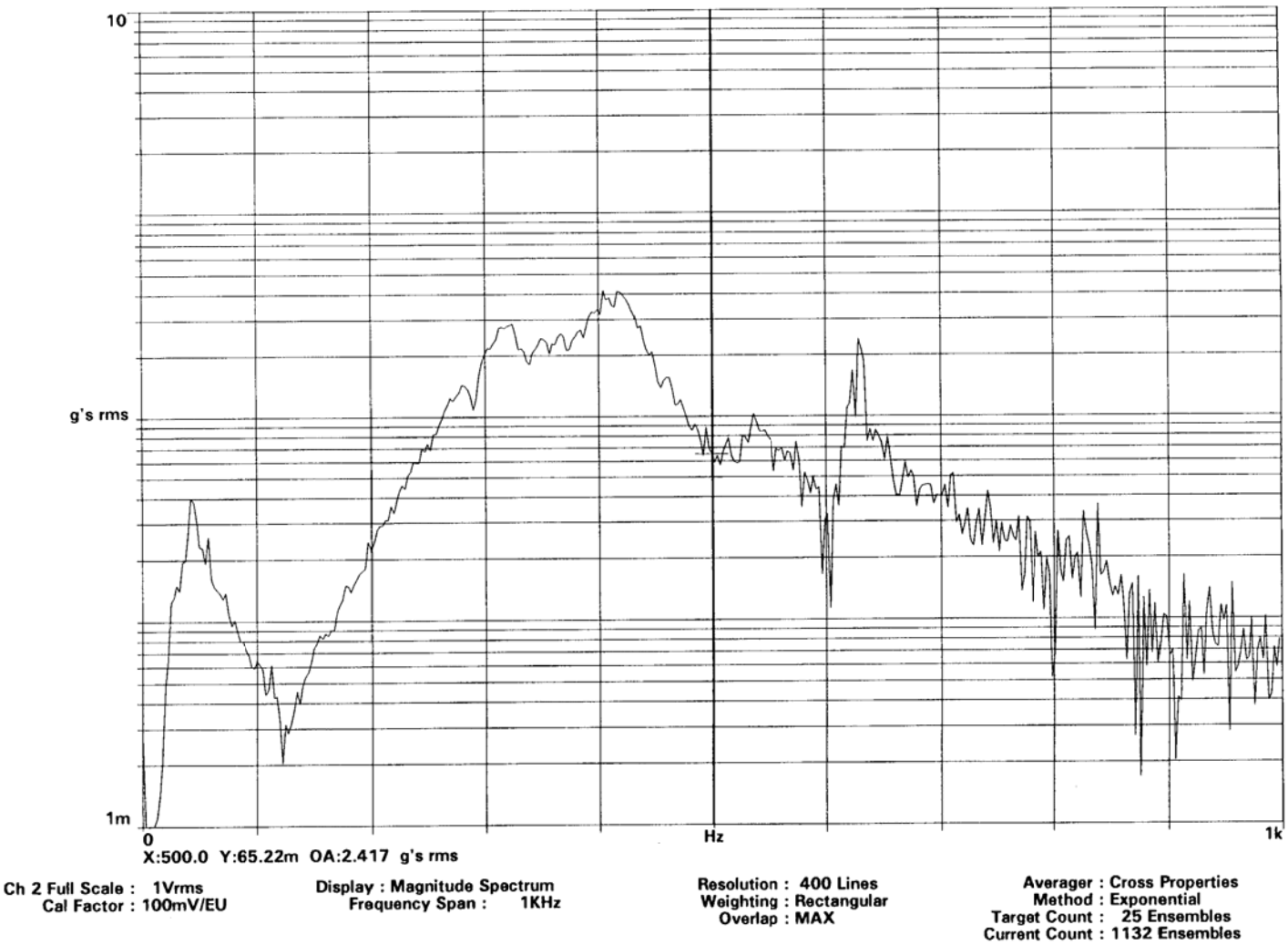


Figure 4-20. R1k-17 B, vertical R embedded block block acceleration, 15,000 lb. preload

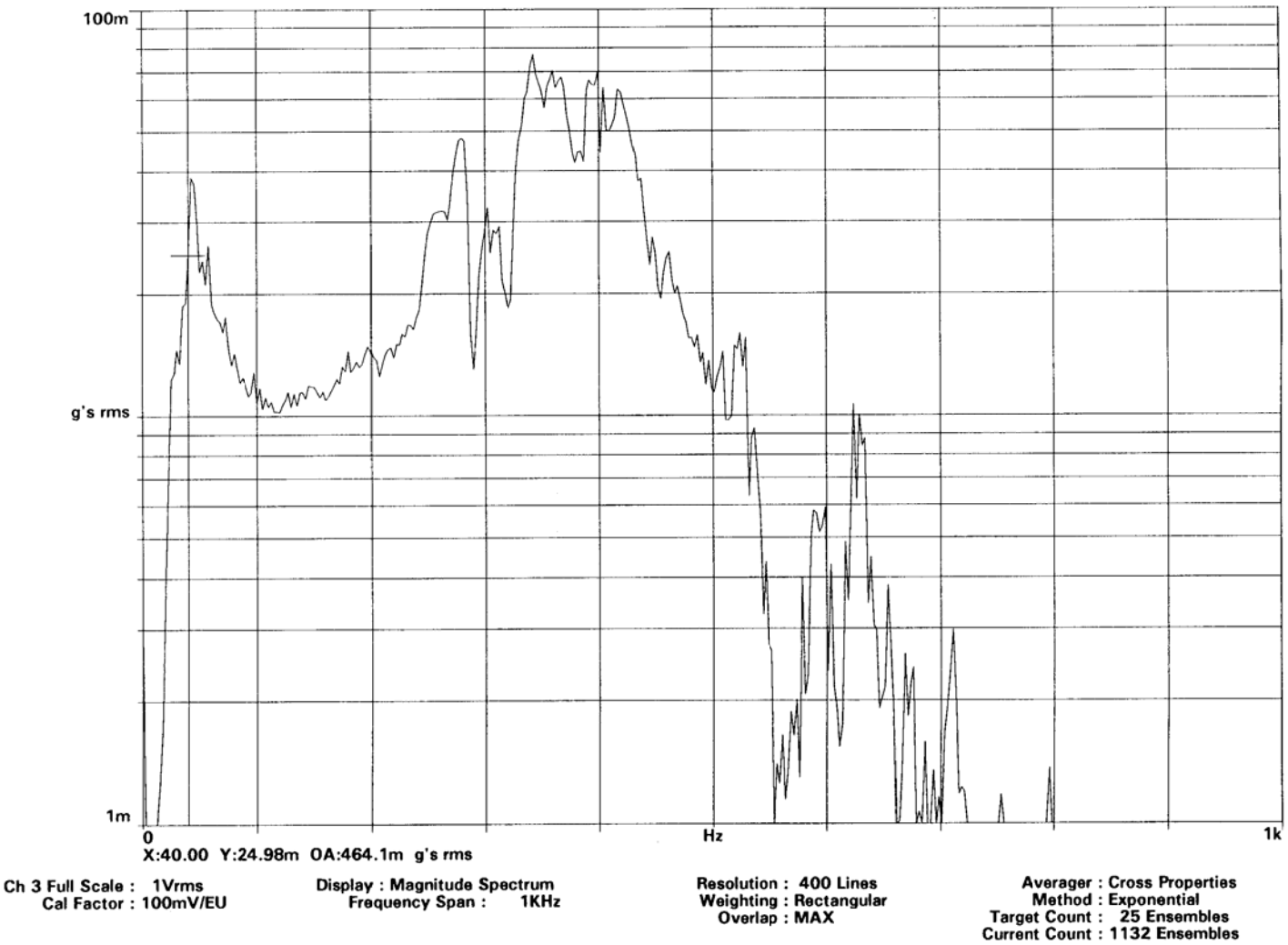


Figure 4-21. R1k-17 C, vertical reaction mass acceleration with R embedded block system, 15,000 lb. preload

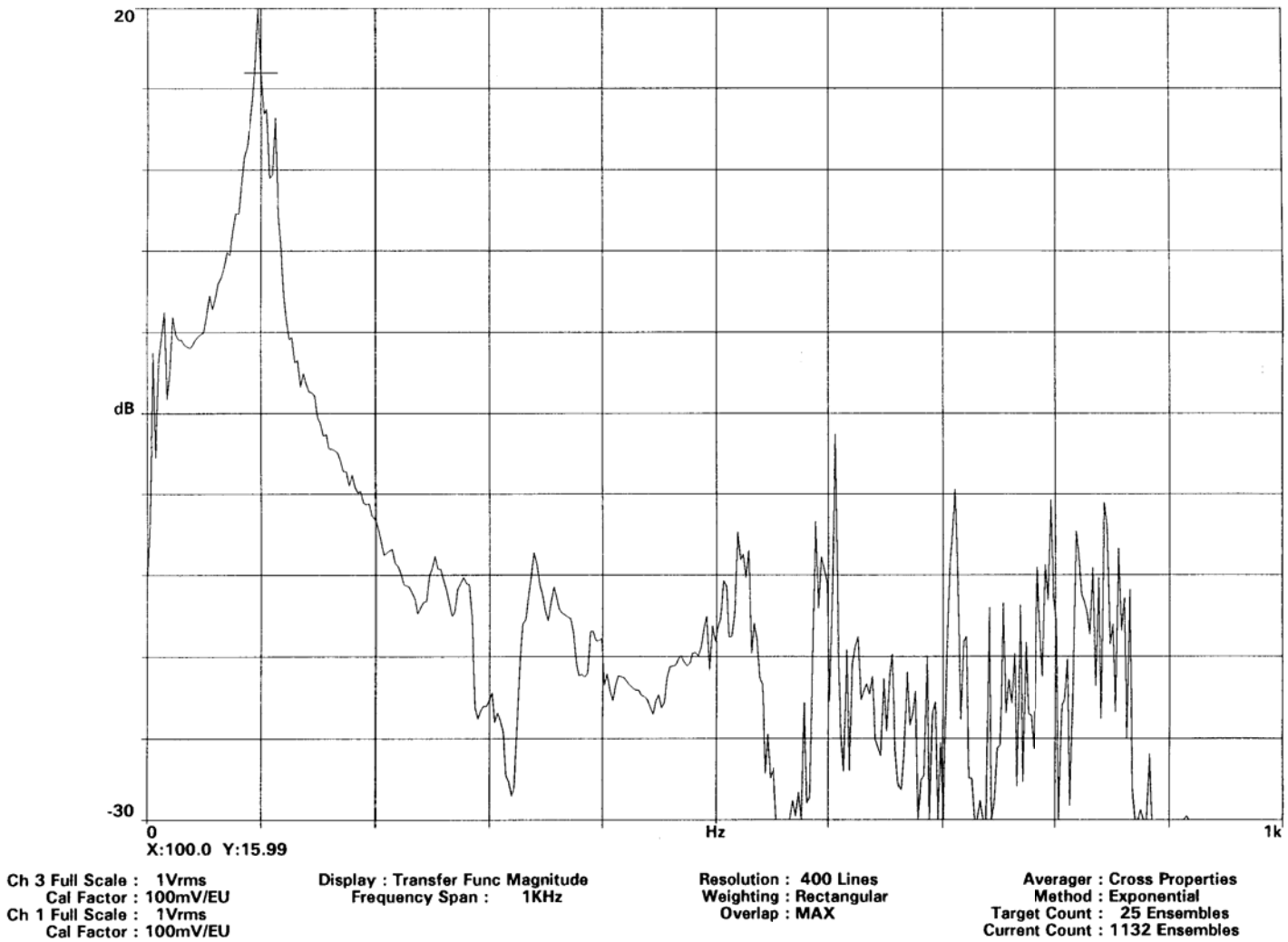


Figure 4-22. R1k-17 D, vertical transfer function for R embedded block system, 15,000 lb. preload

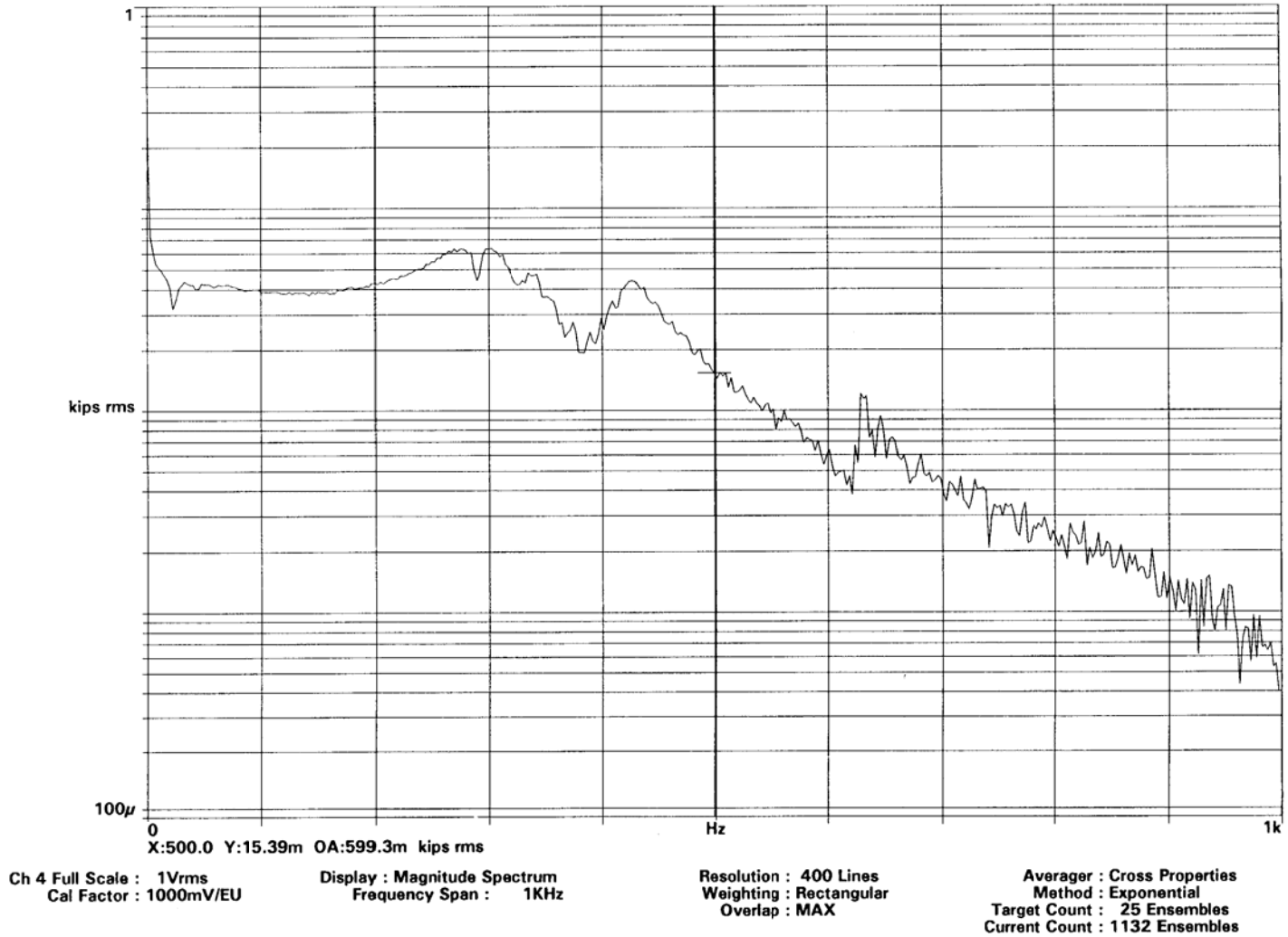


Figure 4-23. R1k-17 E, vertical force input for R embedded block system, 15,000 lb. preload

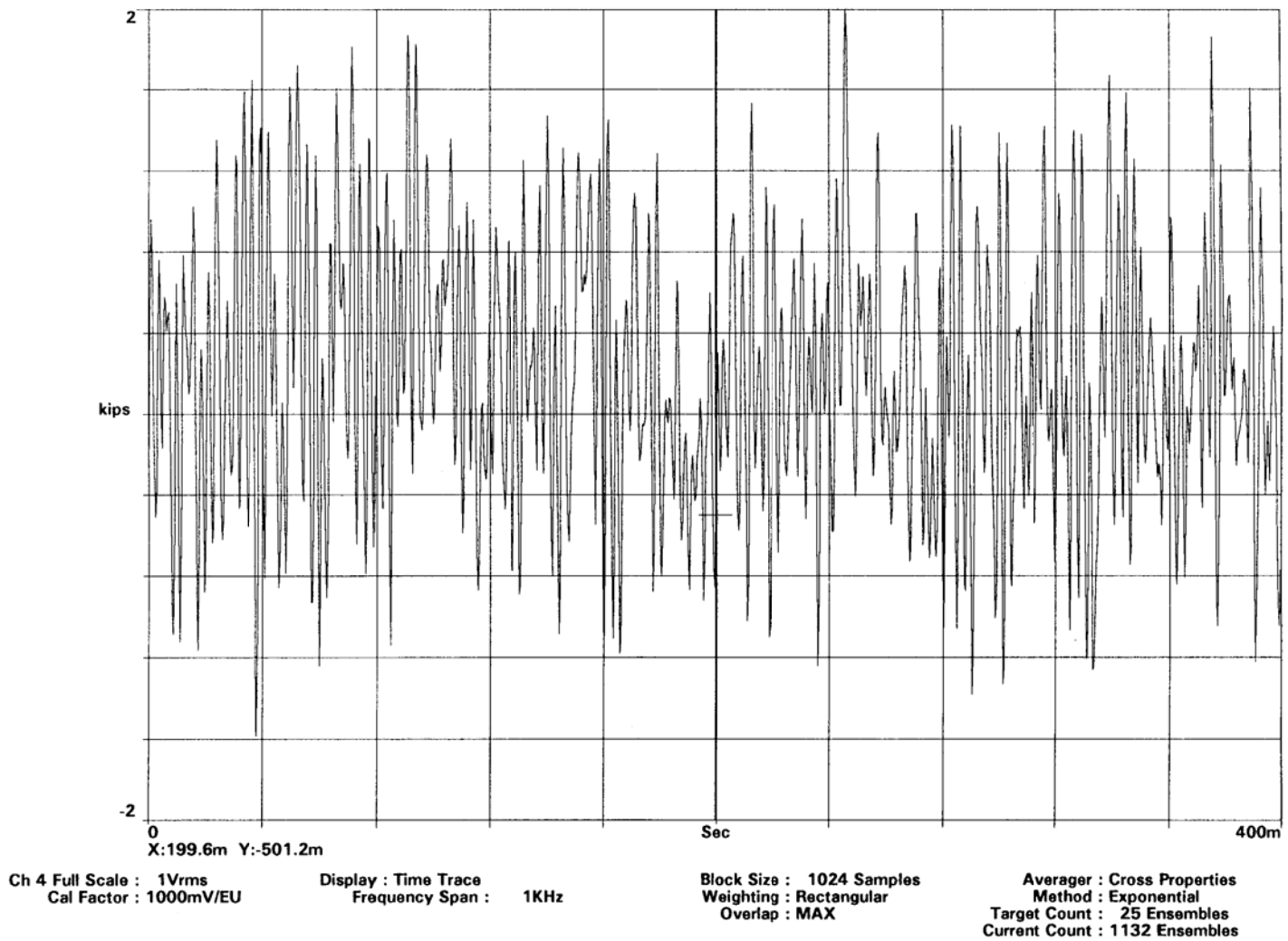


Figure 4-24. R1k-17 F, vertical force input time history with R embedded block system, 15,000 lb. preload

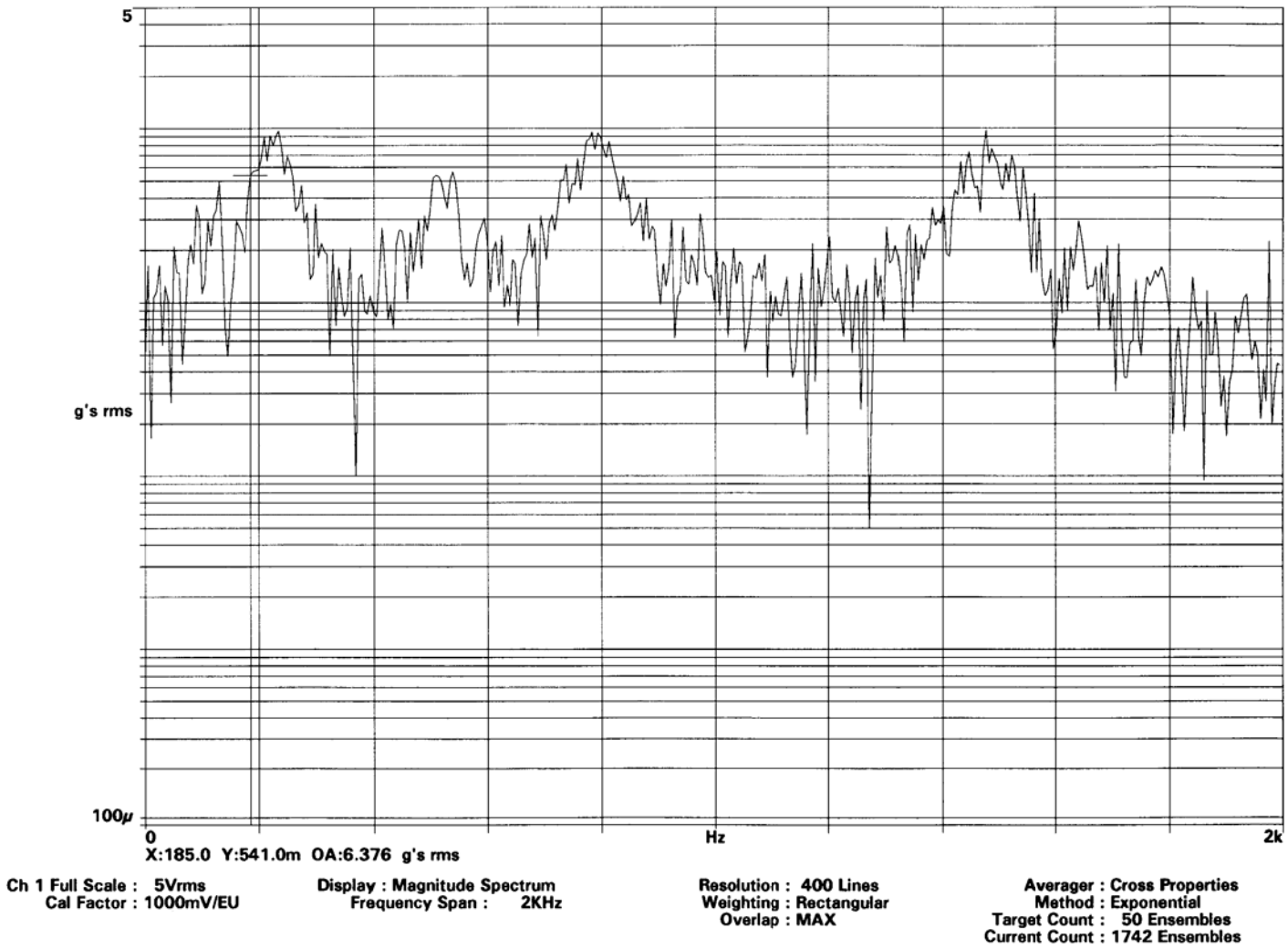


Figure 4-25. Rlt2k 42 A, lateral rail acceleration with R embedded block system, 9,000 lb. preload

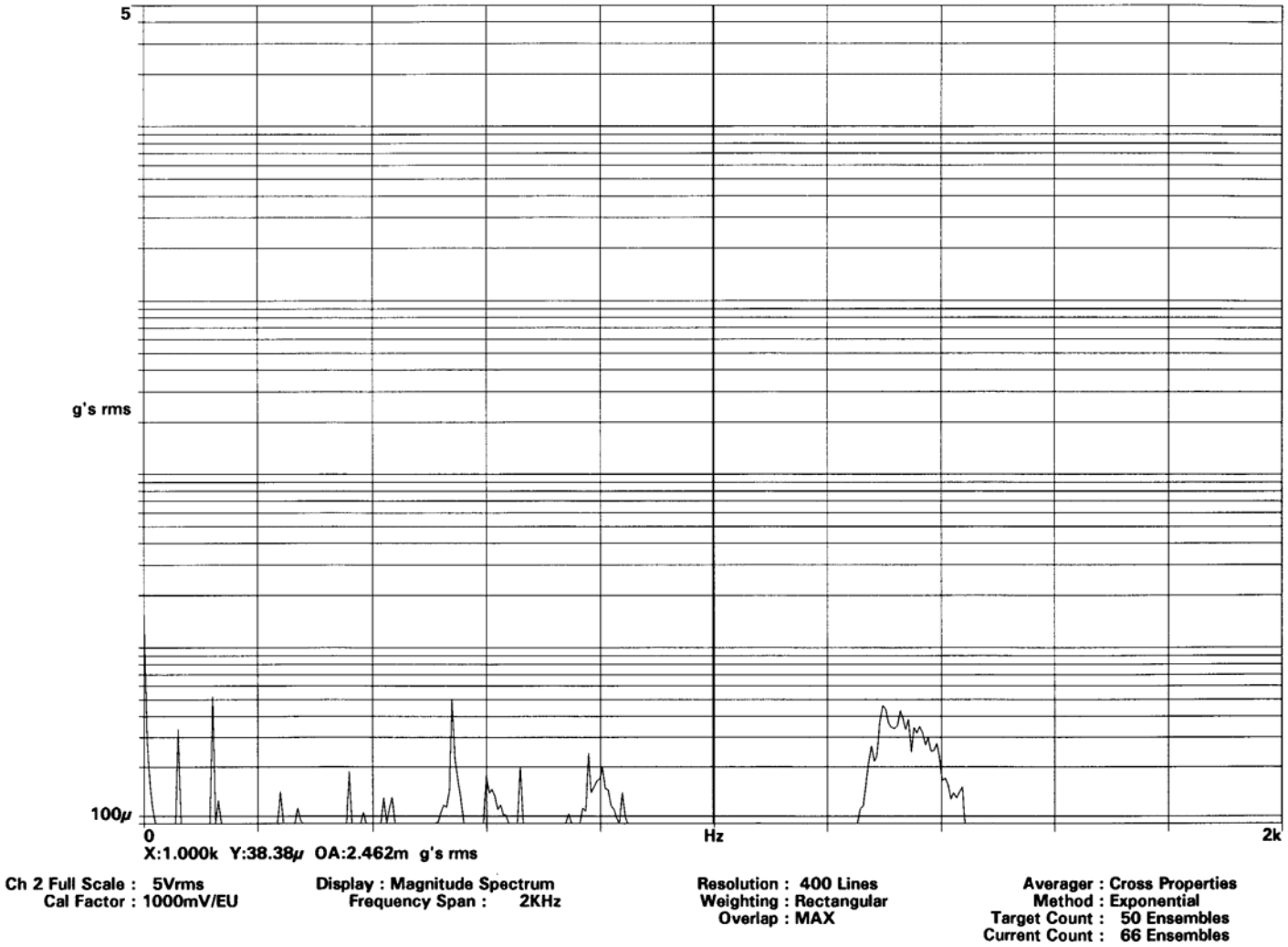


Figure 4-26. Rlt2k 42 B, lateral R embedded block block acceleration, 9,000 lb. preload

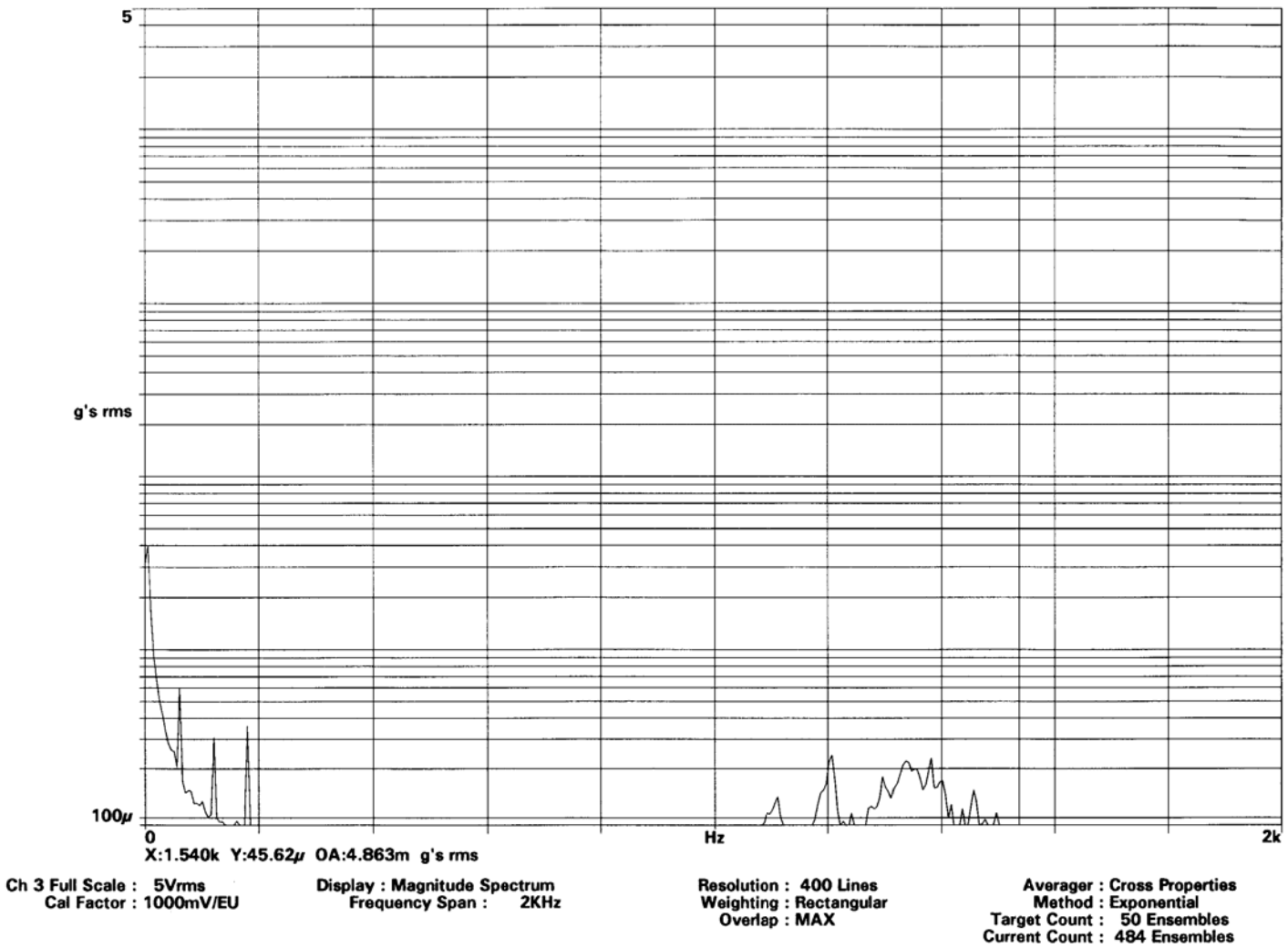


Figure 4-27. Rlt2k 42 C, lateral reaction mass acceleration with R embedded block system, 9,000 lb. preload

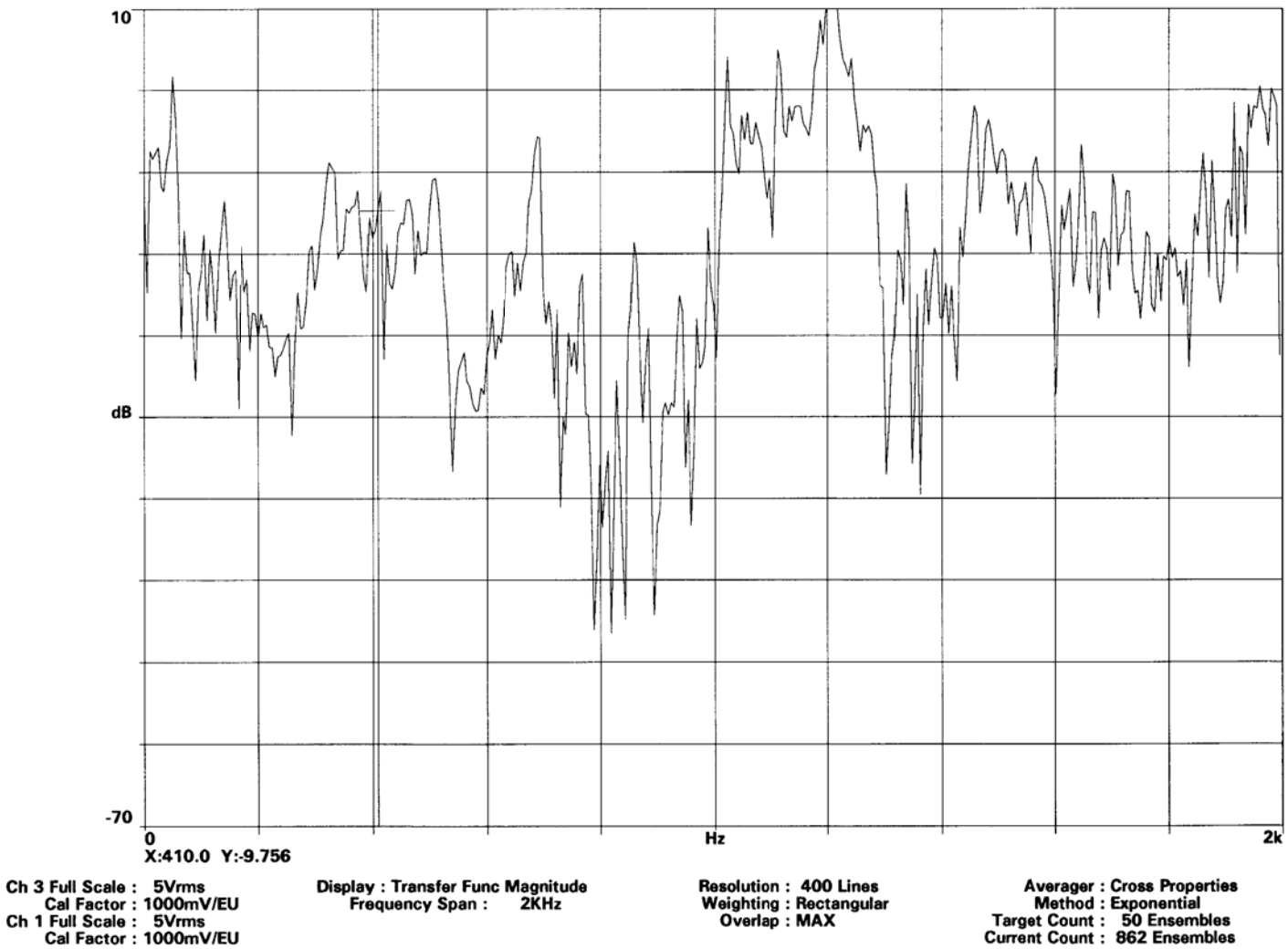


Figure 4-28. Rlt2k 42 D, L lateral transfer function for R embedded block system, 9,000 lb. preload

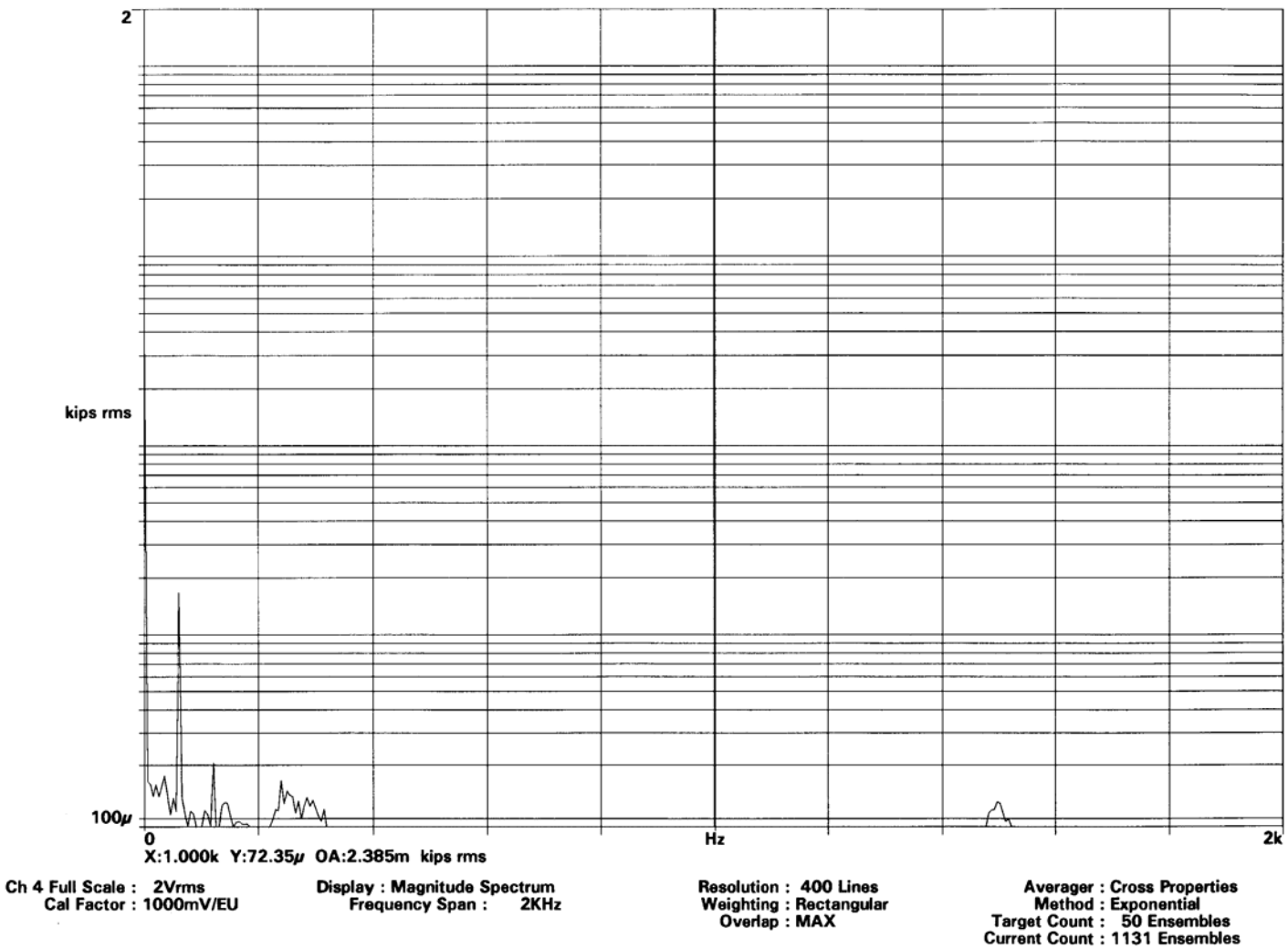


Figure 4-29. Rlt2k 42 E, lateral force input for R embedded block system, 9,000 lb. preload

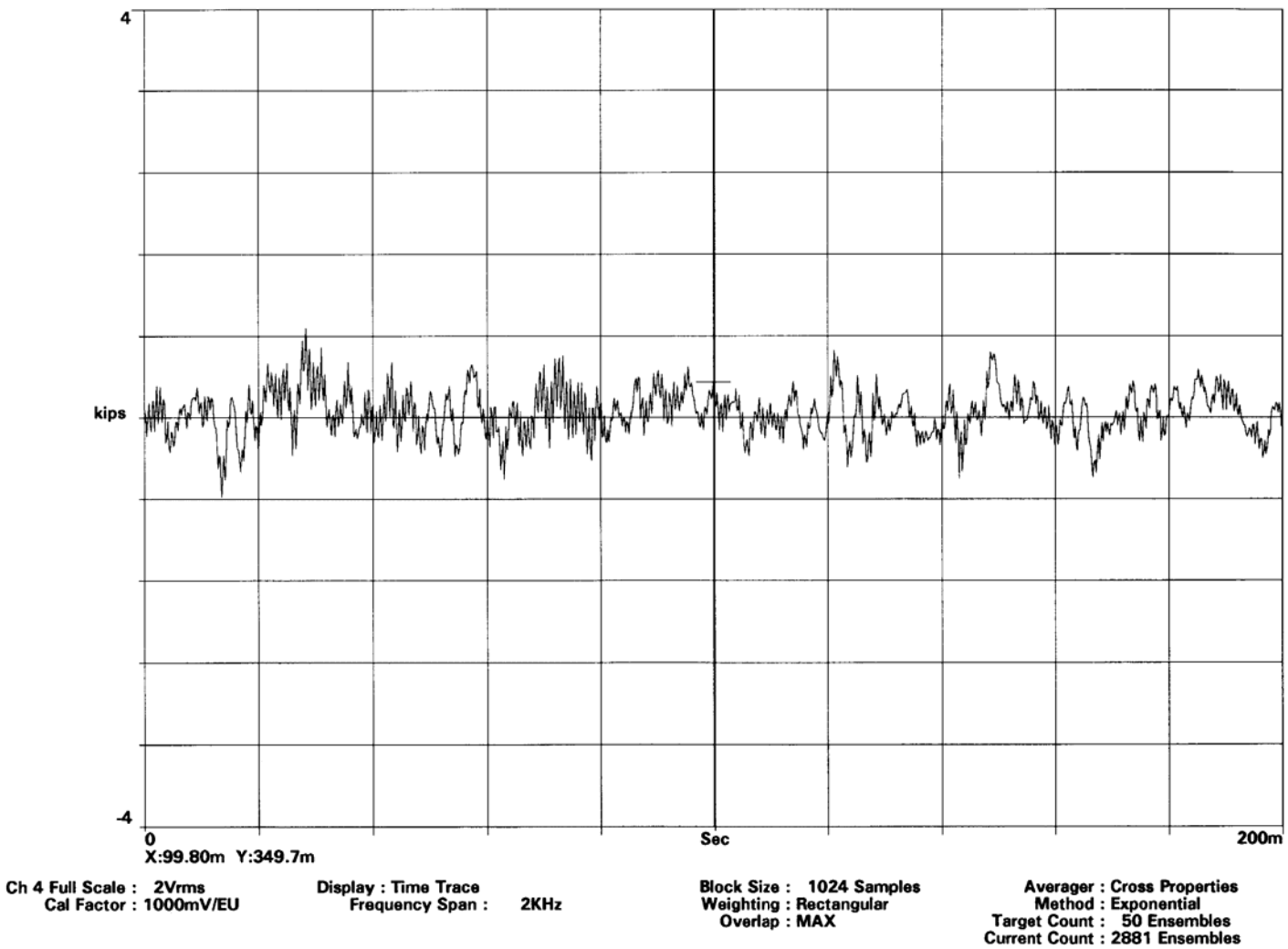


Figure 4-30. Rlt2k 42 F, lateral force input time history with R embedded block system, 9,000-lb. preload

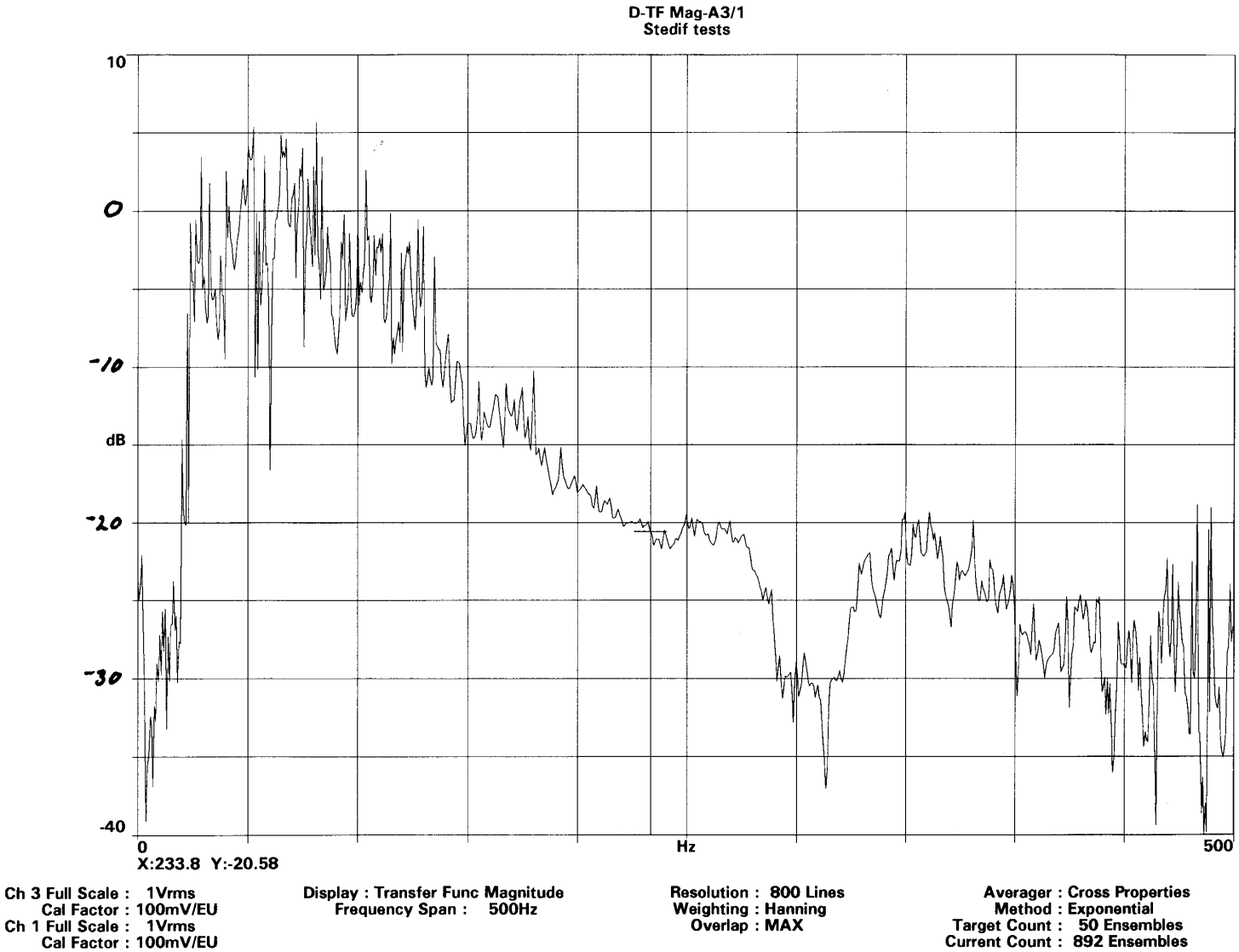


Figure 4-31. Fas Q D, vertical transfer function for Q embedded block , 9,000-lb. preload

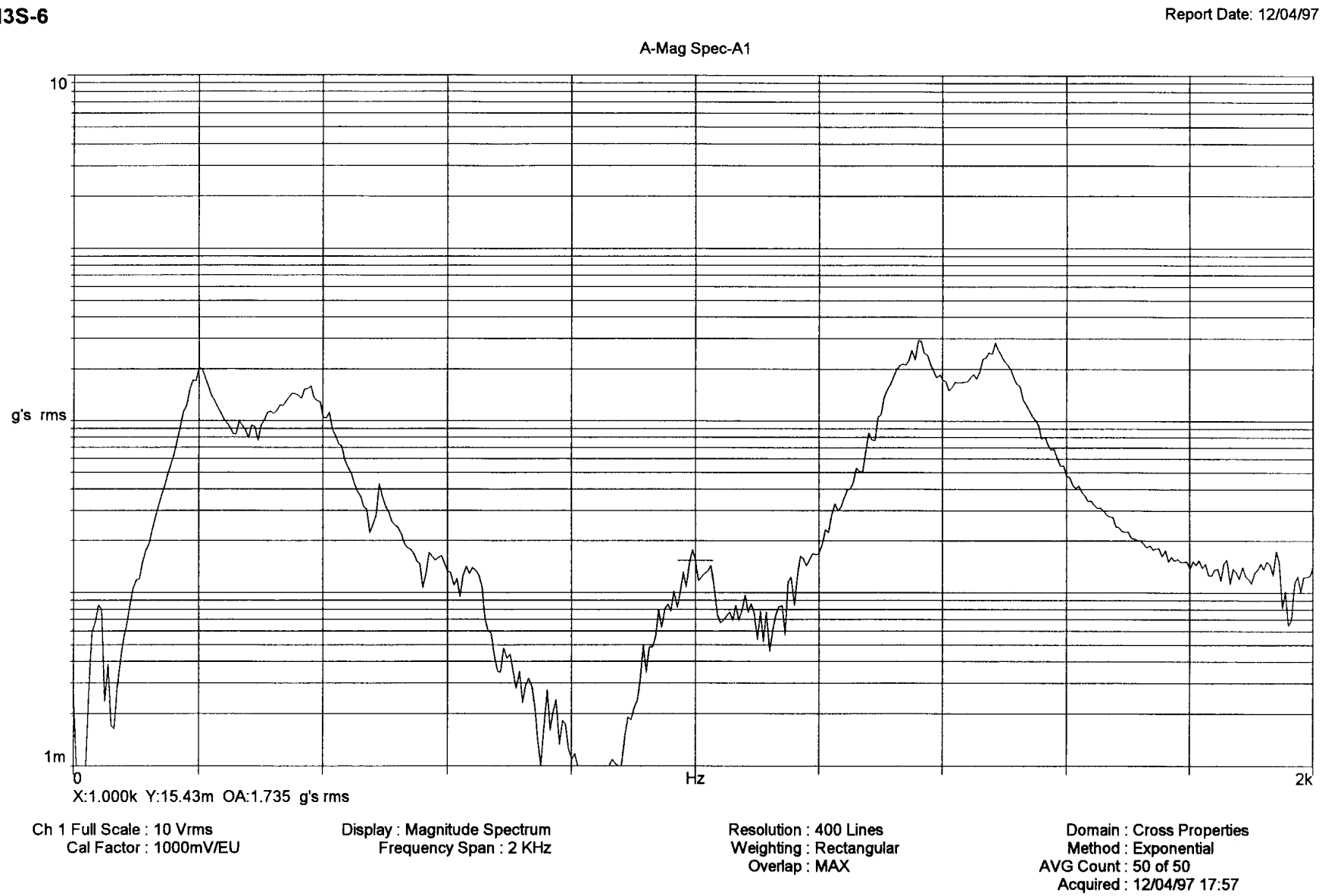


Figure 4-32. P3S-6 A, vertical rail acceleration with P unbonded 3 pad fastener, 9,000-lb. preload

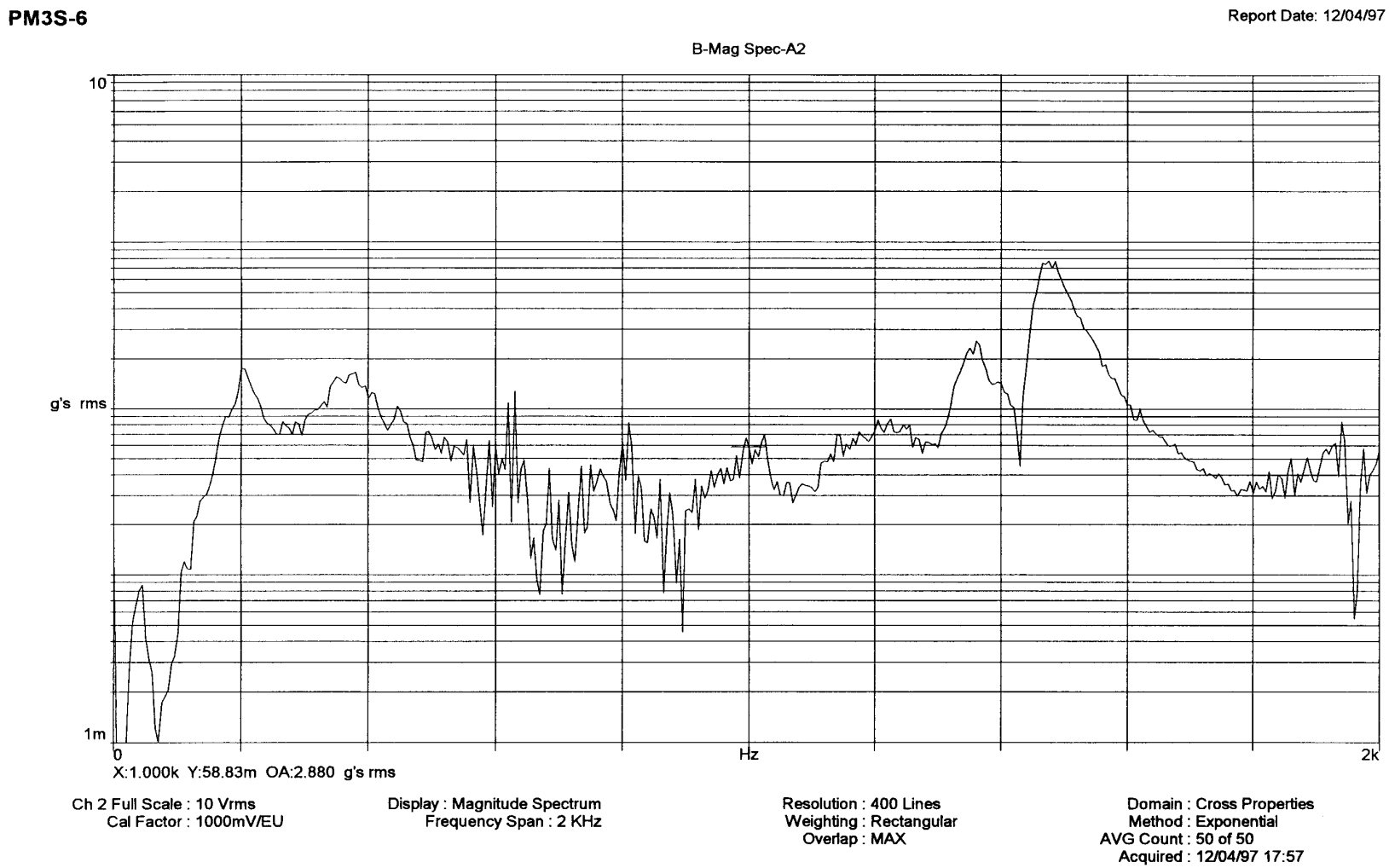


Figure 4-33. P3S-6 B, vertical reaction mass acceleration with P unbonded 3 pad fastener, 9,000-lb. preload

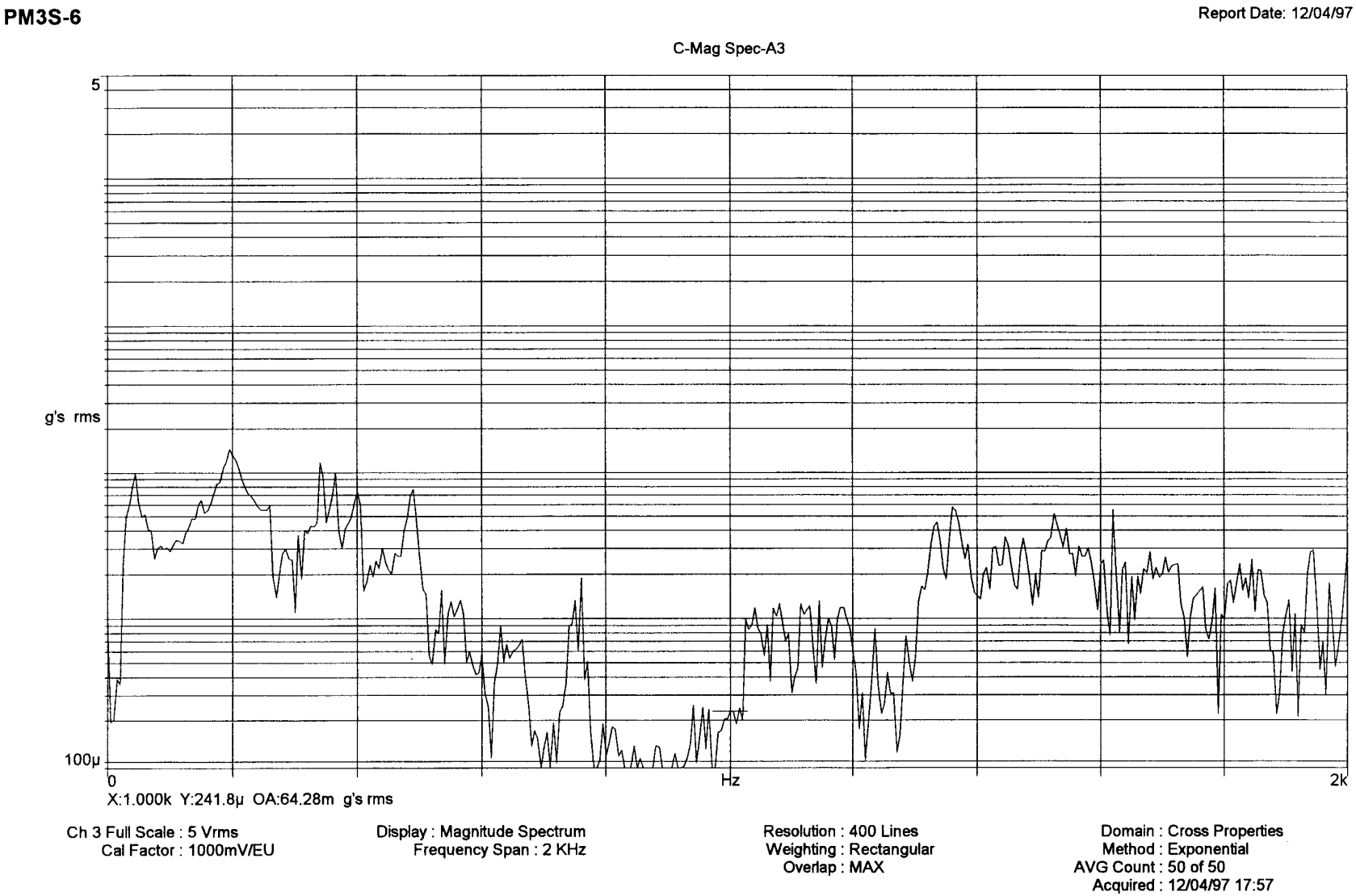


Figure 4-34. P3S-6 C vertical reaction mass acceleration with P unbonded 3 pad fastener, 9000-lb preload

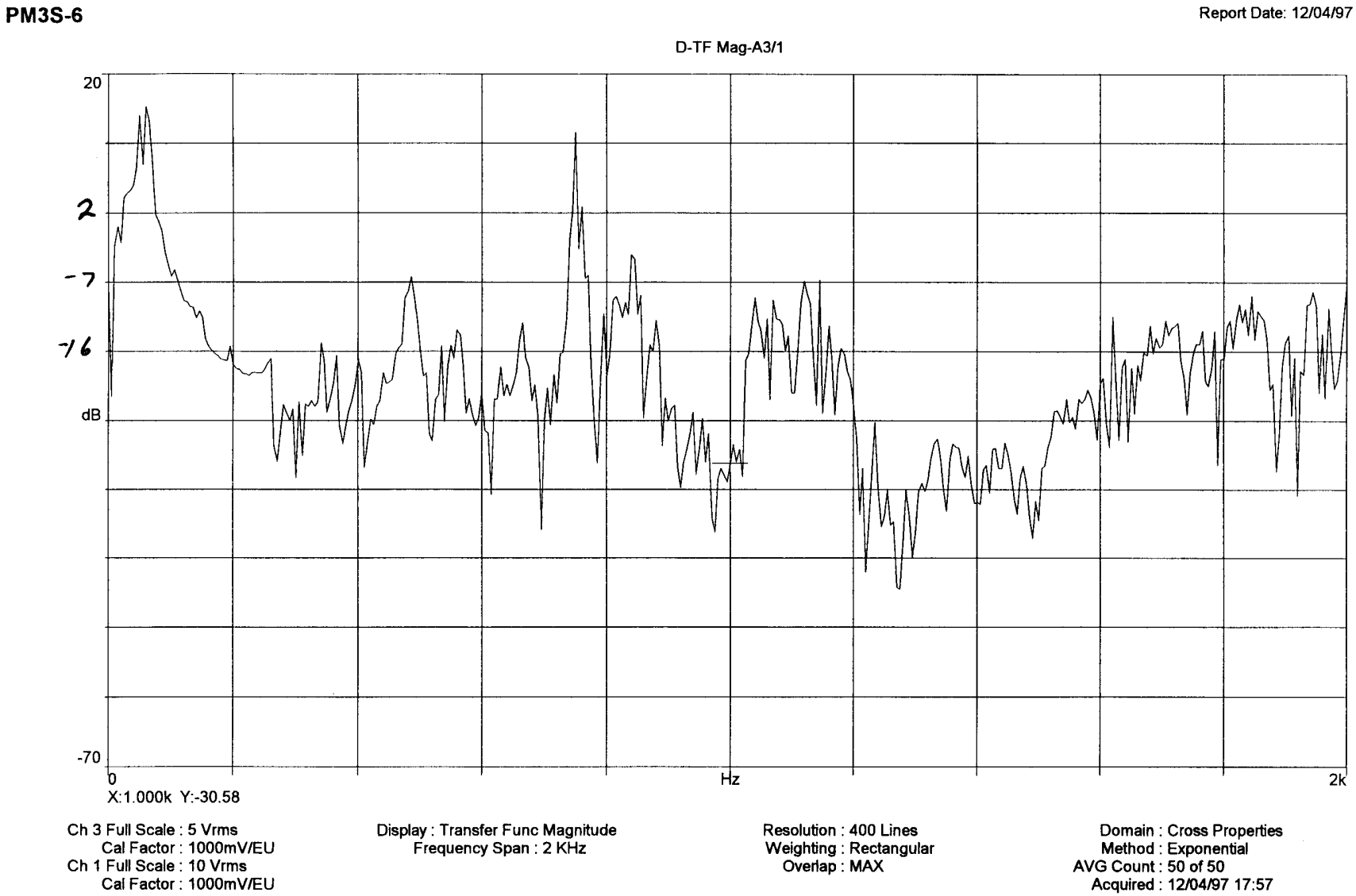


Figure 4-35. P3S-6 D, vertical transfer function for O unbonded 2 pad fastener, 9,000-lb. preload

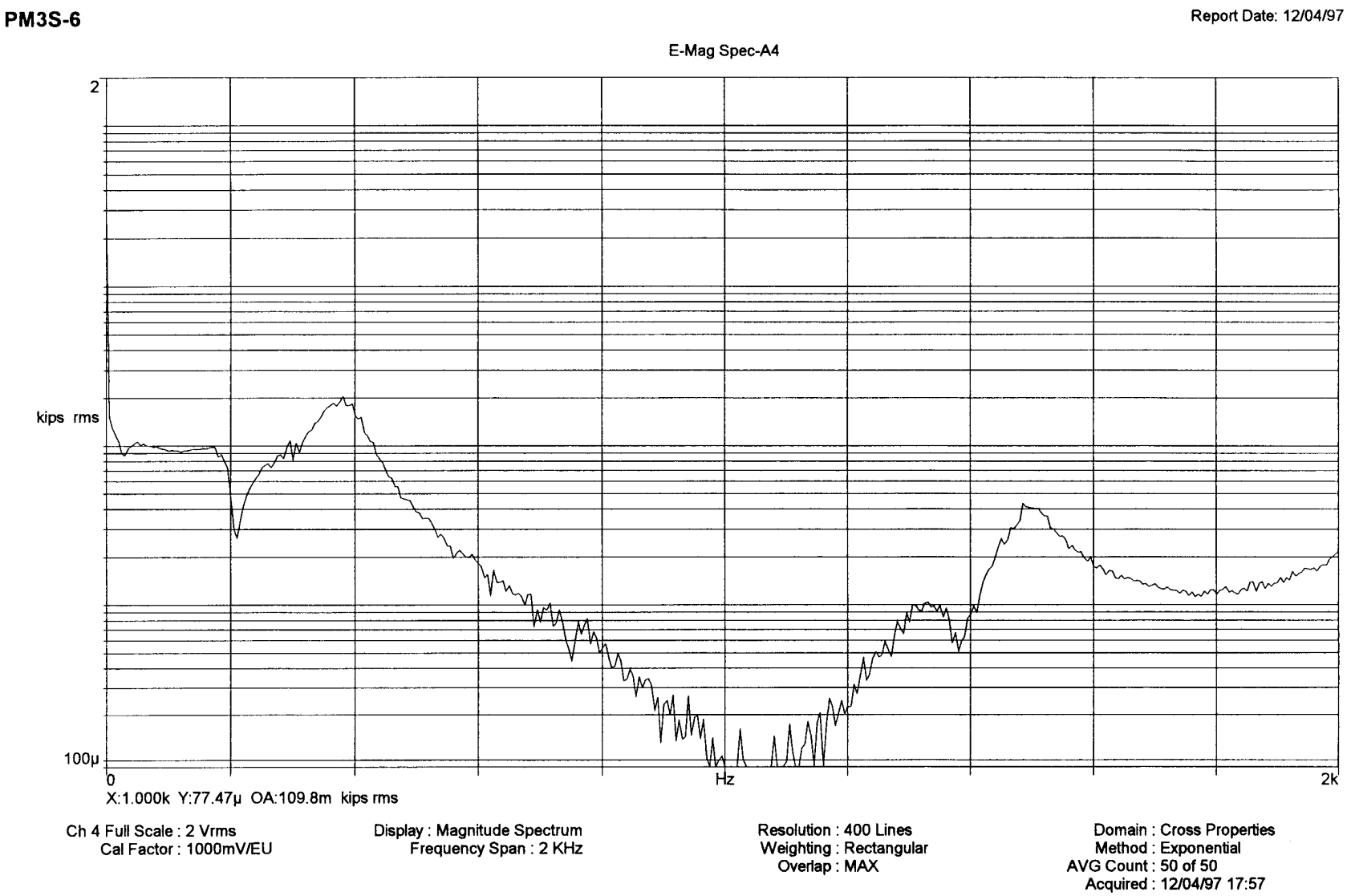


Figure 4-36. P3S-6 E, vertical force input for P unbonded 3 pad fastener, 9,000-lb preload

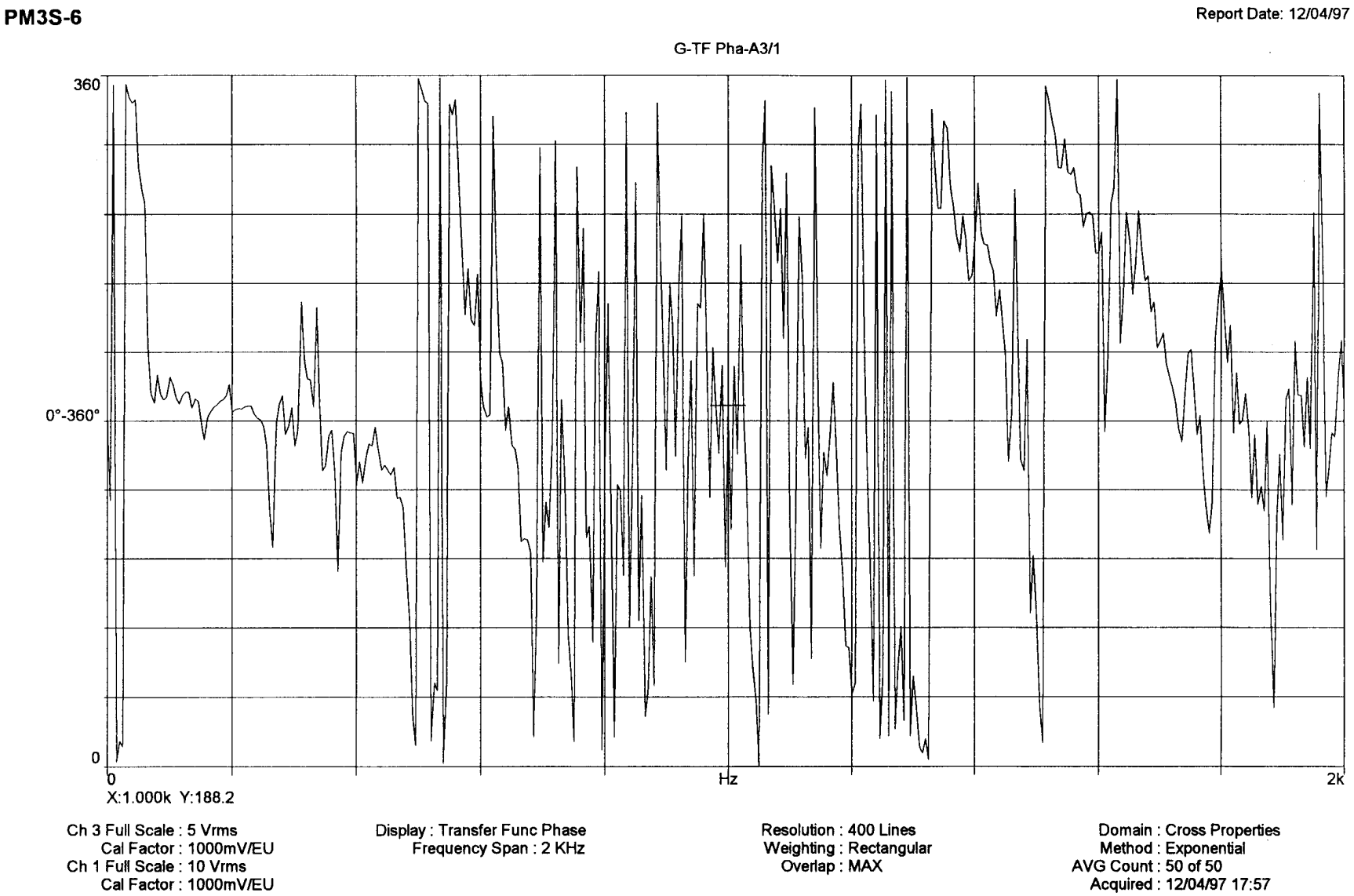


Figure 4-37. P3S-6 G, vertical transfer function phase with O unbonded 2 pad fastener system, 9,000-lb preload

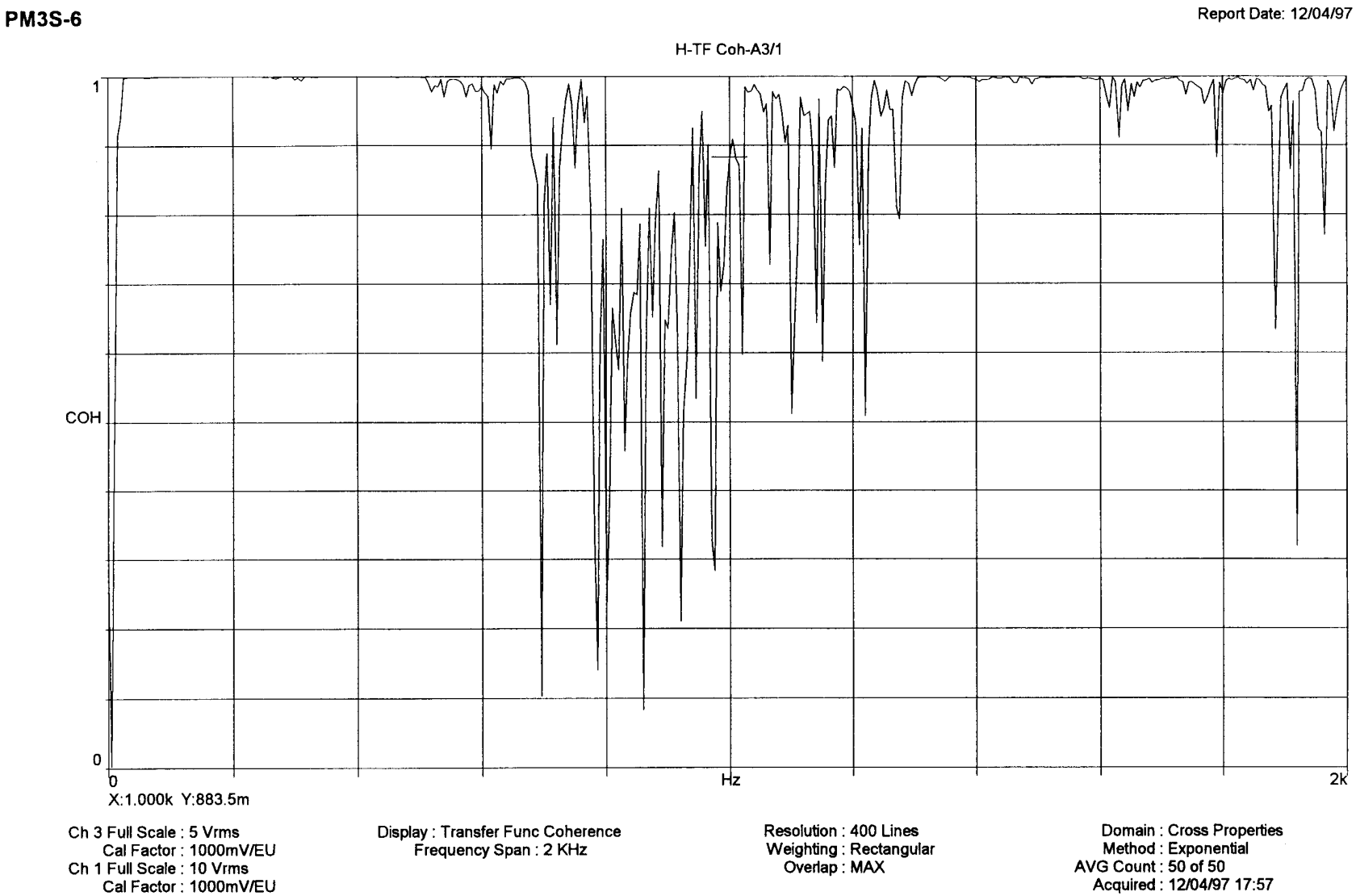


Figure 4-38. P3S-6 H, vertical transfer function coherence for O unbonded 2 pad fastener system, 9,000-lb. preload

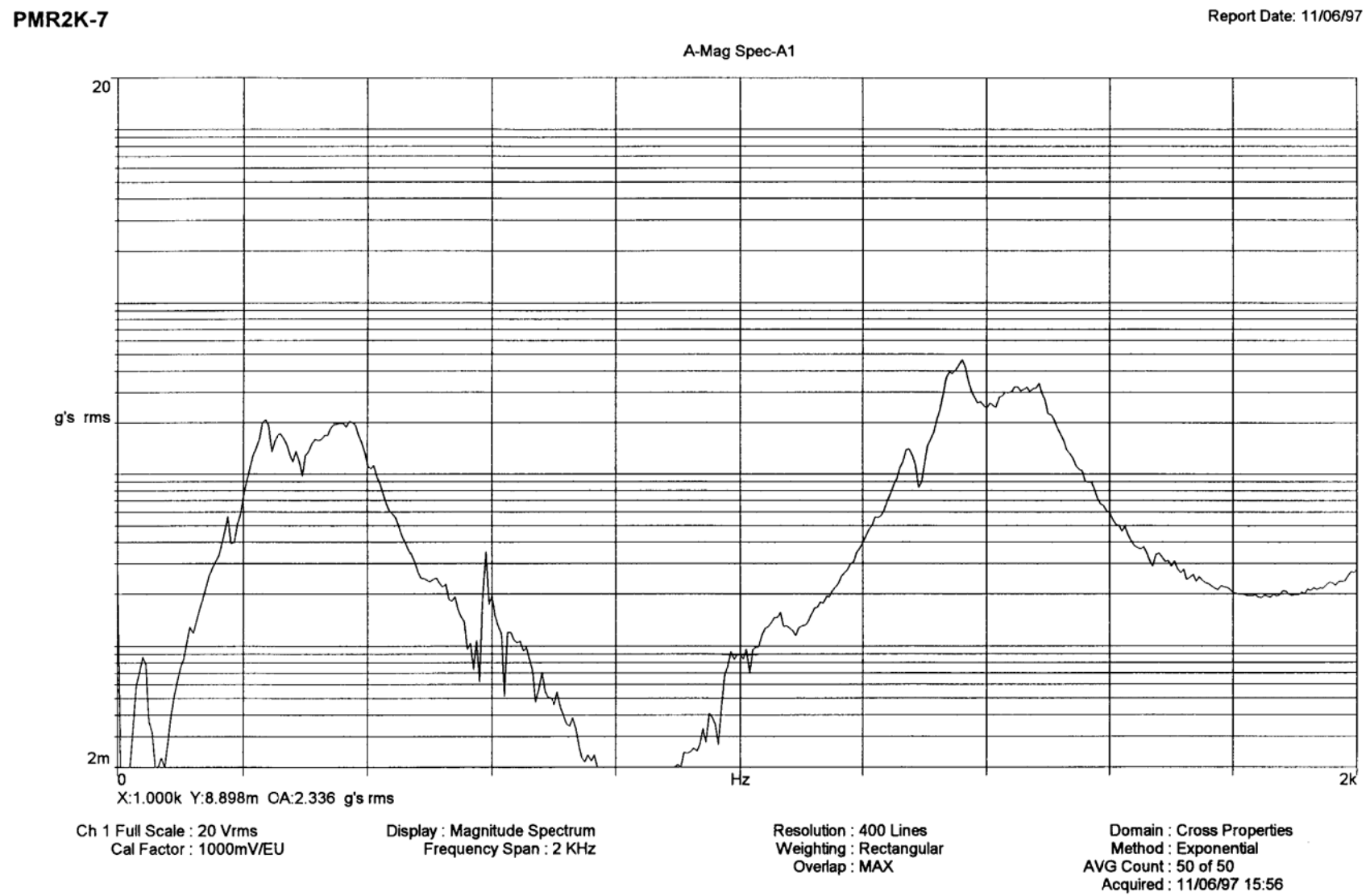


Figure 4-39. PMR 2k-7 A, vertical rail acceleration with O unbonded 2 pad fastener 9,000-lb. preload

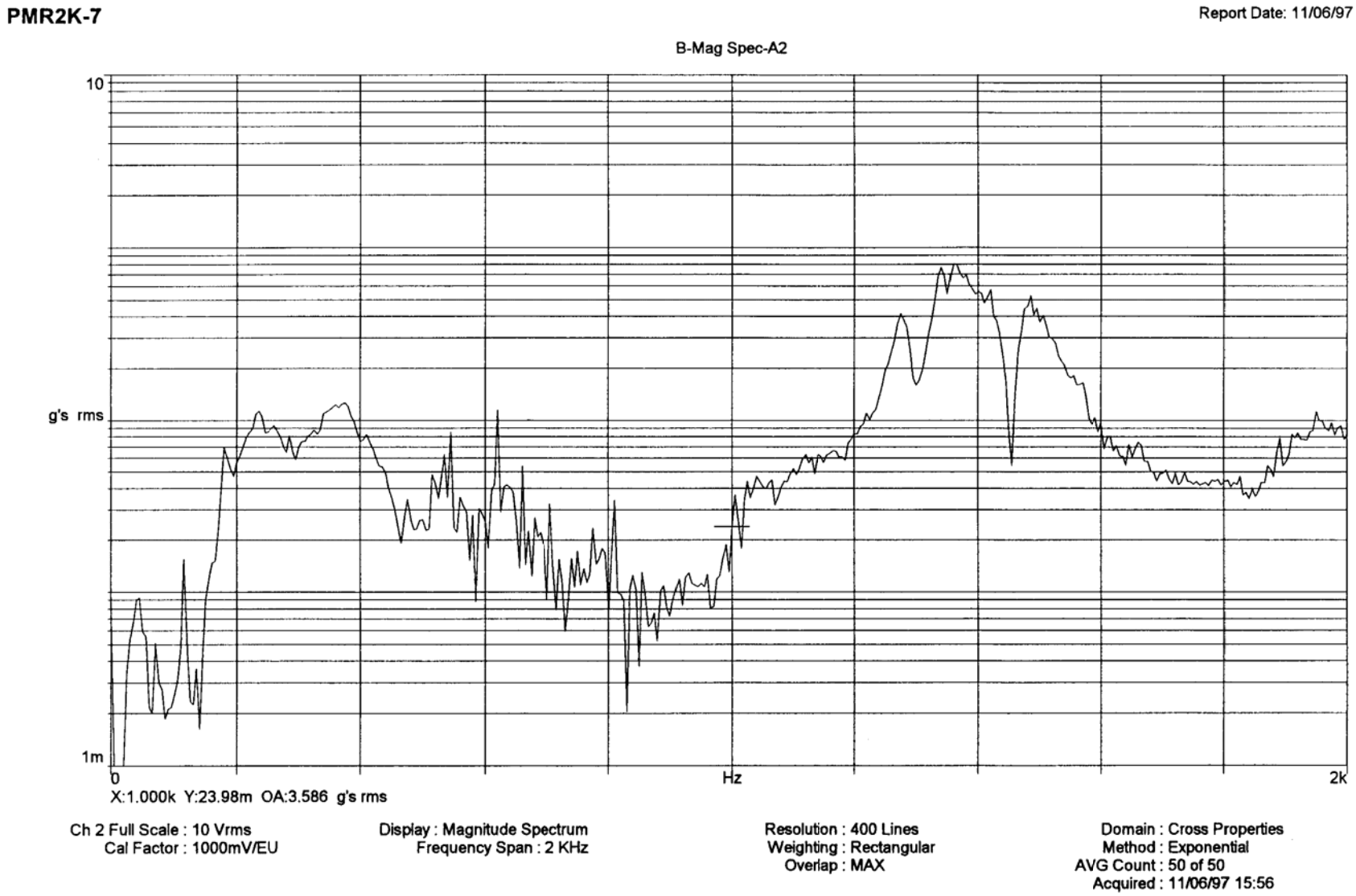


Figure 4-40. PR2 k-7, vertical unbonded 2 pad fastener O top plate acceleration, 9,000-lb. preload

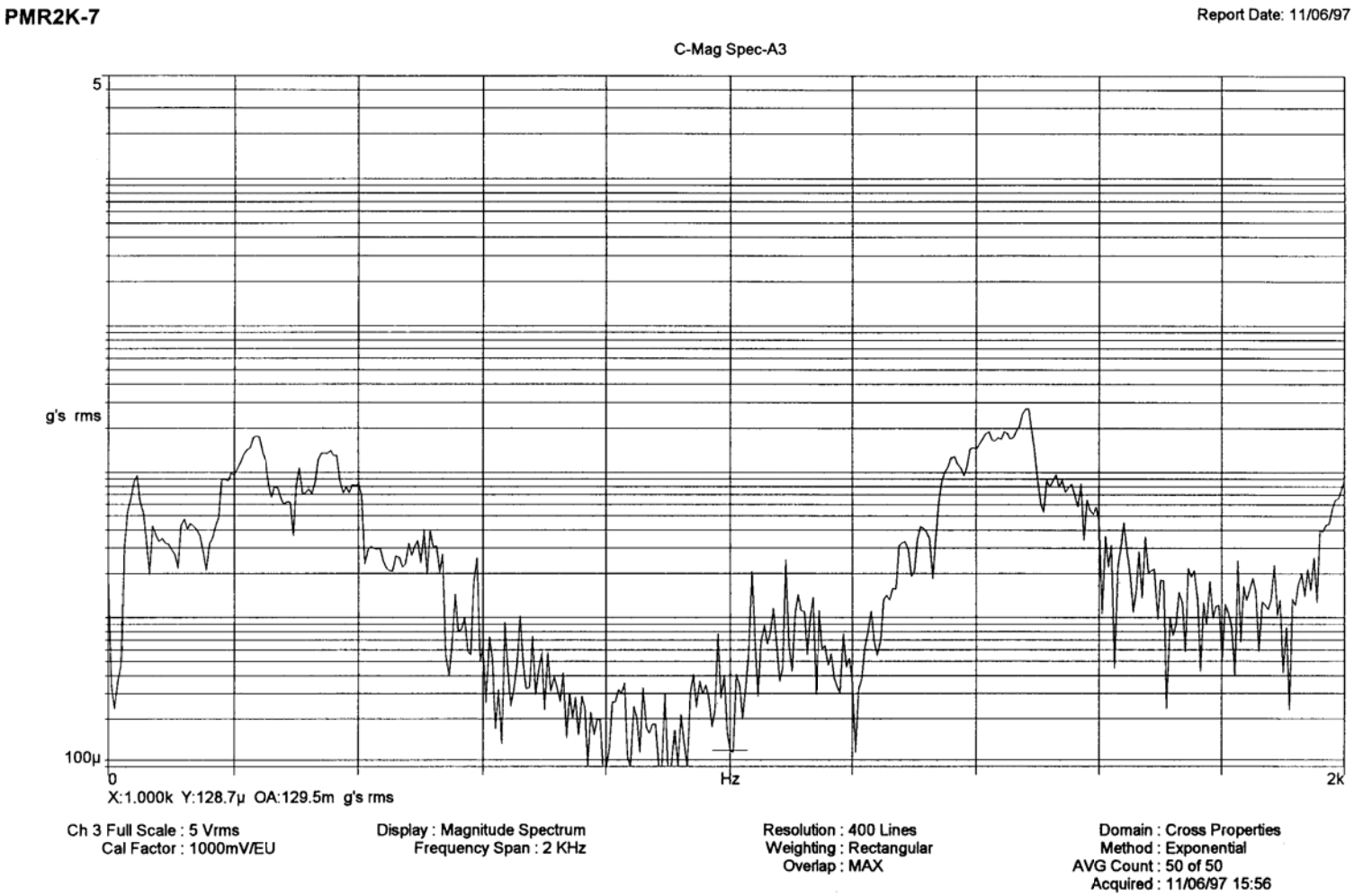


Figure 4-41. PR 2k-7 C, vertical reaction mass acceleration with O unbonded 2 pad fastener, 9,000-lb. preload

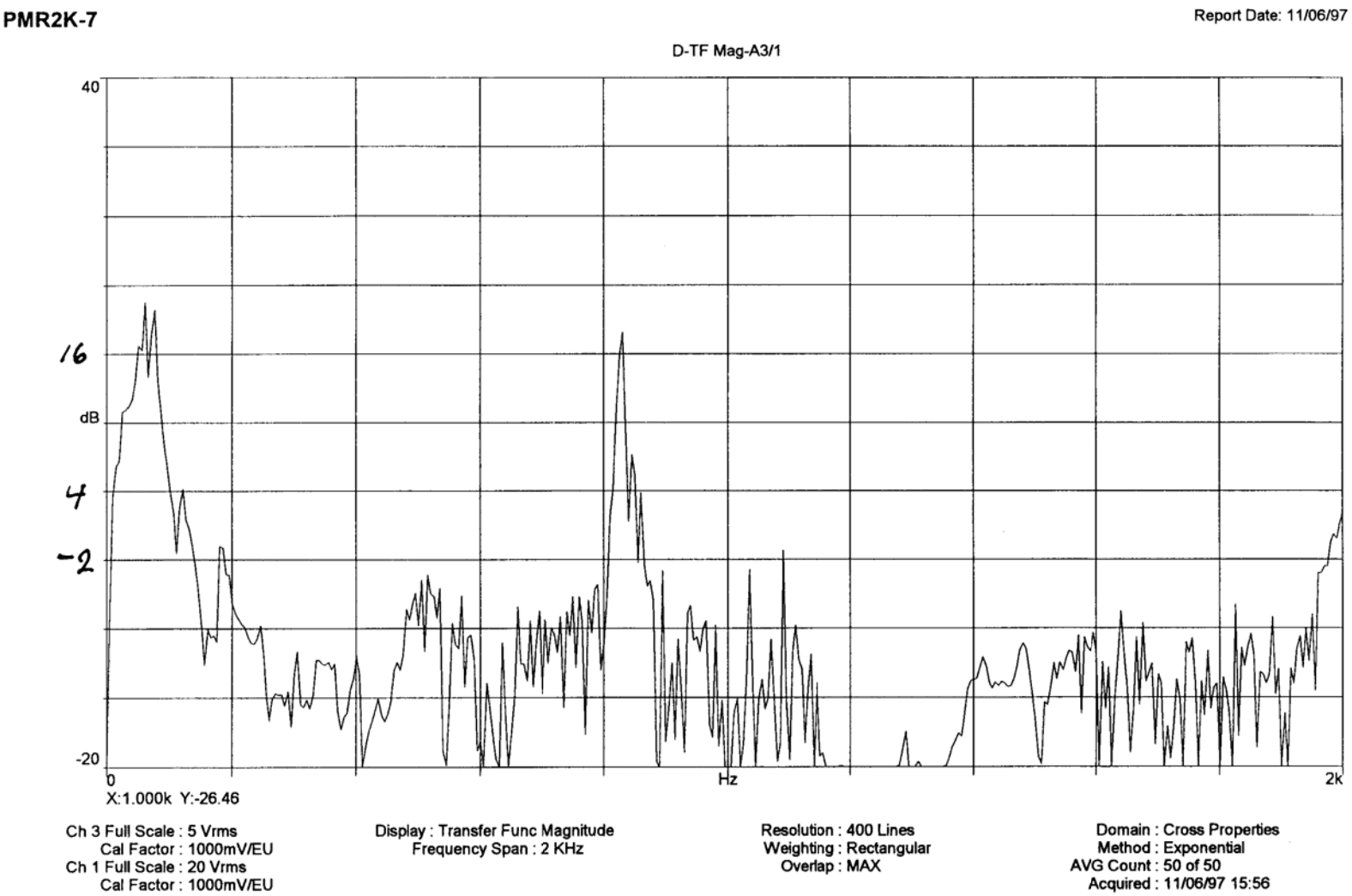


Figure 4-42. PR 2k-7 D, vertical transfer function for O unbonded 2 pad fastener, 9,000-lb. preload

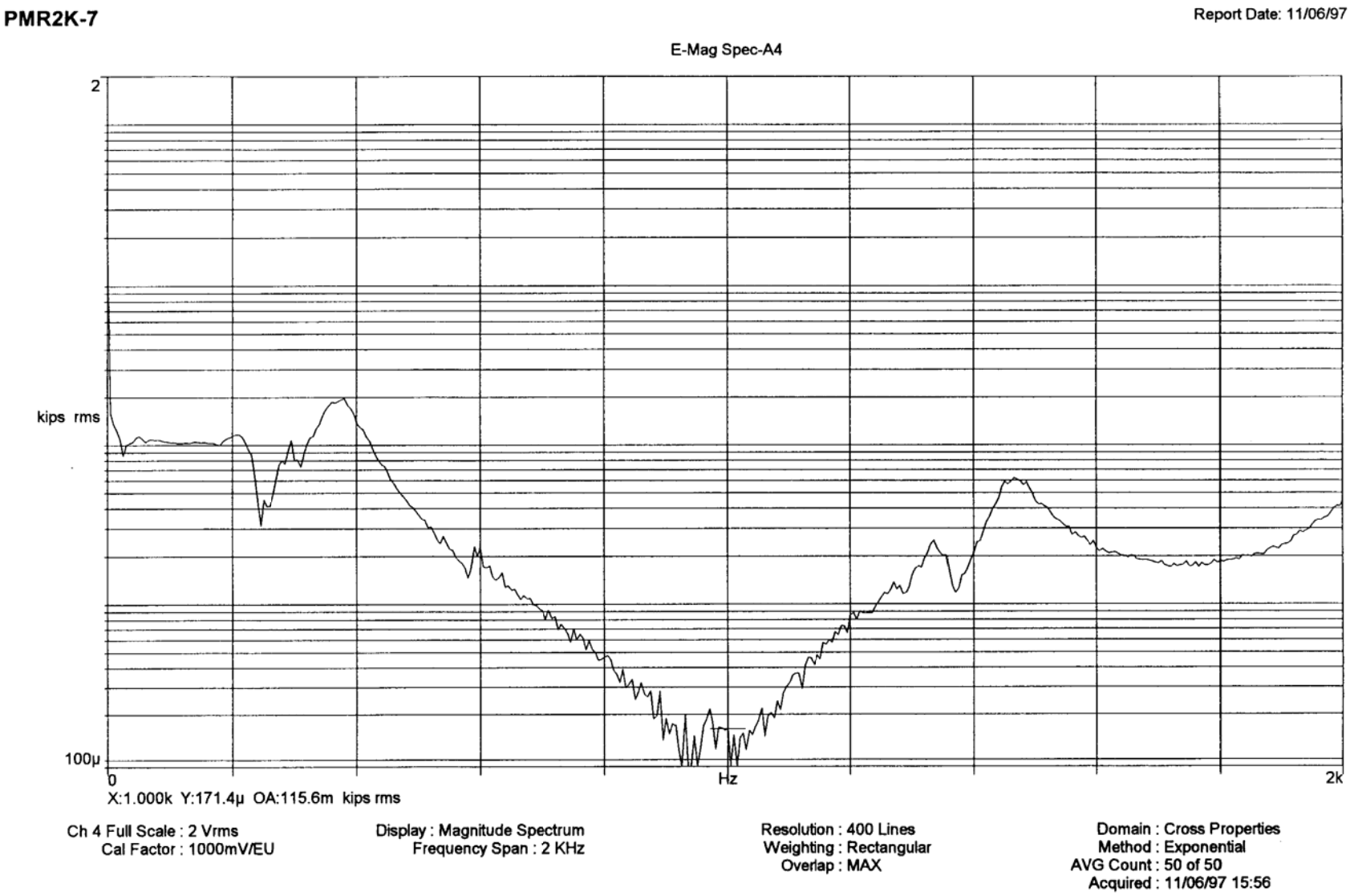


Figure 4-43. PR 2k-7 E, vertical force input for O unbonded 2 pad fastener system, 9,000-lb preload

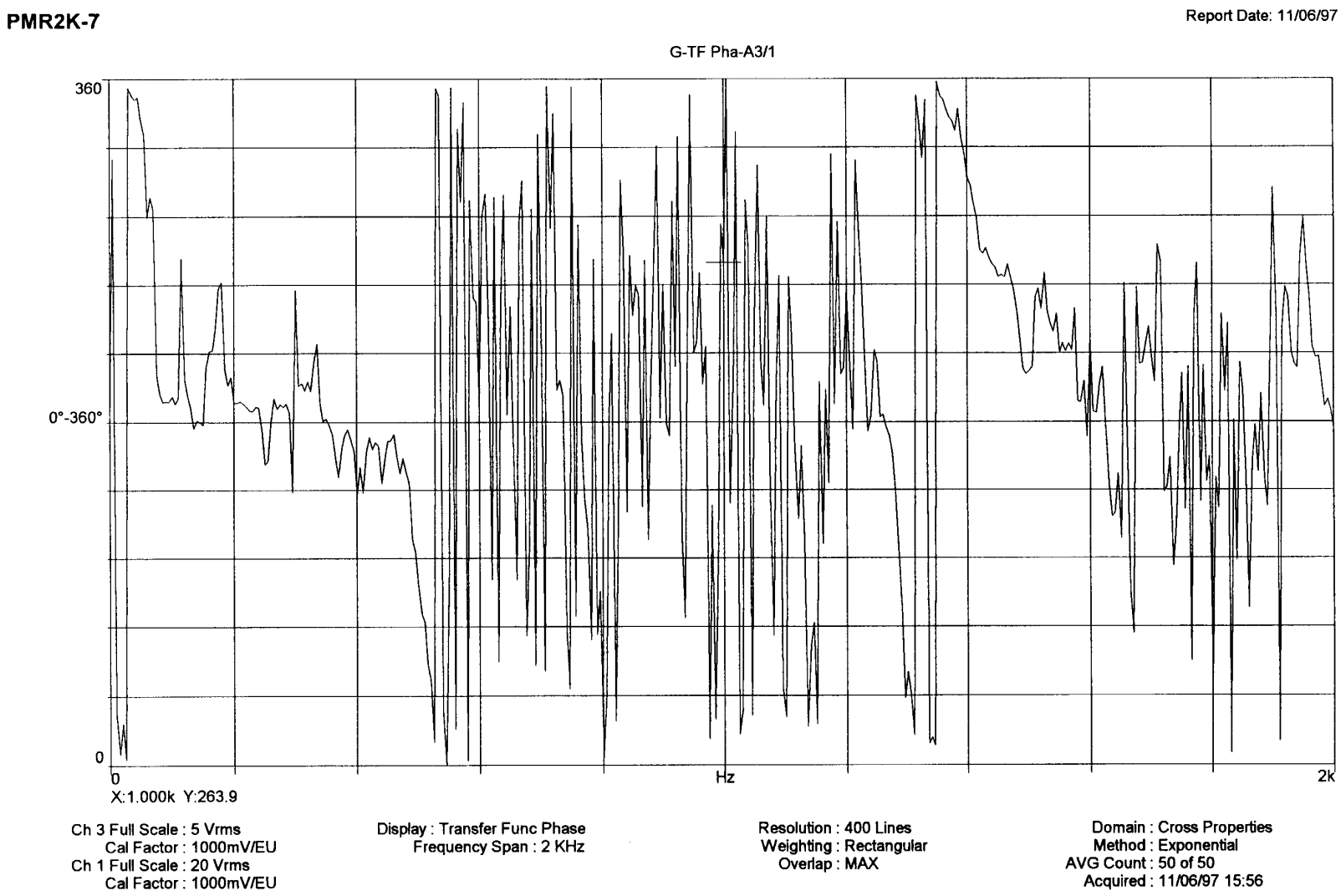


Figure 4-44. PR 2k-7 G, vertical transfer function phase with O unbonded2 pad fastener system, 9,000-lb. preload

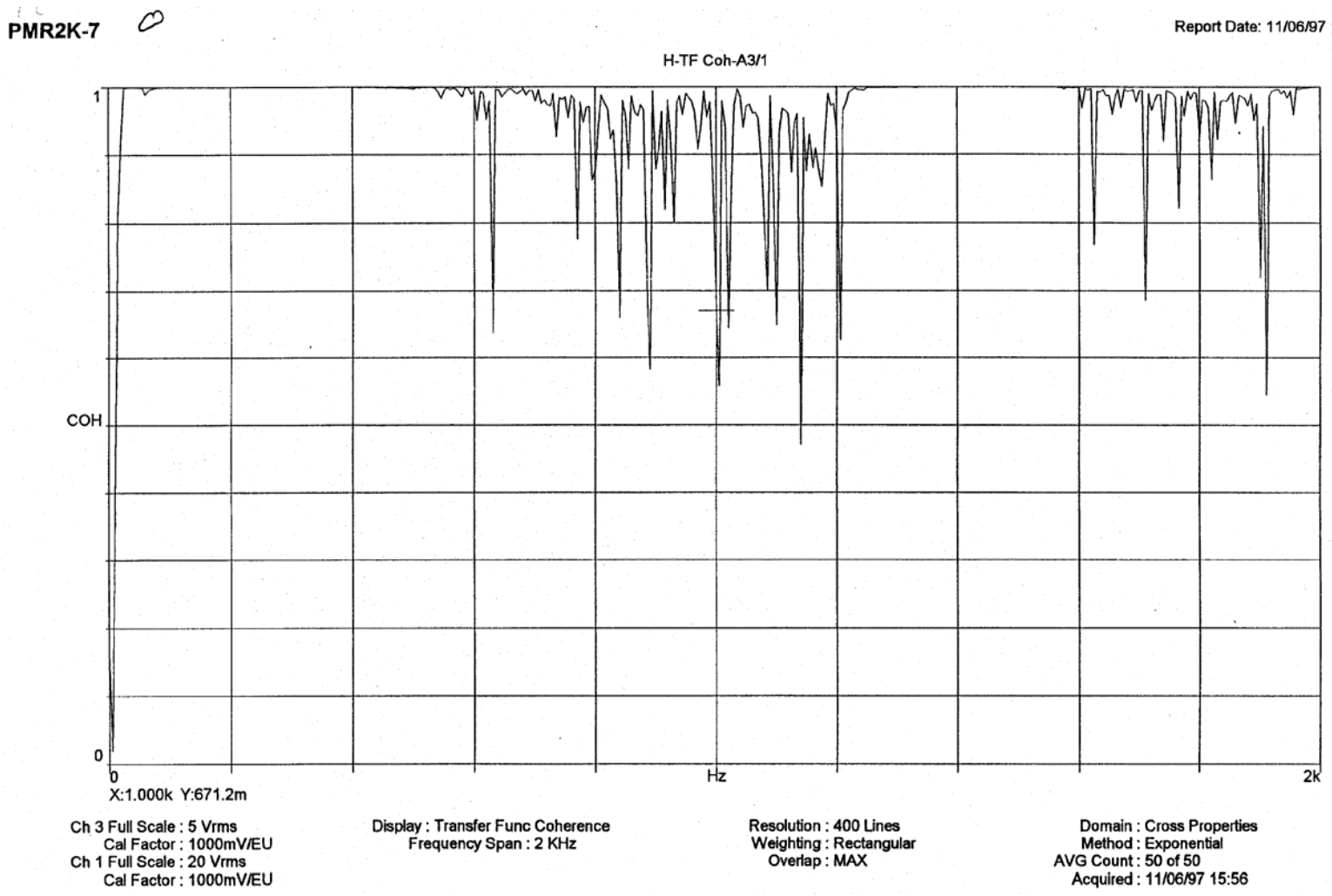


Figure 4-45. PR 2k-7 H, vertical transfer function coherence for O unbonded 2 pad fastener system, 9,000-lb preload

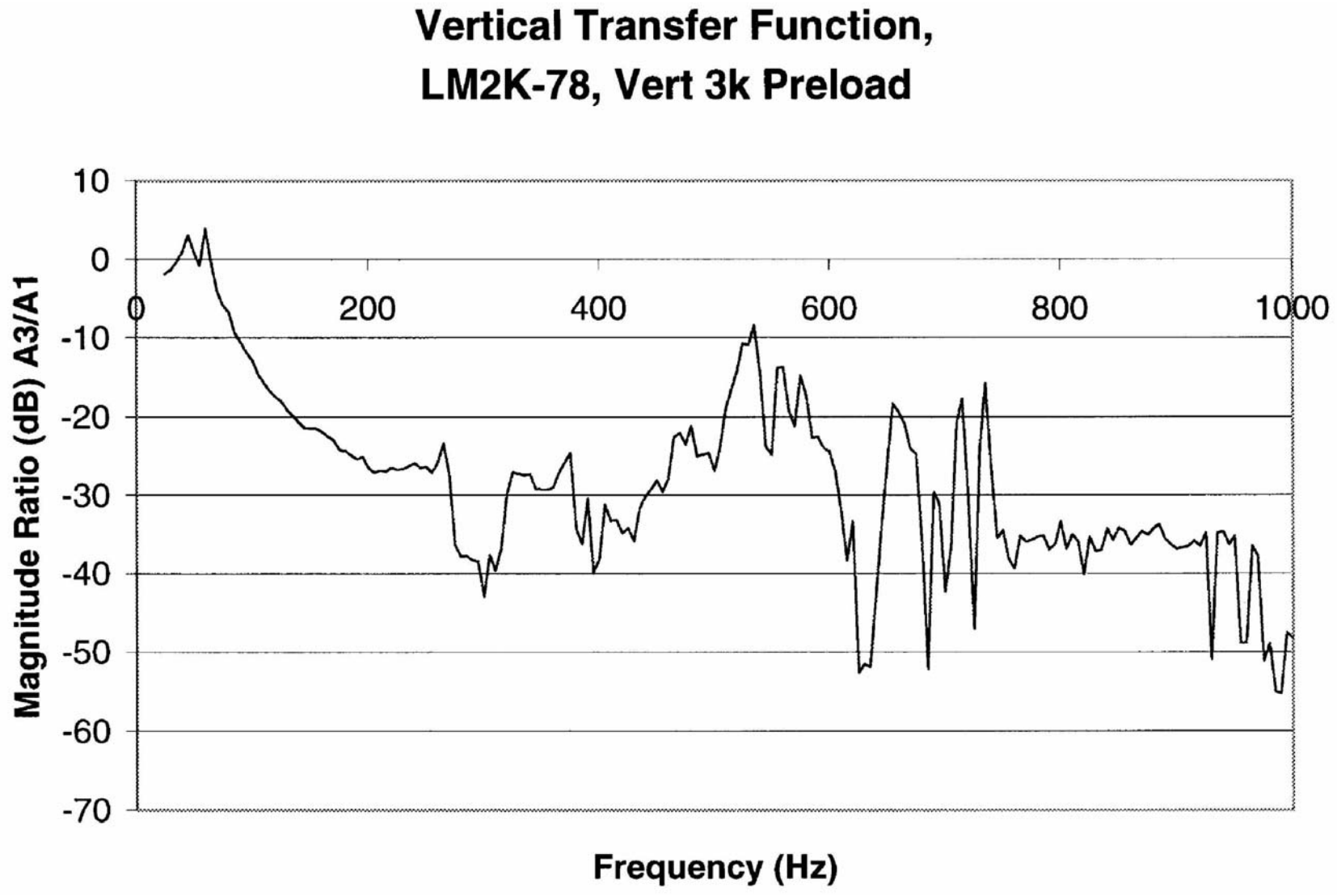


Figure 4-46. Lm2k-78, vertical transfer function for Frame Fastener 1 system, 3,000-lb preload

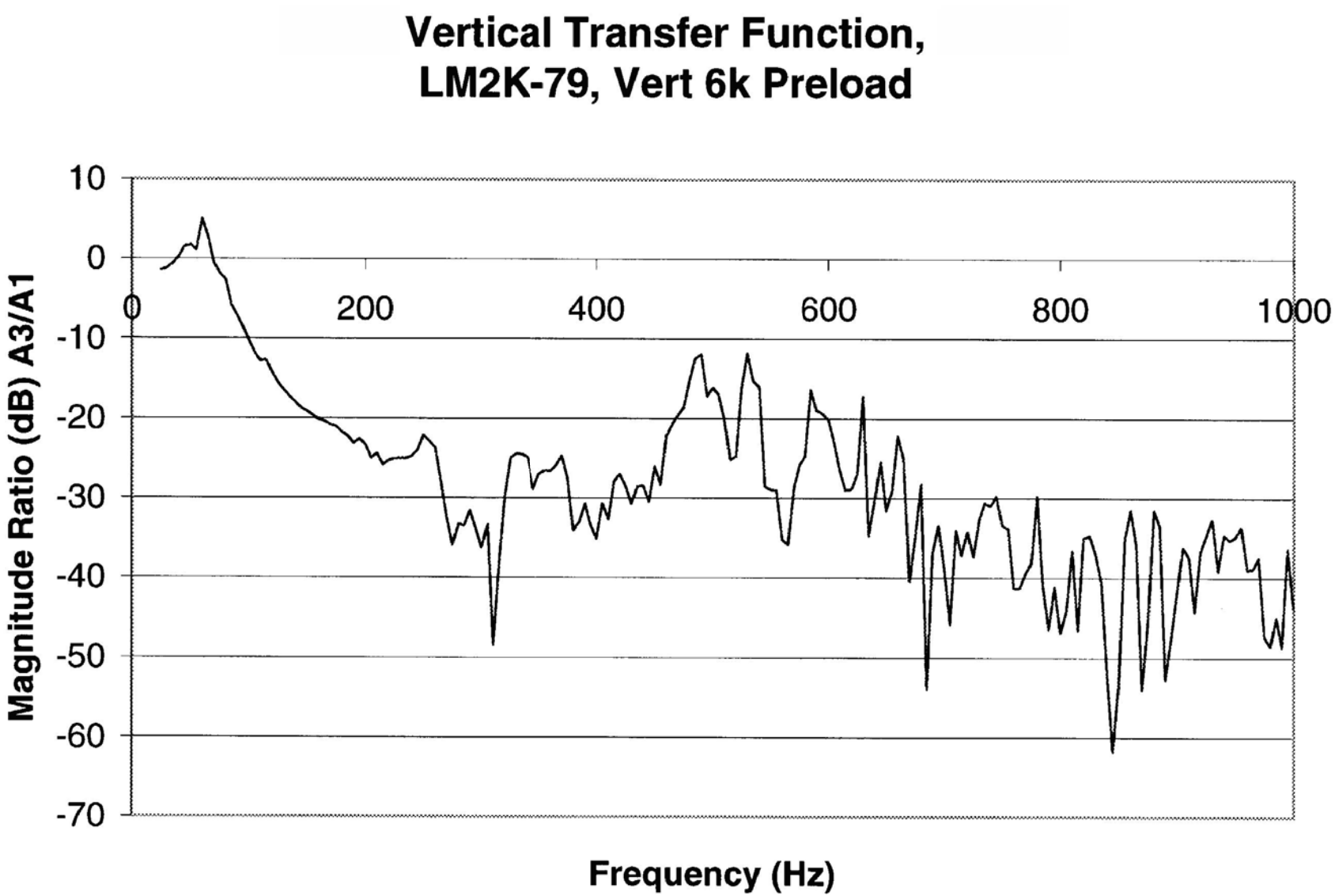
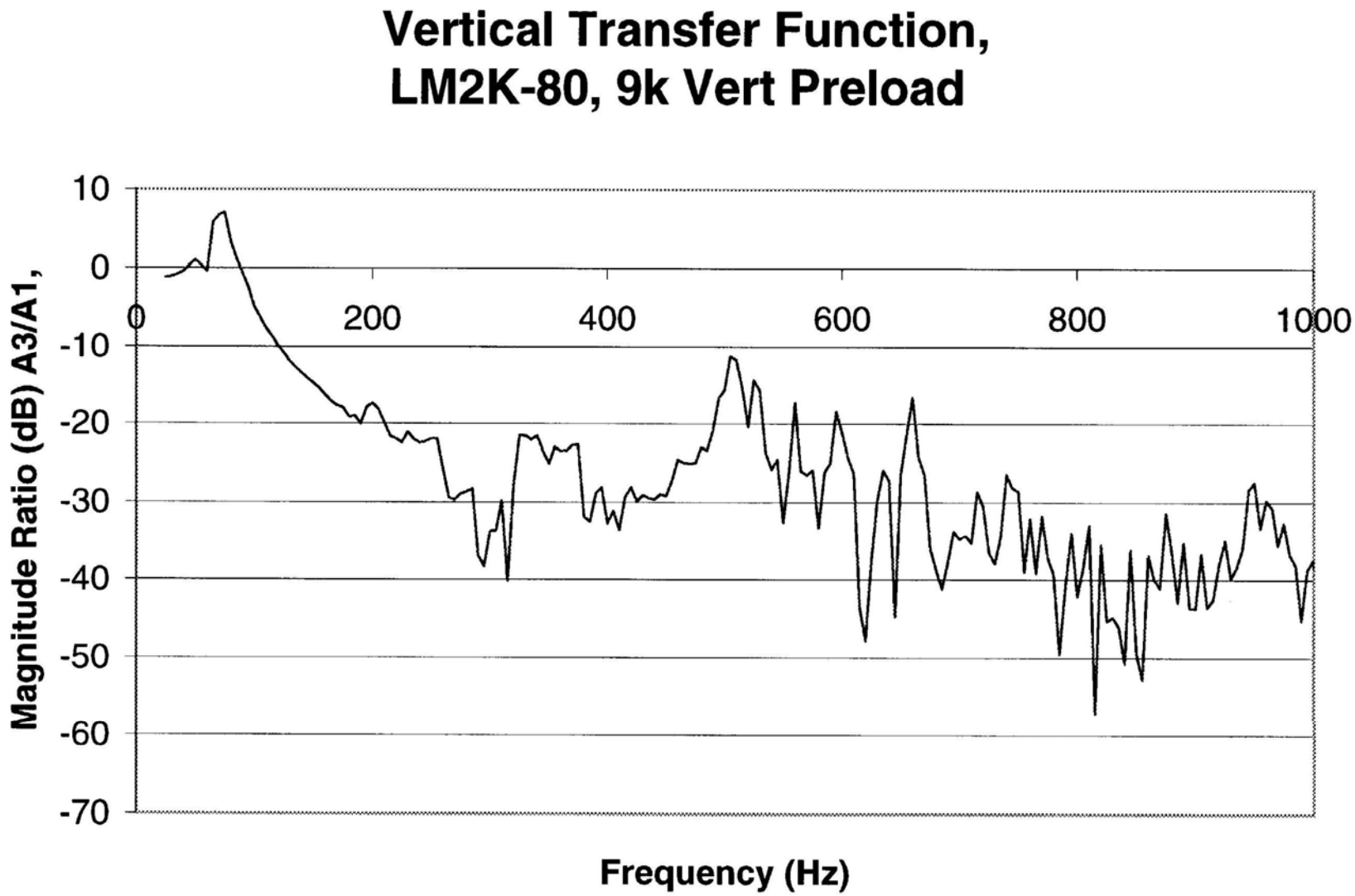


Figure 4-47. Lm2k-79, vertical transfer function for Frame Fastener 1 system, 6,000-lb preload



0

Figure 4-48. Lm2k-80, vertical transfer function for Frame Fastener 1 system, 9,000-lb. preload

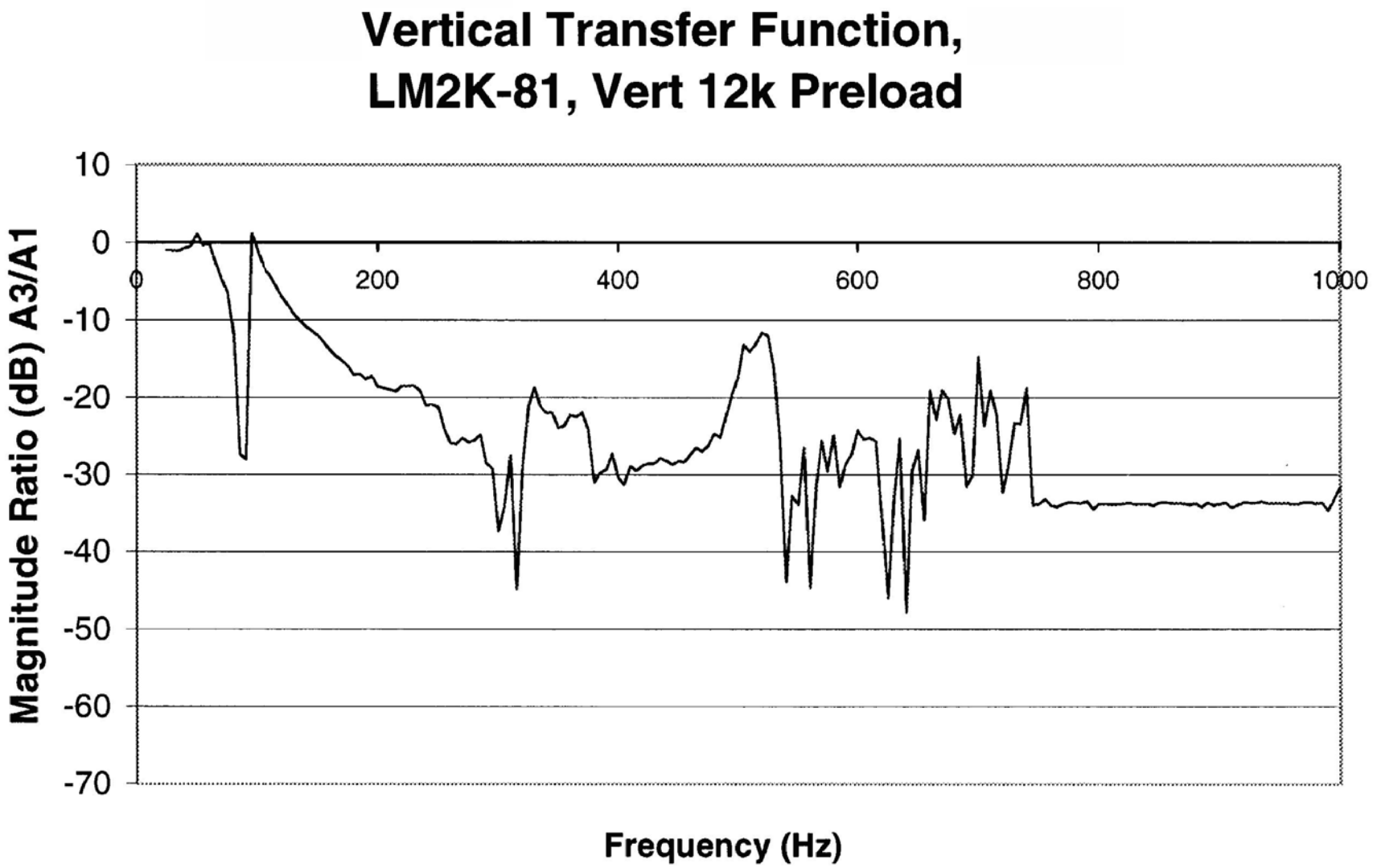


Figure 4-49. Lm2k-81, vertical transfer function for Frame Fastener 1 system, 12,000-lb. preload

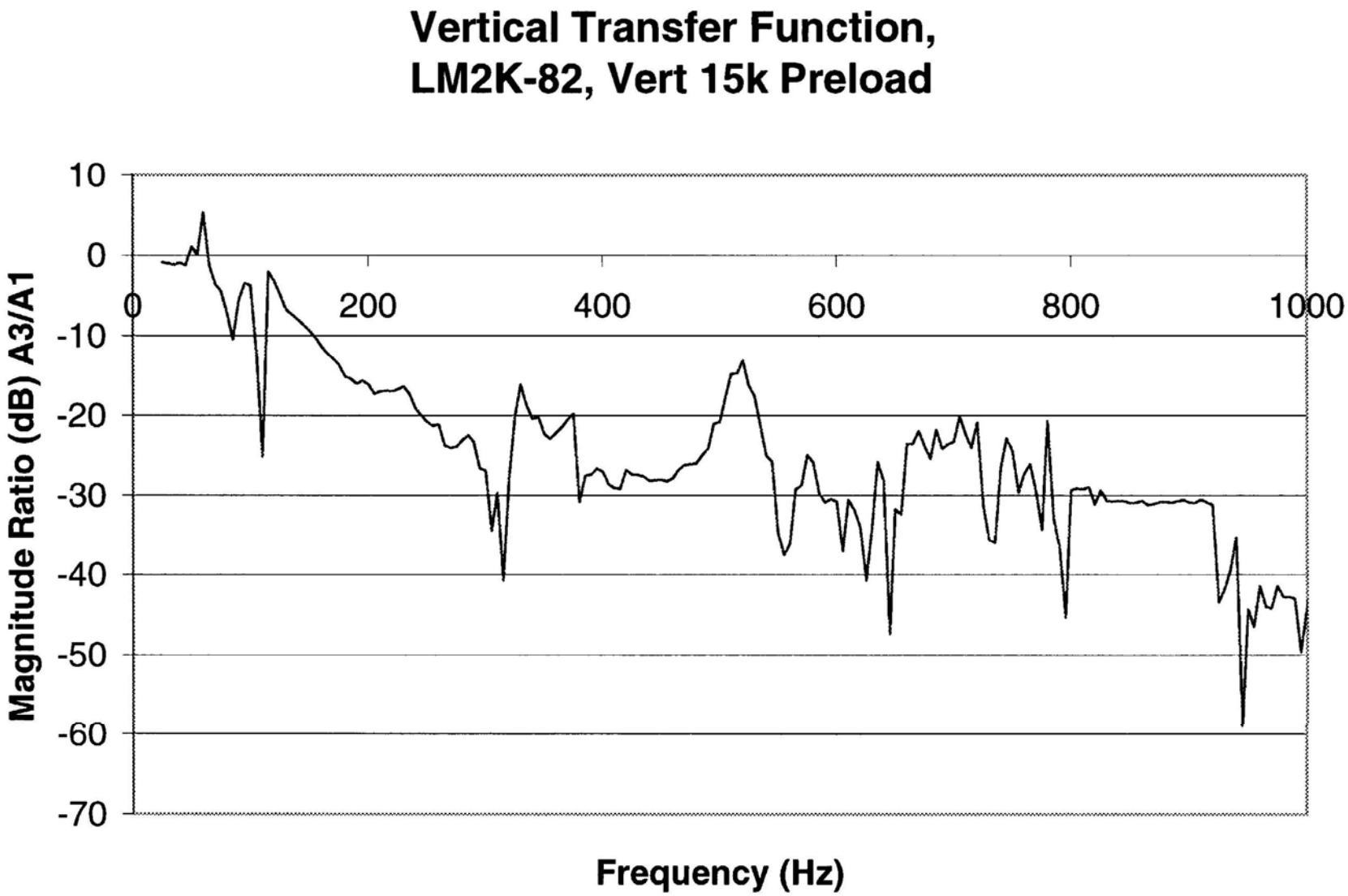


Figure 4-50. Lm2k-82, vertical transfer function for Frame Fastener 1 system, 15,000-lb. preload

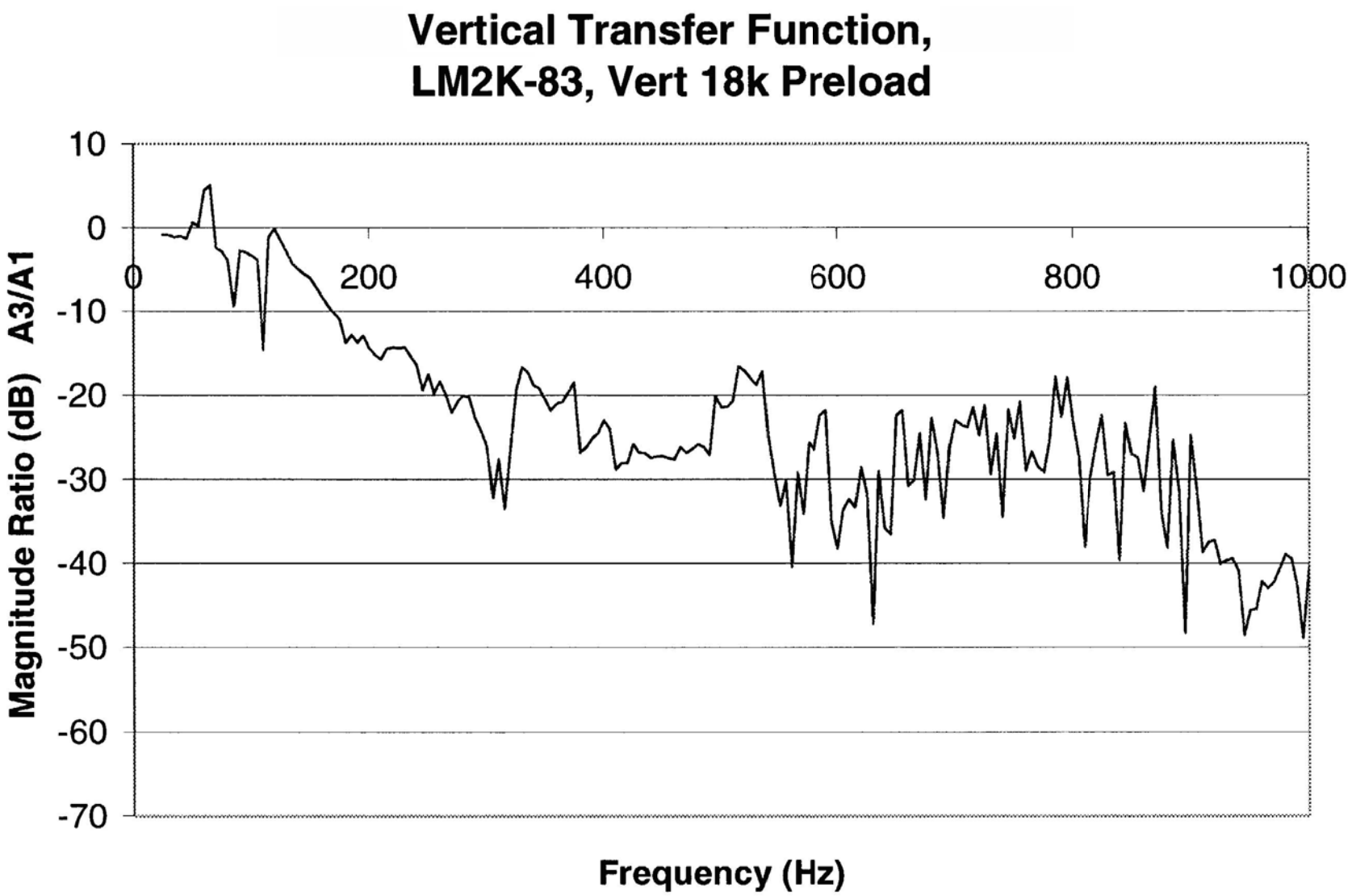


Figure 4-51. Lm2k-83, vertical transfer function for Frame Fastener 1 system, 18,000-lb. preload

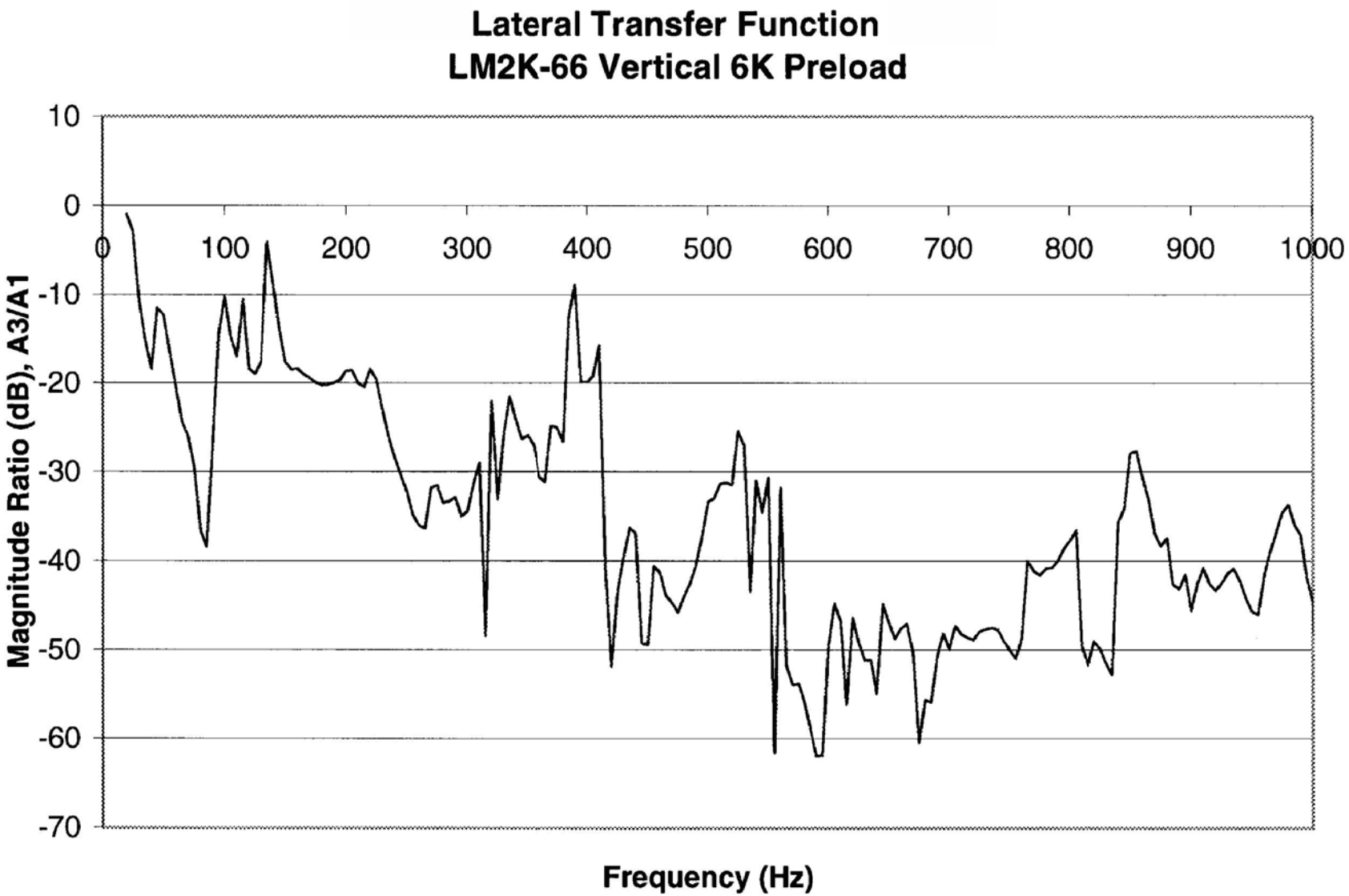


Figure 4-52. Lm2k-66, lateral transfer function for Frame Fastener 1 system, 6,000-lb. preload

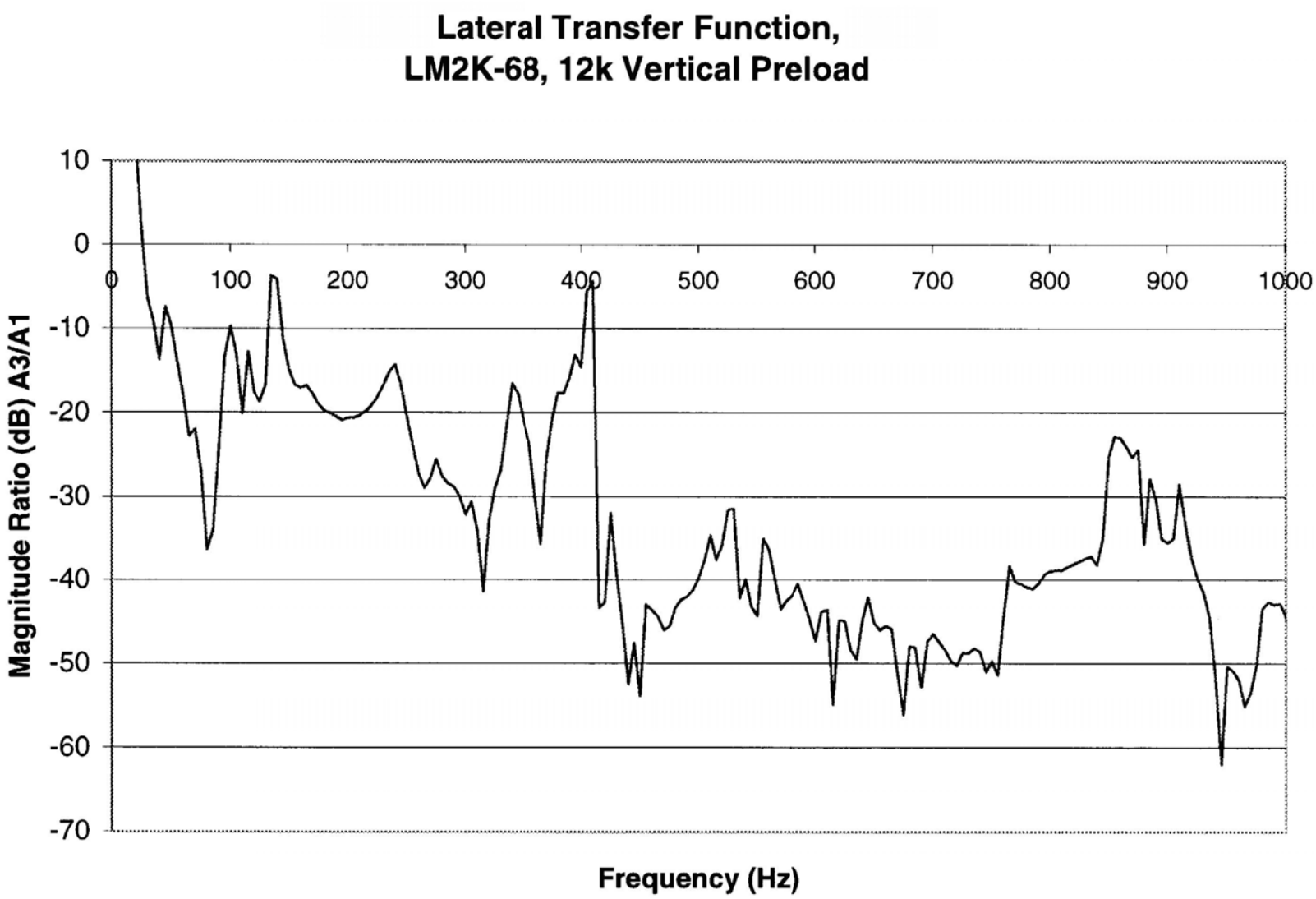


Figure 4-53. Lm2k-68, lateral transfer function for Frame Fastener 1 system, 12,000-lb. preload

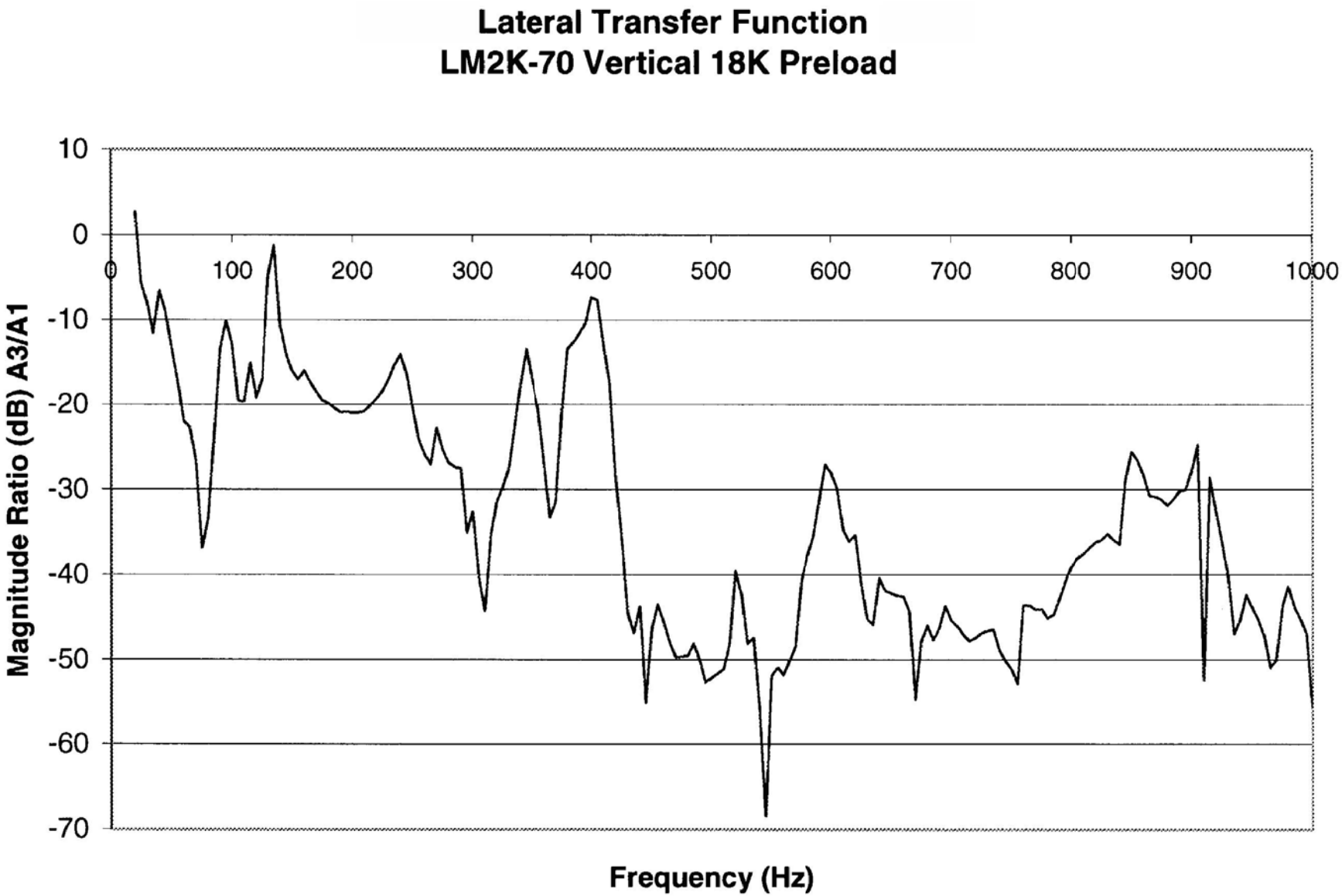


Figure 4-54. Lm2k-70, lateral transfer function for Frame Fastener 1 system, 18,000-lb. preload

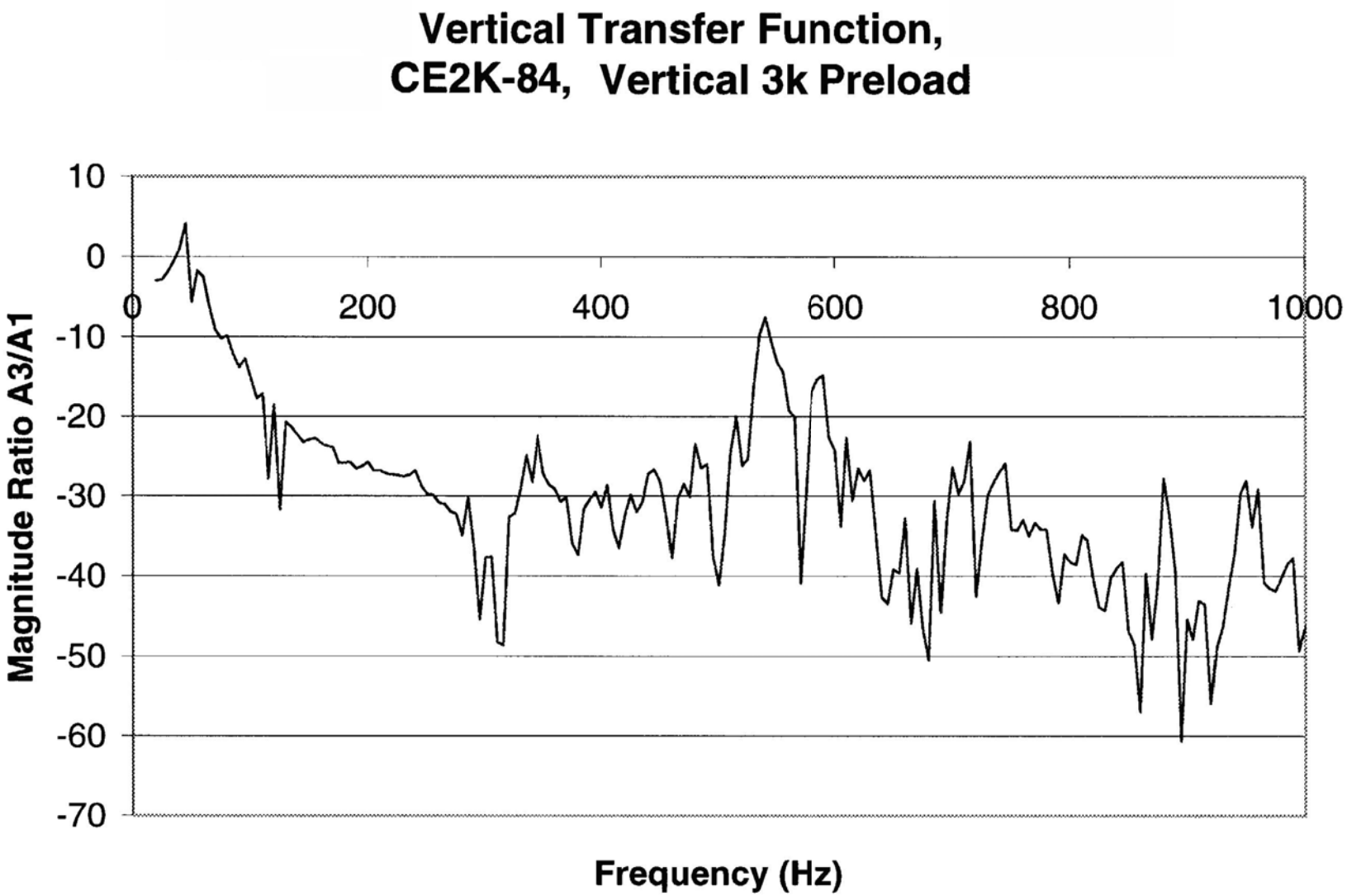


Figure 4-55. Ce2k-84, vertical transfer function for frame fastener 2 system, 3,000-lb. preload

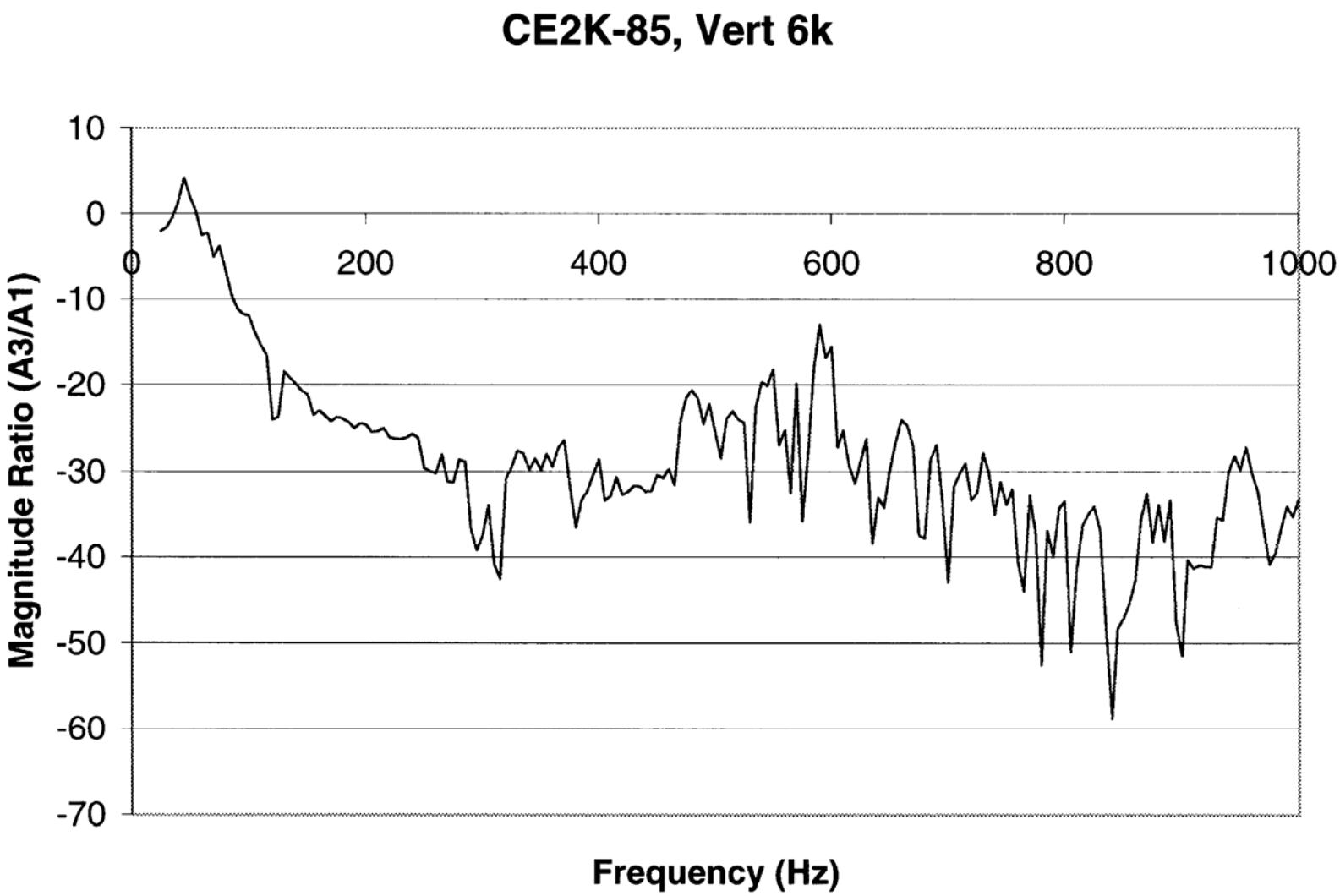


Figure 4-56. Ce2k-85, vertical transfer function for frame fastener 2 system, 6,000-lb. preload

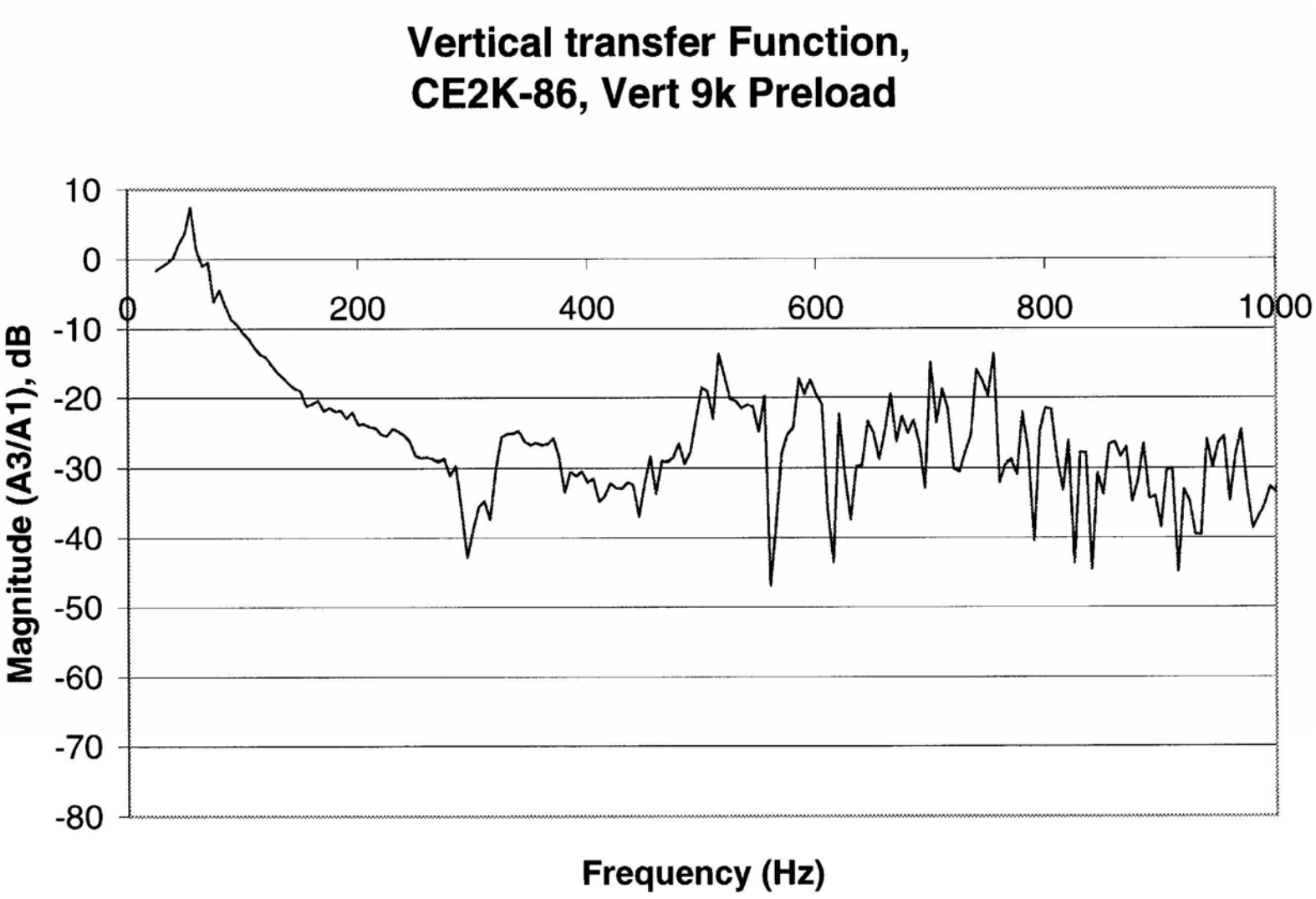


Figure 4-57. Ce2k-86, vertical transfer function for frame fastener 2 system, 9,000-lb. preload

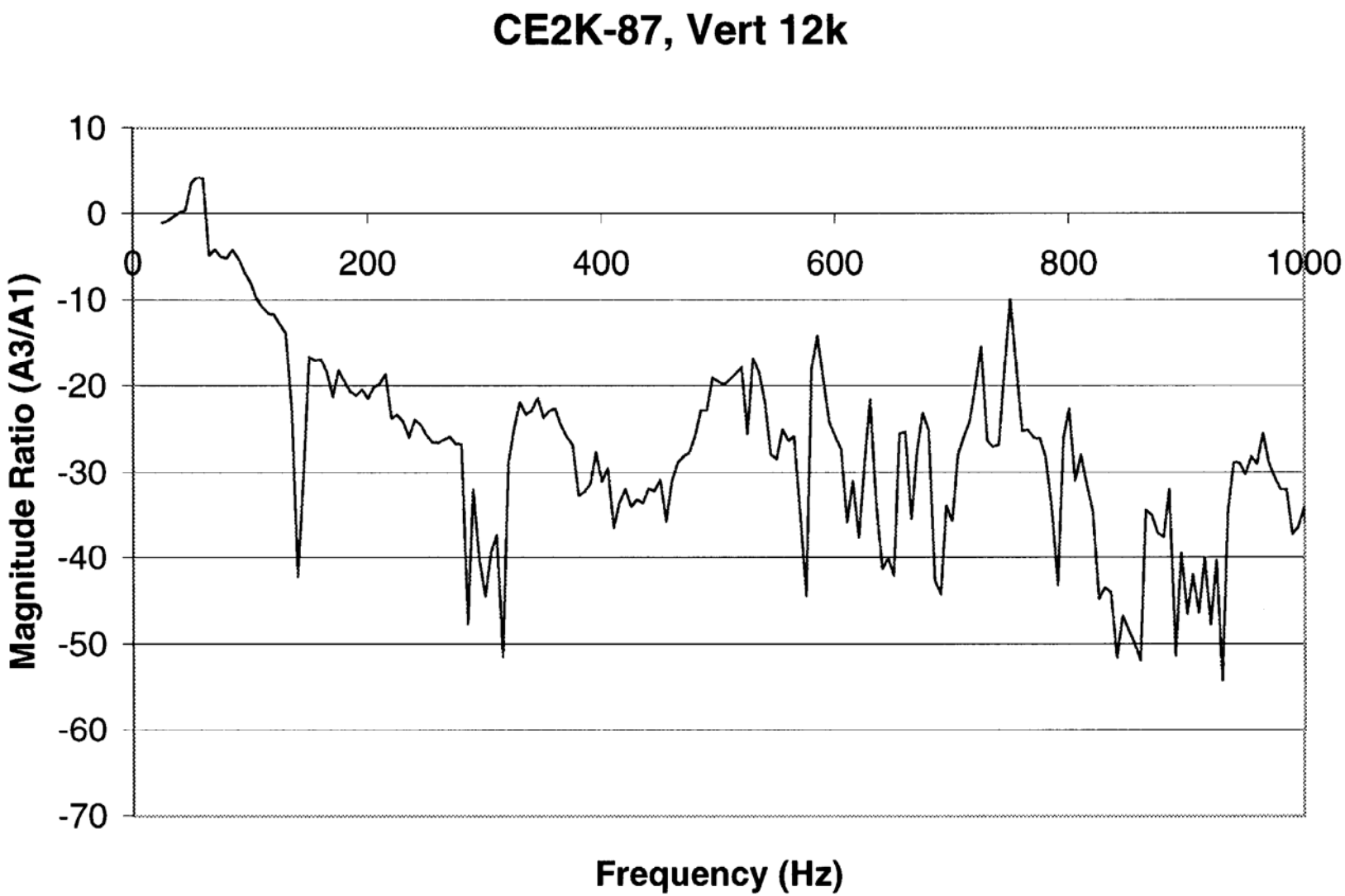


Figure 4-58. Ce2k-87, vertical transfer function for Frame Fastener 2 system, 12,000-lb. preload

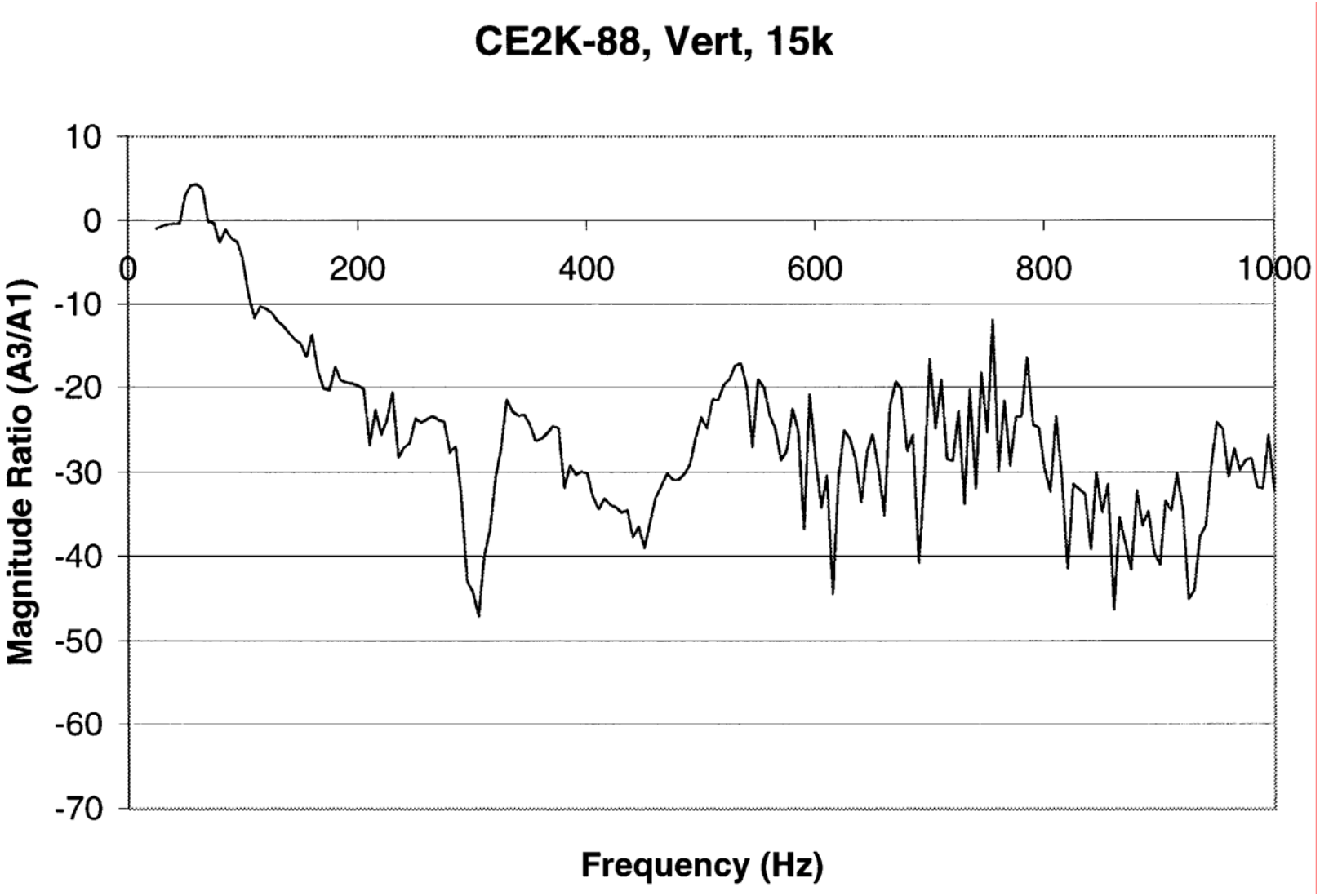


Figure 4-59. Ce2k-88, vertical transfer function for Frame Fastener 2 system, 15,000-lb. preload

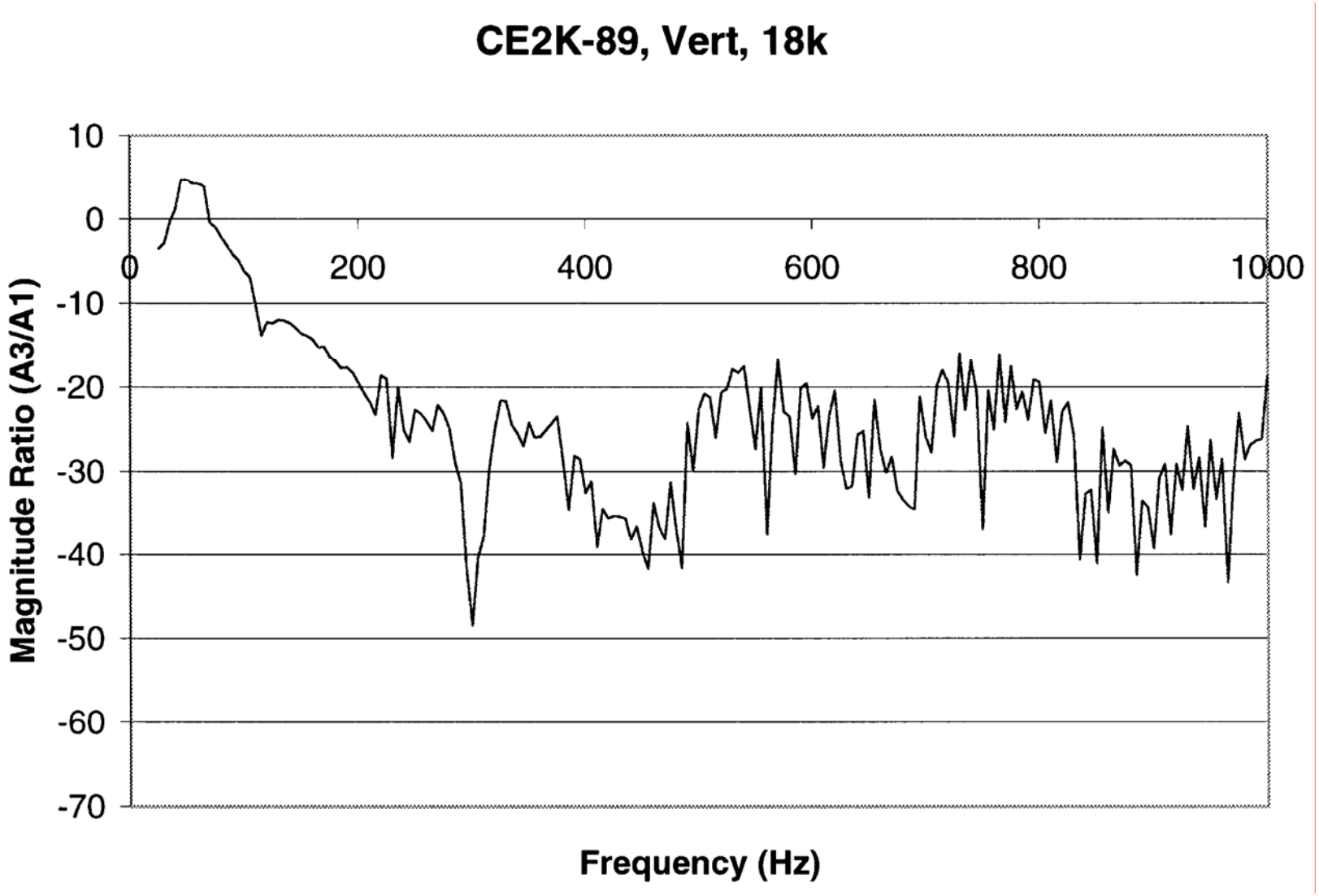


Figure 4-60. Ce2k-89, vertical transfer function for Frame Fastener 2 system, 18,000-lb. Preload

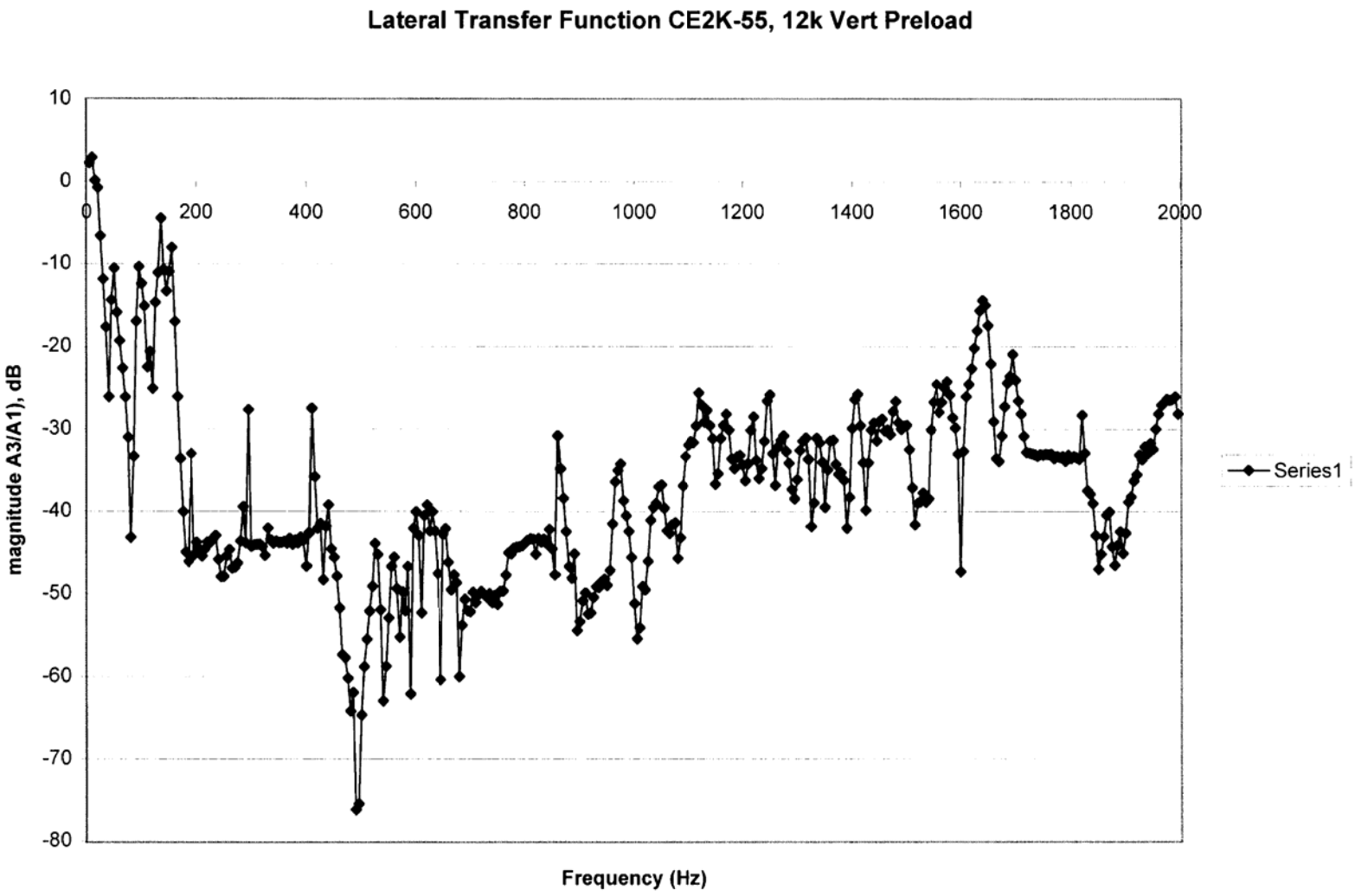


Figure 4-61. Frame Fastener 2 lateral transfer function

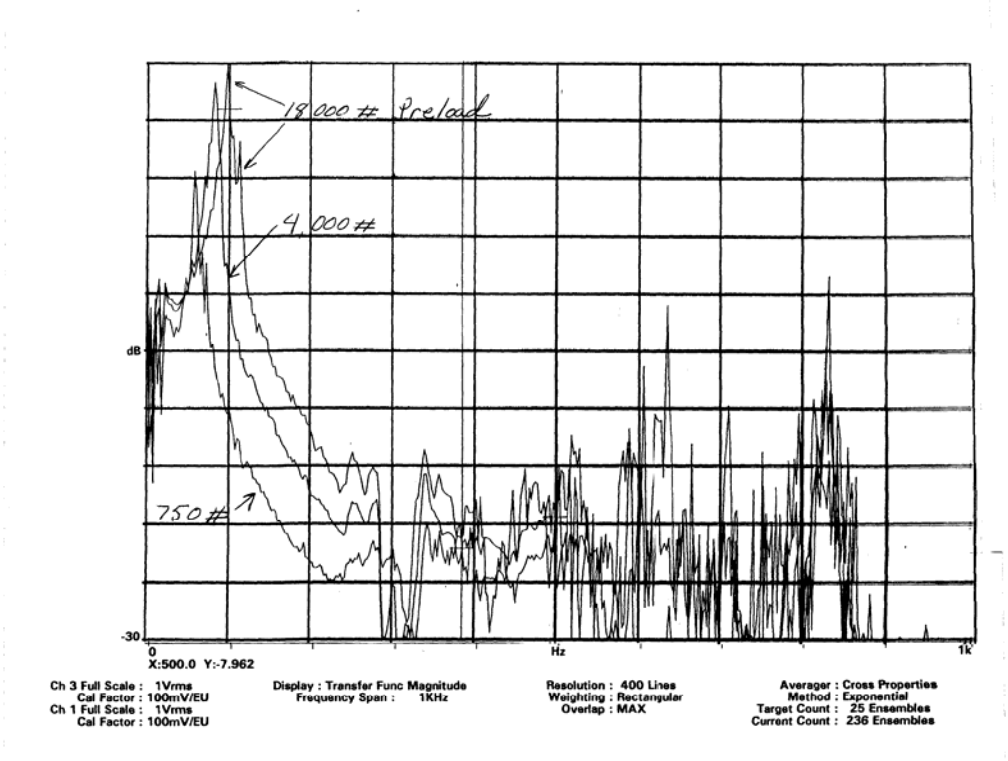


Figure 4-62. Frequency shift with load for Frame Fastener 1 system

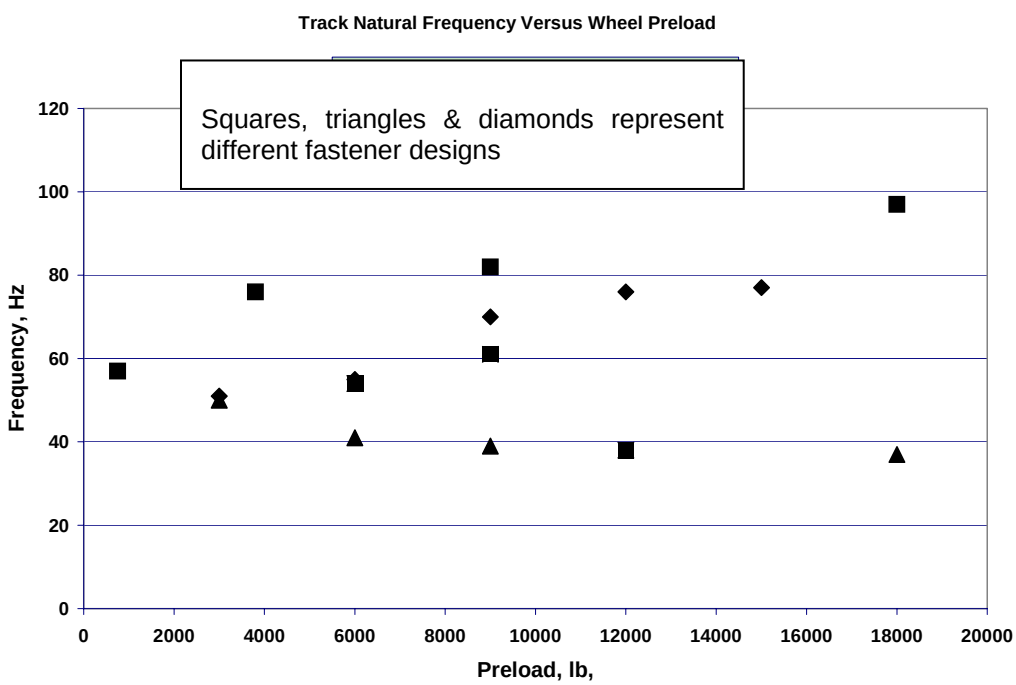


Figure 4-63. Track natural frequency vs. wheel preload, 4 different fastener systems

5. Rail Seat Friction Testing and Push Pull with Misalignment

An element of Direct Fixation track design is control of longitudinal forces. The design balances the need to have as much longitudinal restraint as practical (control rail end gaps that may occur if the rail breaks and to constrain the rail from running through the fastener during train braking and acceleration) with concern for supporting structures that may incur increased pier loads (and therefore more expensive structures) from high longitudinal restraint. The value of rail seat and rail clip friction is a defining parameter in the analysis that must be performed to access the ability of a particular track form and fastener to satisfy the particular requirements of specific applications.

5.1 Objective

The first objective is to determine rail seat forces and friction values for in-service conditions. It is important to determine the variation due to normal conditions that affect the assumptions in design. As an example, if wet conditions significantly modify friction values, an adjustment in design assumptions may be needed.

The second objective is to determine values of rail longitudinal resistance from construction misalignments within tolerances. The second objective is very important in partial and low longitudinal restraint track systems. In zero restraint systems, a real support structure design assumes that the rail will produce little or no longitudinal force. If the normal misalignments between fasteners produce restraint then a design assumption is invalidated.

5.2 Expected Results

The expected result from this activity is practical friction values that are essential for determining longitudinal rail restraint of fasteners. It is necessary to assure realistic values are used for design analysis rather than values that are at the extreme end of practical friction values.

The expected result from the misalignment work is information on the effects of probable field conditions on longitudinal restraint and fastener degradation. The results have application in low longitudinal restraint systems and, in the qualification tests, for all fasteners.

5.3 Approach

The tests experimentally determined rail seat friction values from longitudinal restraint tests with common rail seat conditions of moisture and contaminants. A fastener was mounted in a rail longitudinal test fixture and a rail set in place with rail clip assemblies installed. Several different rail clips were used in the test matrix. The clip toe load was measured in all cases using existing fixtures.

The rail seat friction of the fastener and the clip-rail contact was tested under conditions varying from dry to highly slippery using water and grease as a lubricant. The moisture levels and application methods will simulate light, moderate and heavy rainfall occurring in the field. Flooded conditions (as in tunnel flooding) were not relevant to the more day-to-day conditions sought in this exercise. The test matrix also included conditions from clean to contaminated, using fine sand as a contaminant.

The rail clamping force was measured with specialized-instrumented clip pull devices in an objective manner, so that variations in toe load are properly accounted.

5.4 Experimental Procedures

Testing for the rail seat friction of fasteners and toe loads was completed in the Structural Fatigue Laboratory at Battelle in Columbus, Ohio.

5.4.1 Rail Seat Friction Forces

The rail seat friction forces were experimentally determined from longitudinal restraint tests. The longitudinal test fixture consists of a 7-foot (2135 mm) long wide-flange steel beam used as a base with a 20,000-pound (89 kN) hydraulic actuator mounted horizontally at one end. Loads from the horizontal cylinder are transmitted through a 20,000-pound (89 kN) load cell to record the loads during testing. An LVDT was connected from the base to the rail to measure rail deflection. A computer controlled data acquisition system recorded load, displacement, and time. Three rail fasteners were positioned on the rail longitudinal test fixture and securely bolted down. An 8-foot (2440 mm) section of 115 lb rail was set in place with rail clip assemblies installed and properly tightened to manufacturer requirements. Figures 5-1 and 5-2 show an overview of the setup. In these initial tests plate type fasteners were used with a low restraint spring clip and rigid clip combination clip in use at SEPTA.

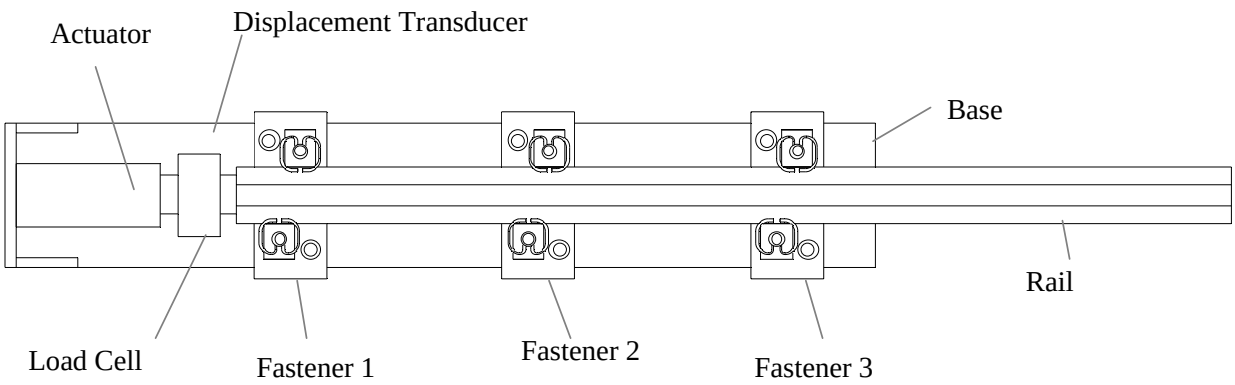


Figure 5-1. Layout of longitudinal test system

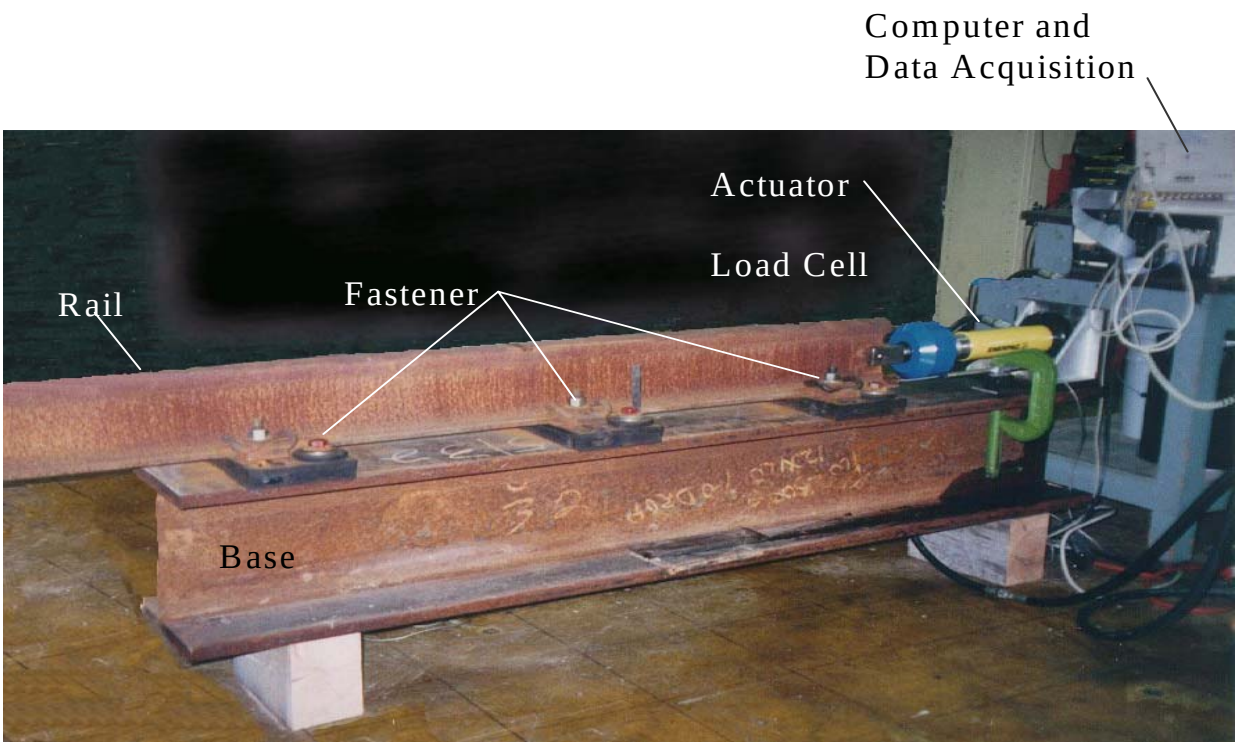


Figure 5-2. Photo of longitudinal test system

The initial set of baseline tests determined the longitudinal force necessary to cause the rail to slip in a dry, clean environment. From this baseline data, the rail seat friction was determined. The rail exhibited a normal degree of oxidation. The rail was positioned into the test fixture and a longitudinal force was applied while the load and displacement were measured. To complete one testing cycle, the load is applied until the rail slides approximately 4 in. (111mm). The hydraulic pump driving the actuator is a little small, on purpose, so that the sliding of the rail decreases the force applied to the rail and the rail stops sliding until the pump and the corresponding cylinder pressure again reached the breakaway force. The rail then slides with this stick-slip motion. The static friction force, F`, is the average of the force required to move the rail and the sliding or kinetic friction, F_k, is the force when the rail is sliding. The static and kinetic coefficients of frictions are:

Coefficient of static friction (f): $f = F`/N$

Coefficient of kinetic friction (f_k): $f_k = F_k/N$

where the normal load, (N) is due to the clip toe load and rail weight. An example of this is shown in Figure 5-3.

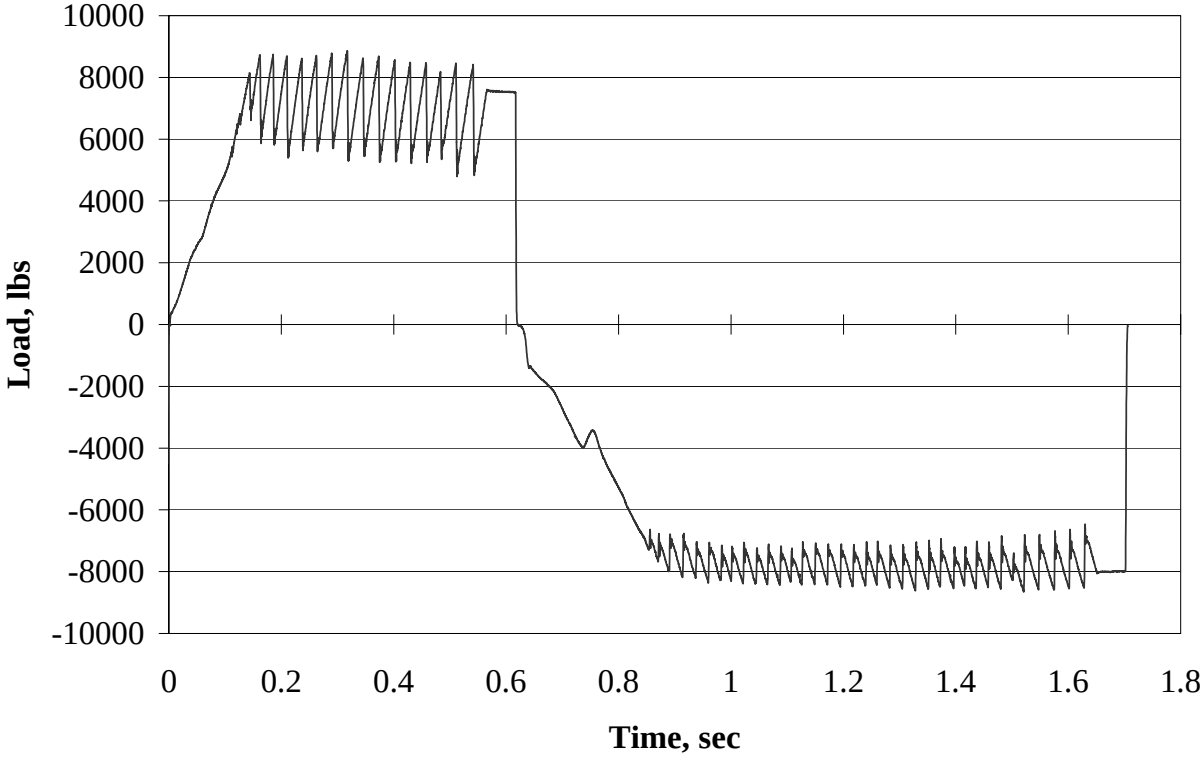


Figure 5-3. Single cycle from baseline longitudinal testing

5.4.2 Contamination

To determine the effects of contamination on the rails, longitudinal restraint testing was completed with different levels of three contaminates, water, sand, and grease. For the light and moderate contamination levels, the contamination was placed between the rail and the rail clips. For the heavy level of contamination, the contamination was placed between the rail and the rail clips and the rail and the rail pad. During testing, the load and deflection in the longitudinal direction were measured and contaminant was added if necessary. After testing, the rails and the areas under the rail clips were cleaned and dried. All tests were completed with a constant toe load.

5.4.3 Push Pull with Misalignment

To determine the effects of vertical misalignment of a fastener support, longitudinal restraint testing was completed with different shims placed under the fasteners. The shims were 1/16, 1/8, and 3/16 inch (1.6, 3.2, 4.8 mm) thick. The shims were placed under only the center fastener for one set of tests to simulate a high fastener support and under both end fasteners to simulate a low fastener support. During the test, the load and deflection in the longitudinal direction were measured. The tests were completed with a constant toe load.

5.4.4 Longitudinal Stiffness

Longitudinal stiffness of the fastener assemblies was determined from the data taken during the longitudinal restraint tests. The load and displacement from the initial slope before slip were used to

calculate the longitudinal stiffness of the fasteners. The longitudinal stiffness tests were completed using only one fastener.

5.4.5 Rail Normal Force

The toeload on each fastener was determined by vertically loading and unloading the toe of the rail clip and measuring the force using a specially designed clip puller and a load cell. The toe load was measured on each rail clip of each fastener. The results were averaged for fasteners with multiple legs. To begin the testing, a shim was placed between the clip toe and the rail. A clamp grasped the toe of the fastener and a jackscrew applied the vertical load while a force transducer measured the tension load. As the toe load was reduced to zero, the shim was removed. The load was recorded and time was recorded on a computer data acquisition system. The fixture used for these measurements is shown in Figure 5-4 being used to measure the toe load on a common elastic rail clip.

Figure 5-4. Rail clip toeload measuring device

5.4.6 Measurement of the Effect of Vibration on Longitudinal Restraint

Rail seat friction forces in a vibration environment were experimentally determined from modified longitudinal restraint tests. The same longitudinal test fixture consisting of the wide-flange steel beam, hydraulic actuator mounted horizontally at one end, load cell to record the loads during testing, and LVDT to measure rail deflection were used in conjunction with a 6000 LB electro-dynamic shaker to perform the tests. A computer controlled data acquisition system recorded horizontal load, displacement, and time. Three fasteners were positioned on the rail longitudinal test fixture. The rail was set in place with fasteners and rail clip assemblies installed and properly tightened to manufacturer requirements. The dynamic shaker was attached to the rail by a 3 foot (0.91 m) bar perpendicular to the railhead. The shaker applied random frequency vertical loads varying between 100 and 500 lbs. RMS (0.45 and 2.22 kN). The loads were measured from a load cell mounted in series with the bar and shaker. The load was not recorded on the data acquisition system, but was controlled via the shaker controller to a preset RMS level with a broad band random input spectrum of frequencies from 0 to 2,000 Hz. These frequencies are similar to those observed during previous field tests for wheel rollby induced vibrations. Friction forces and stiffness were determined from the testing. This testing was completed using Frame fastener 2 fasteners and elastic rail clips. A photo of the laboratory setup is shown in Figure 5-5. In this photo the longitudinal test frame and the shaker bar are shown. The shaker is out of the photo to the right.

5.5 Experimental Results

The experimental results for the standard low-restraint rail clip and a common spring rail clip are presented in the next sections.

5.5.1 Standard Bonded Plate 4 Rail Fasteners and Multileg Railclip

Standard Bonded plate 4 rail fasteners and low restraint multileg rail clips in conjunction with a rigid rail clip are used as the baseline rail restraint. These DF fasteners have a vertical stiffness of approximately 300,000 Lb-in. This is a low restraint system unless an extra metal spacer is added between the rail and the rigid clip to make them a full restraint system. The fasteners are shown in Figure 5-6. The fasteners consist of an elastic rail clip held in place by a bolt passing through the top of a solid rigid clip. The added spacer is located between the elastic rail clip and the rail to make the system a full restraint configuration. Testing was completed with and without the spacer so both low restraint and full restraint values were obtained.

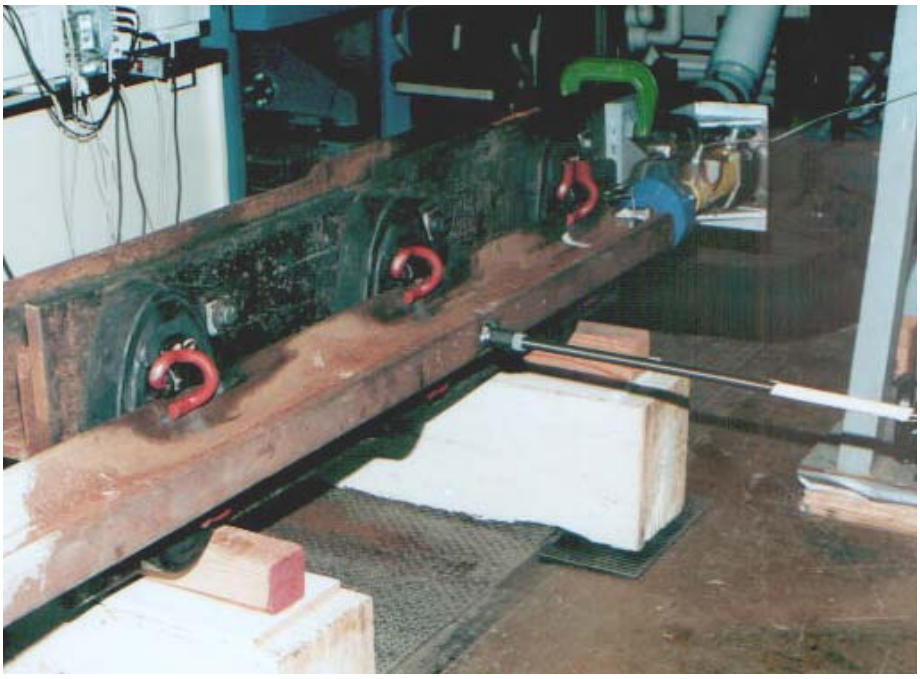


Figure 5-5. Test to determine effects of vibration on longitudinal restraint

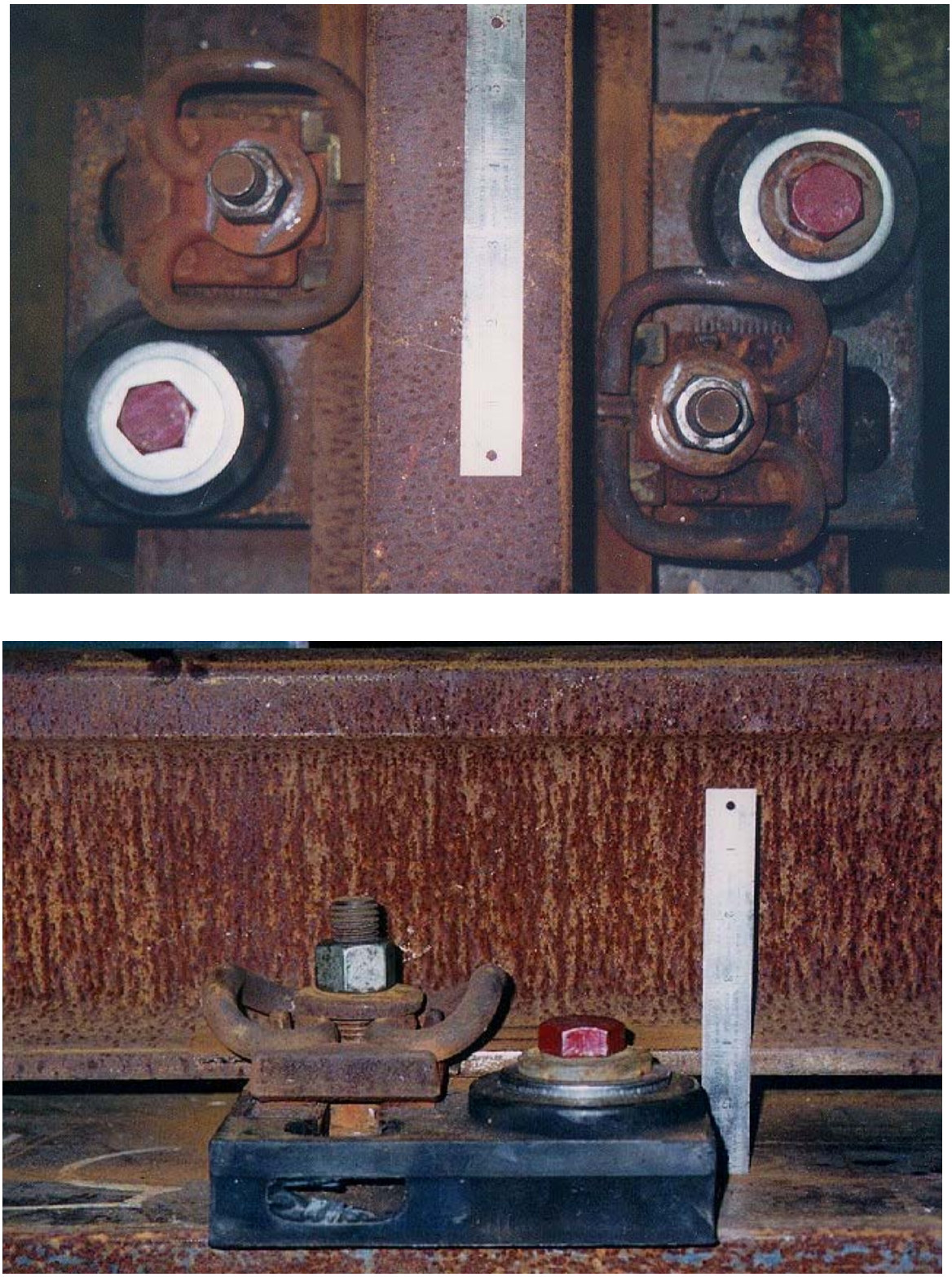


Figure 5-6. Bonded plate 4 rail fasteners and multileg clip

5.5.1.1 Friction Forces

The longitudinal test was completed on the standard rail fasteners as described in the above sections. Figure 5-7 shows one complete loading cycle on a time basis. Figures 5-8 and 5-9 show the load and deflection of the three bonded plate 4 fasteners with and without spacers for one cycle. Tables 5-2 and 5-3 show the results from three complete cycles of static and kinetic friction force for both Retraction and Extension on the rail with and without the spacer.

From the friction force determined above and the normal loads, N, of 8,227 pounds (36.6 kN) determined from the toe load (discussed in the following section) the coefficients of friction were determined. From the longitudinal testing in a dry, clean environment with the spacers, the average coefficient of static friction is 0.924 and the average coefficient of kinetic friction is 0.641. Without the spacers, the average coefficient of static friction is 0.583 and the average coefficient of kinetic friction is 0.519.

5.5.1.2 Contamination

The toe load for these tests was 8227 lbs. Tables 5-4 and 5-5 show the average static friction force and sliding friction force for the contamination tests with spacers and without spacers. Figure 5-10 shows the effects of the contaminant on the static friction force with and without spacers (full versus low restraint). As can be seen, the effect of dirt and grease may alter the friction force by as much as 50%

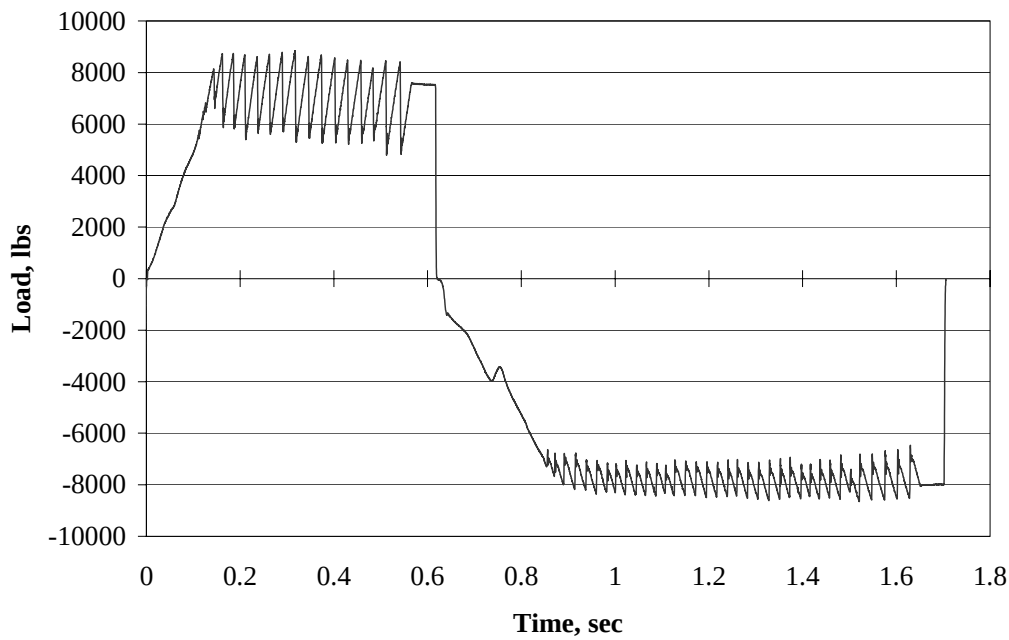


Figure 5-7. Single cycle from baseline longitudinal testing

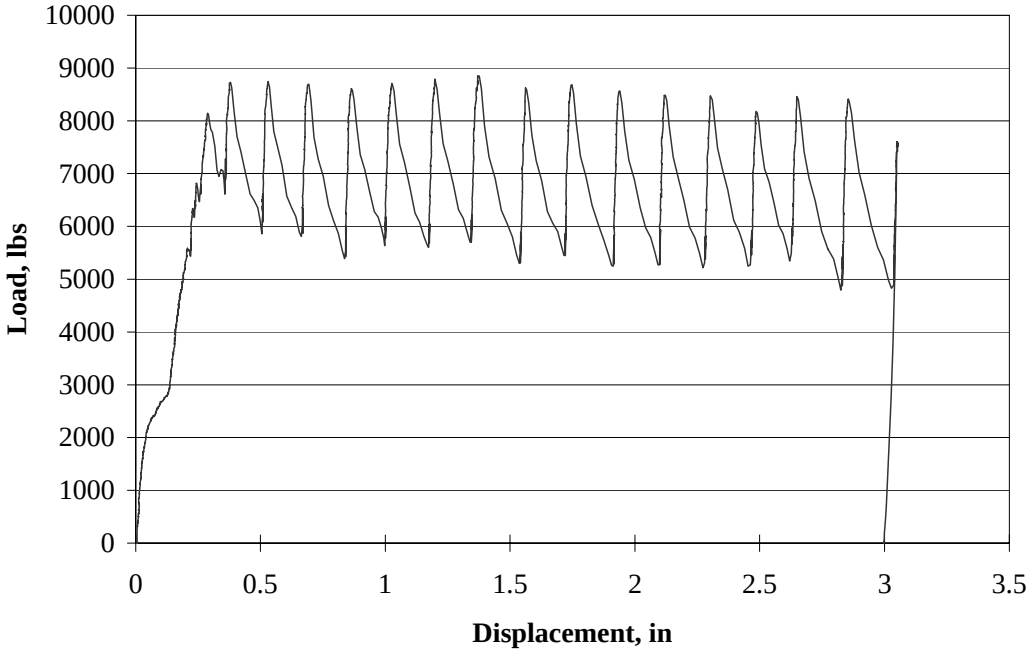


Figure 5-8. Load and deflection of three bonded plate 4 fasteners with spacer for one cycle (full restraint configuration)

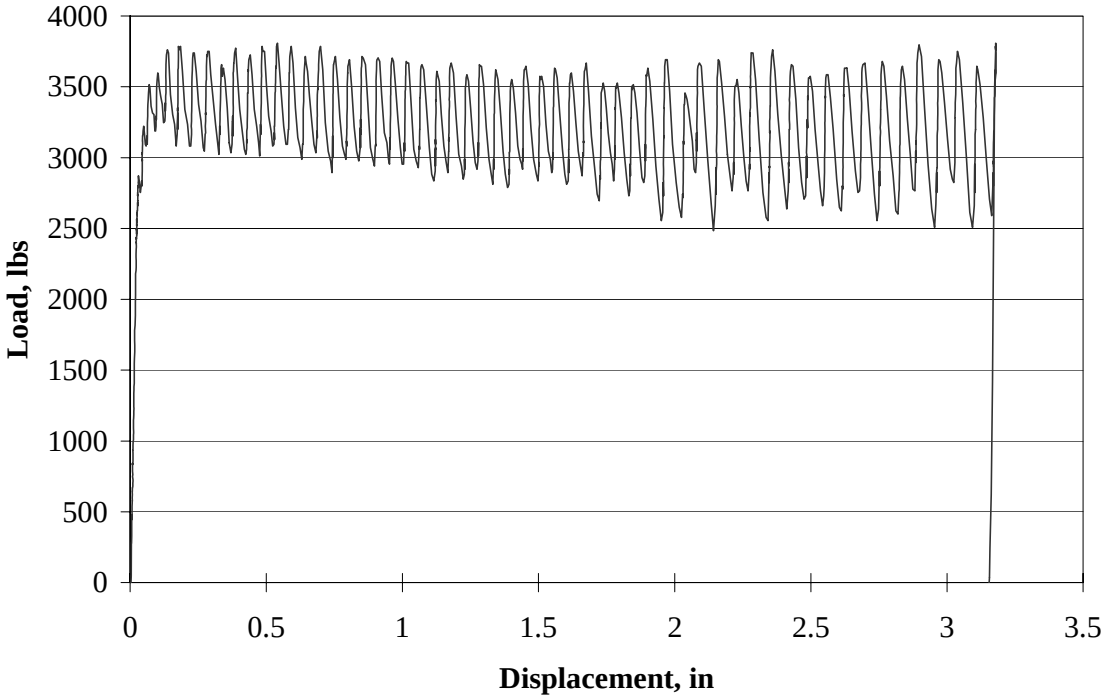


Figure 5-9. Load and deflection of three bonded plate 4 fasteners without spacer for one cycle (low restraint configuration)

Table 5-2. Friction force on the bonded plate 4 fasteners due to longitudinal loading with spacers

	Cycles			Average
	Friction Force, lbs.	Friction Force, lbs.	Friction Force, lbs.	Friction Force, lbs.
Extend				
Static	7586	7702	7775	7688
Sliding	4961	4878	5124	4988
Retract				
Static	7441	7464	7644	7516
Sliding	5571	5515	5581	5556

Table 5-3. Friction force for three bonded plate 4 fasteners due to longitudinal loading without spacers, (low restraint configuration)

	Cycles			Average
	Friction Force, lbs.	Friction Force, lbs.	Friction Force, lbs.	Friction Force, lbs.
Extend				
Static	4025	4843	5791	4886
Sliding	3374	4530	5408	4438
Retract				
Static	3737	4689	5689	4705
Sliding	2905	4306	5072	4094

5.5.1.3 Push Pull with Misalignment

In this series of tests the variation of restraint force with different levels and configuration of the fastener support misalignment is shown. All these tests were run in a nominal dry clean environment. Tables 5-6 and 5-7 show the average static friction force and sliding friction force for the tests with spacers and without spacers. Figure 5-11 shows the effects of the shims on the static friction force with and without spacers. In all cases, the restraint load increased with misalignment, usually substantially.

5.5.1.4 Longitudinal Stiffness

Longitudinal stiffness of the fastener elastomer was determined from the data taken during the longitudinal restraint tests. The initial load and displacement of the three bonded plate 4 fasteners with and without spacers are shown in Figures 5-12 and 5-13. The stiffness for the bonded plate 4 fastener with spacer was 24.0 kips./in (4.2 kN/mm) with a dry and clean rail. Without the spacers, the stiffness was 34.6 kip./in (6.1 kN/mm). The increase in stiffness is due to removing contact surfaces where slippage could occur. In this case the stiffness reflects the small motion of the top plate of the fastener on the elastomer in shear. Changes in loading and contamination may change the longitudinal stiffness.

Table 5-4. Average force on the bonded plate 4 fasteners for contamination tests with spacers

	Retraction		Extension	
	Static Friction Force, lbs.	Sliding Friction Force, lbs.	Static Friction Force, lbs.	Sliding Friction Force, lbs.
Dry, Clean	7516	5556	7688	4988
Water, Light	7531	5105	7679	6186
Water, Moderate	7565	5061	7670	6130
Water, Heavy	6665	4105	7215	4470
Sand, Fine	8493	6149	8264	6786
Sand, Course	6497	4629	7243	5980
Grease, Heavy	5475	2967	5538	3774
Grease – Heavy, Sand – Course	4979	3928	5184	4158

Table 5-5. Average force on the bonded plate 4 fasteners for contamination tests without spacers

	Retraction		Extension	
	Static Friction Force, lbs.	Sliding Friction Force, lbs.	Static Friction Force, lbs.	Sliding Friction Force, lbs.
Dry, Clean	4705	4094	4886	4438
Water, Light	4624	3899	4722	4083
Water, Moderate	4558	3908	4708	4078
Water, Heavy	4460	3855	4665	4037
Sand, Fine	4460	3688	4796	4147
Sand, Course	4684	4008	5144	4532
Grease, Heavy	4119	2881	4349	3460
Grease – Heavy, Sand – Course	3928	3064	4171	3464

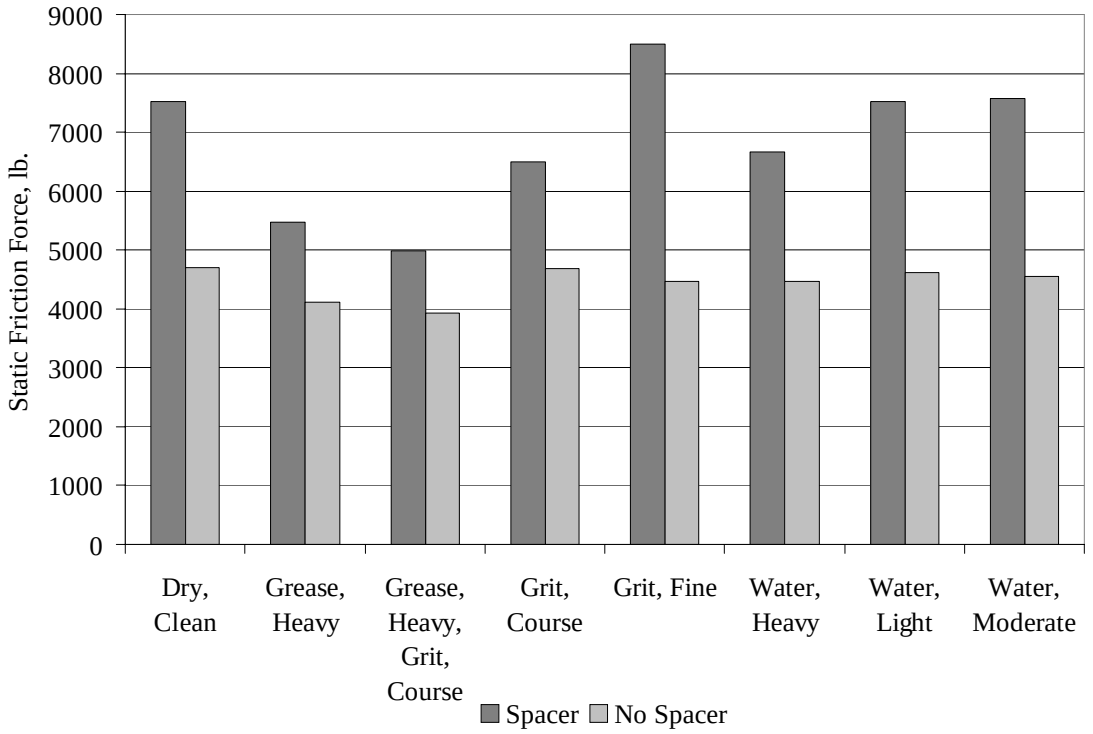


Figure 5-10. The effect of contamination on the static friction force for three bonded plate 4

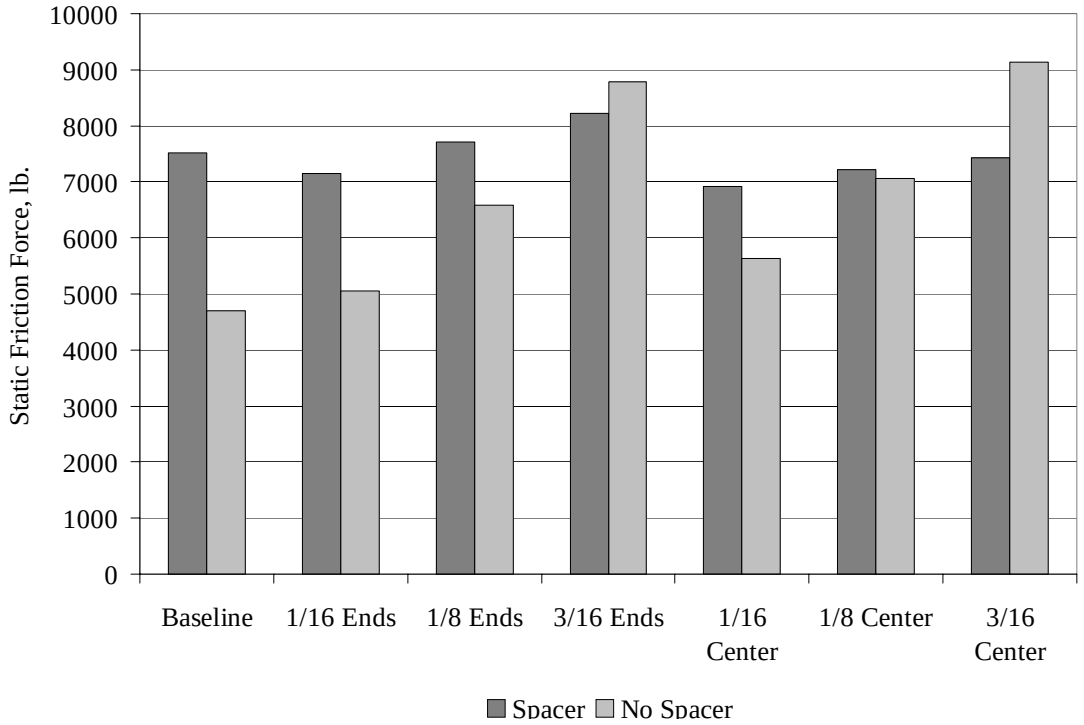


Figure 5-11. The effect of fastener vertical misalignment on the static friction force for three bonded plate 4 fasteners

Table 5-6. Average force on the Bonded Fastener 4 fasteners with spacers

		Retraction		Extension	
		Static Friction Force, lb.	Sliding Friction Force, lb.	Static Friction Force, lb.	Sliding Friction Force, lb.
Baseline		7516	5556	7688	4988
Ends	1/16" Shim	7142	6874	6470	6122
	1/8" Shim	7706	7371	7637	7217
	3/16" Shim	8226	7467	7757	7384
Center	1/16" Shim	6922	5927	6957	6257
	1/8" Shim	7225	6387	6373	6053
	3/16" Shim	7421	7120	7042	6959

Table 5-7. Average force on the Bonded Fastener 4 fasteners without spacers

		Retraction		Extension	
		Static Friction Force, lb.	Sliding Friction Force, lb.	Static Friction Force, lb.	Sliding Friction Force, lb.
Baseline		4705	4094	4886	4438
Ends	1/16" Shim	5053	4686	5136	5022
	1/8" Shim	6577	5641	6993	5789
	3/16" Shim	8791	6731	9528	7200
Center	1/16" Shim	5632	4547	5639	5455
	1/8" Shim	7051	5150	7227	6215
	3/16" Shim	9142	6282	9676	7815

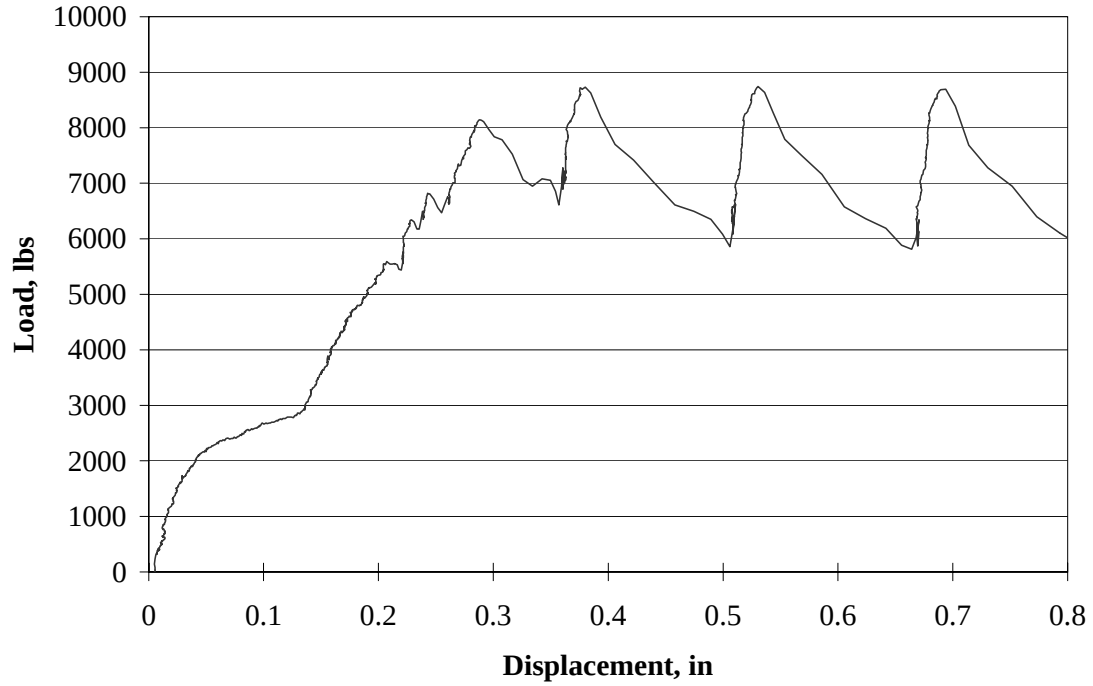


Figure 5-12. Initial load and deflection of three Bonded Fastener 4's with Spacers

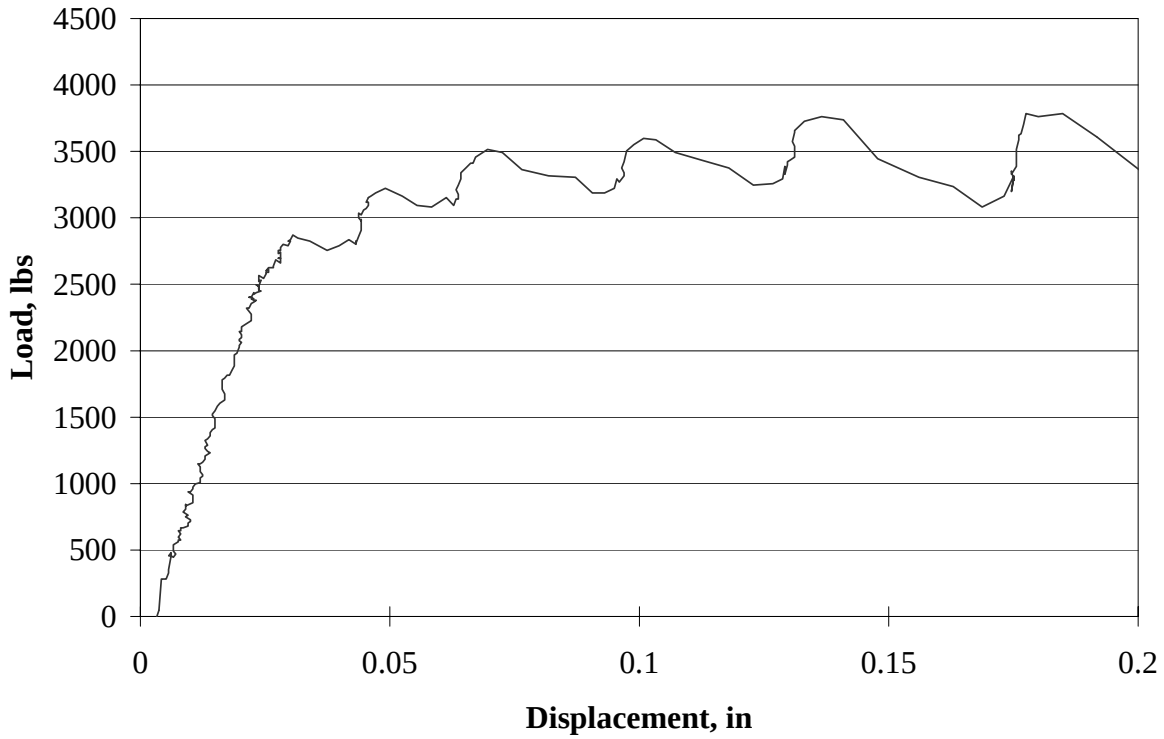


Figure 5-13. Initial load and deflection of three Bonded Fastener 4's without Spacers

5.5.2 Common Elastic Rail Clips with Bonded Fastener 4 Fastener

The common elastic rail clips are used as full restraint fasteners and are shown in Figure 5-14. The Bonded Fastener 4 fasteners are a standard bonded plate type fastener. A plastic insulator is located between the elastic rail clip and the rail.

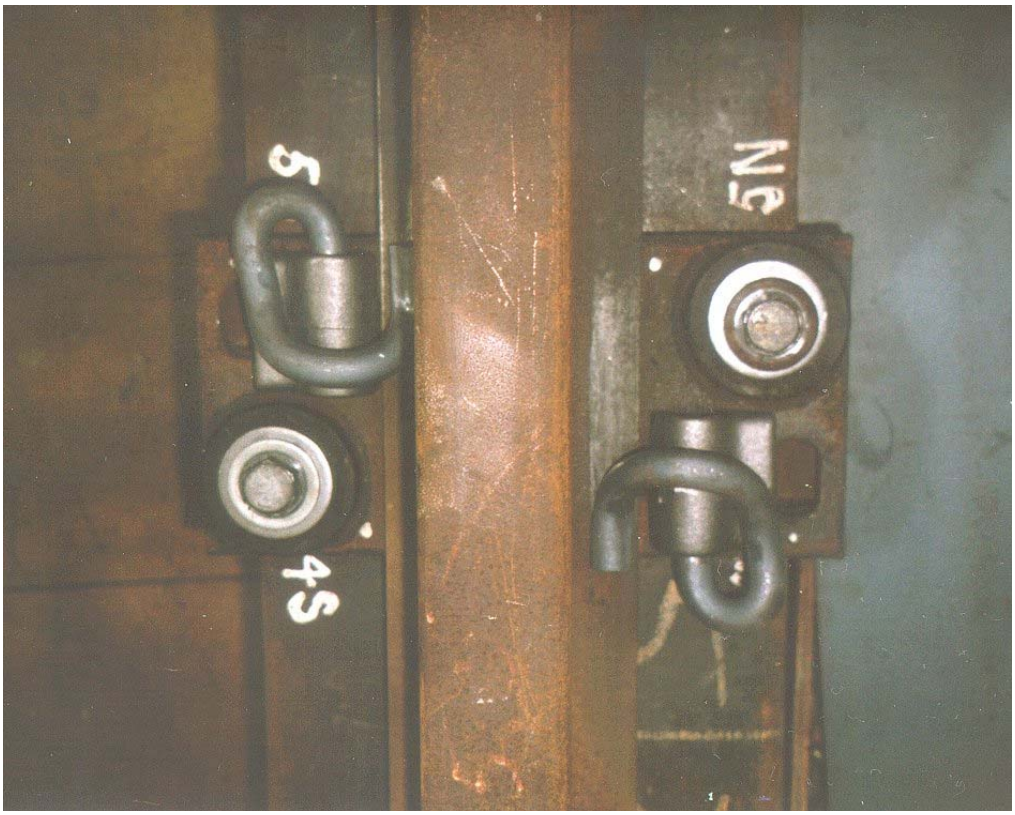
5.5.2.1 Toe Loads

The testing was completed a minimum of four times on each rail clip toe and the values were averaged. Table 5-8 shows the average toe loads for the fasteners. The normal force due to the six fasteners is 14,232 lbs. (63.3 kN) The weight of the 8-foot rail is approximately 307 lbs. (1.4 kN), giving a total normal force, N, of 14,539 lbs. (64.7 kN). This value is used in the previous section to determine the static and dynamic coefficients of friction. During testing, this system was used to determine the rail clamping force for the contamination and loading variation tests.

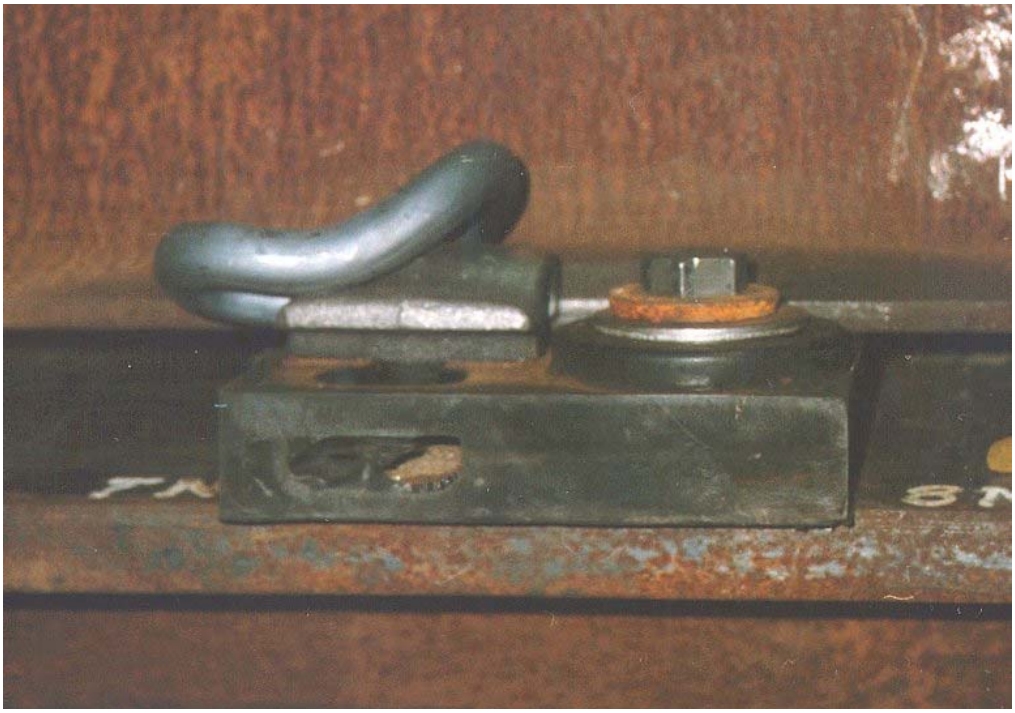
5.5.2.2 Friction Force

The longitudinal test was completed on the standard rail fasteners as described in the above sections. Figure 5-15 shows the load and deflection of the common elastic rail clips for one cycle. Table 5-9 shows the results from three complete cycles of static and kinetic friction force for both retraction and extension.

From the friction force determined above and the normal loads, N, of 14,539 pounds (64.7 kN) determined from the toe load (discussed in an adjoining section) the coefficients of friction were determined. From the longitudinal testing in a dry, clean environment, the average coefficient of static friction is 0.651 and the average coefficient of kinetic friction is 0.526.



Top View



Side View

Figure 5-14. Common elastic rail clips and Bonded Fastener 4 DF fasteners

Table 5-8. Average Toe Load for Common Elastic Rail Clip

Fastener	Average Toe Load pounds
Fastener 1	2102
Fastener 2	2548
Fastener 3	2188
Fastener 4	2489
Fastener 5	2642
Fastener 6	2263
Average Toe Load for Fasteners	2372

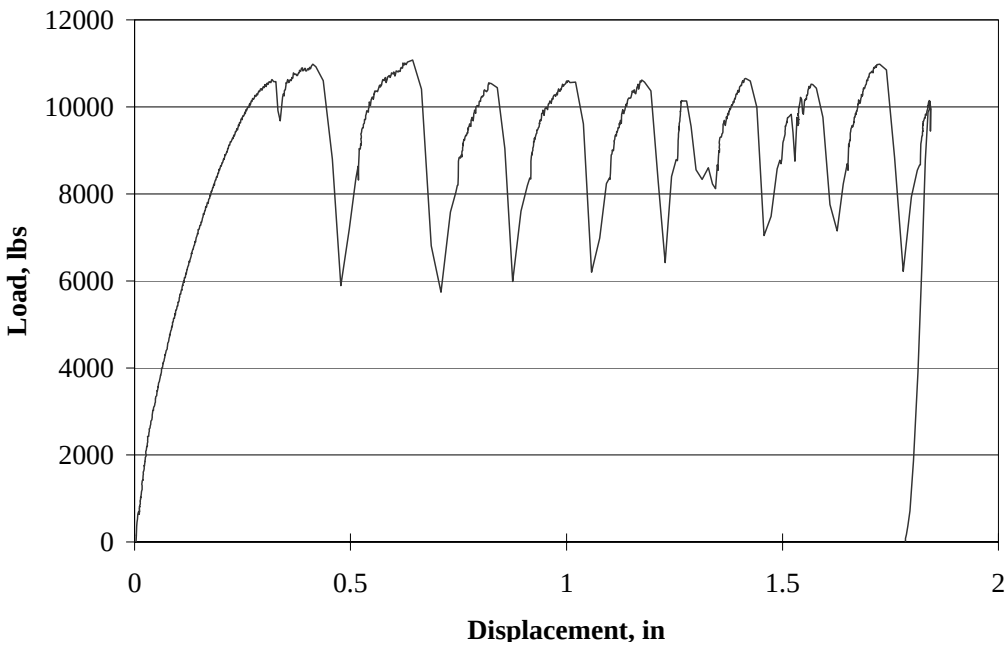


Figure 5-15. Load and deflection using common elastic rail clips with three common fasteners for one cycle

Table 5-9. Friction force from common elastic rail clips due to longitudinal loading

	Cycles			Average
	Friction Force, lbs.	Friction Force, lbs.	Friction Force, lbs.	Friction Force, lbs.
Extention				
Static	9283	10130	9346	9586
Sliding	7271	9081	7441	7931
Retraction				
Static	9194	10004	8875	9358
Sliding	6852	8792	6446	7363

5.5.2.3 Contamination

Table 5-10 shows the average static friction force and sliding friction force for the contamination tests. Figure 5-16 shows the effects of the contaminant on the static friction force in a manner similar to the earlier data with the multileg clip. The heavy grease reduced the friction by a factor of six and a 10% change was normal for the other contaminates.

5.5.2.4 Push Pull with Misalignment

Table 5-11 shows the average static friction force and sliding friction force for the longitudinal tests with misalignment in the fastener support height. Figure 5-17 shows the effects of the fastener misalignment on the static friction force. The variations were again significant, the largest being about 30%.

5.5.2.5 Longitudinal Stiffness

Longitudinal stiffness was determined from the data taken during the longitudinal restraint tests. The initial load and displacement of the three common elastic rail fasteners is shown in Figure 5-18. The stiffness for the common elastic rail fastener with clips was 14.2 kips./in (2.5 kN/mm) for a dry and clean rail.

5.5.3 Frame Fastener 2 Rail Fasteners

The frame fastener 2 fasteners are a soft DF fastener as opposed to the rather stiff bonded plate 4 previously tested. The frame fastener 2 was tested in a full restraint configuration. The full restraint fasteners are shown in Figure 5-19. The fasteners were tested in two configurations. The baseline configuration was a full restraint configuration using common elastic rail clips. The second configuration used a Zero low restraint clip. The low restrain clips provided a gap between the clip and the rail of approximately 3/16 inch. The gap caused no toe load on the rail and friction force was based solely on the weight of the rail. Results from high restraint fastener are provided.

Table 5-10. Average force on common elastic rail fastener for contamination tests

	Retraction		Extention	
	Static Friction Force, lbs.	Sliding Friction Force, lbs.	Static Friction Force, lbs.	Sliding Friction Force, lbs.
Dry, Clean	9358	7363	9586	7931
Water, Light	8542	8263	8873	8657
Water, Moderate	8586	8448	9142	8891
Water, Heavy	8376	8199	8726	8432
Sand, Fine	8426	6060	8107	6287
Sand, Course	7538	5572	7850	5384
Grease, Heavy	1570	1524	1743	1710
Grease – Heavy, Sand – Course	3067	2991	3215	3165

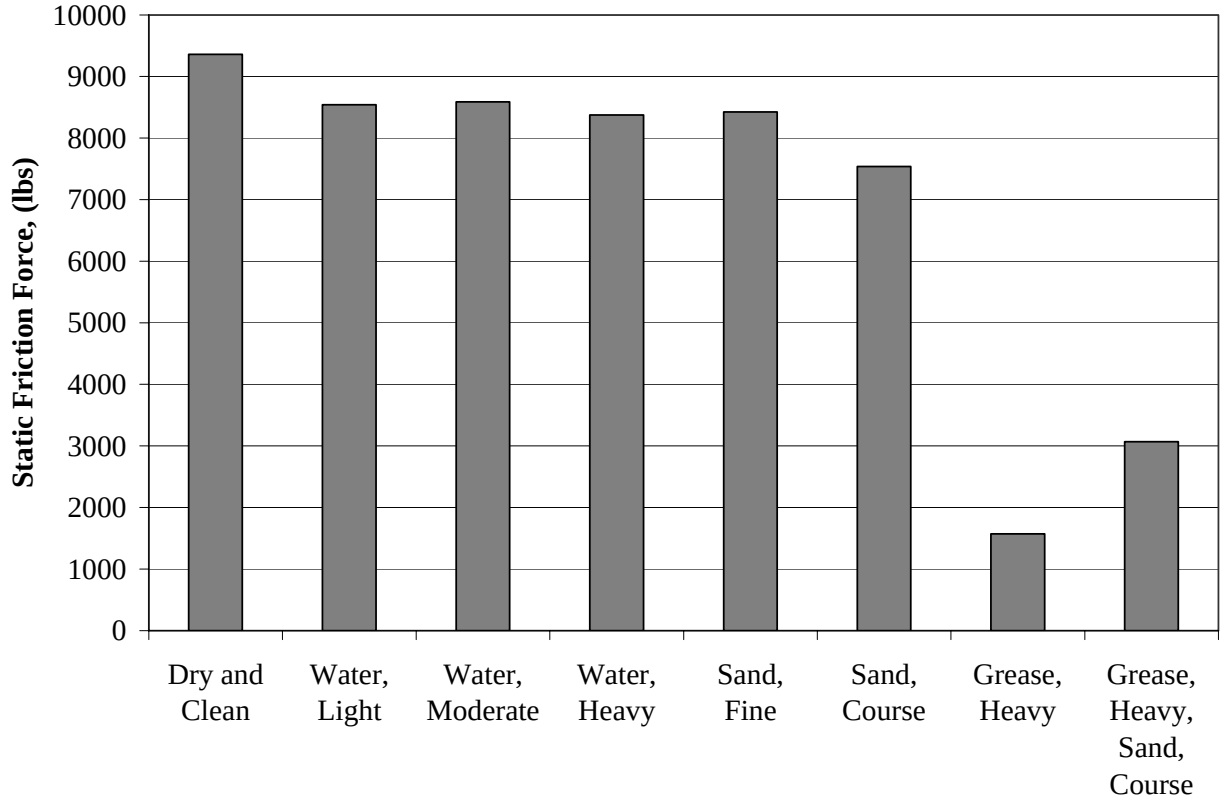


Figure 5-16. The effect of contamination on the static friction force for common elastic rail clips with bonded plate 4 fasteners

Table 5-11. Average force on common elastic rail fastener for vertical misalignment testing

		Retraction		Extension	
		Static Friction Force, lbs.	Sliding Friction Force, lbs.	Static Friction Force, lbs.	Sliding Friction Force, lbs.
Baseline		9358	7363	9586	7931
Ends	1/16" Shim	9922	7469	10438	8461
	1/8" Shim	9864	7723	10507	8884
	3/16" Shim	10033	7555	10786	8247
Center	1/16" Shim	8460	6262	8984	6917
	1/8" Shim	6891	5048	8053	5950
	3/16" Shim	10370	6719	10109	7498

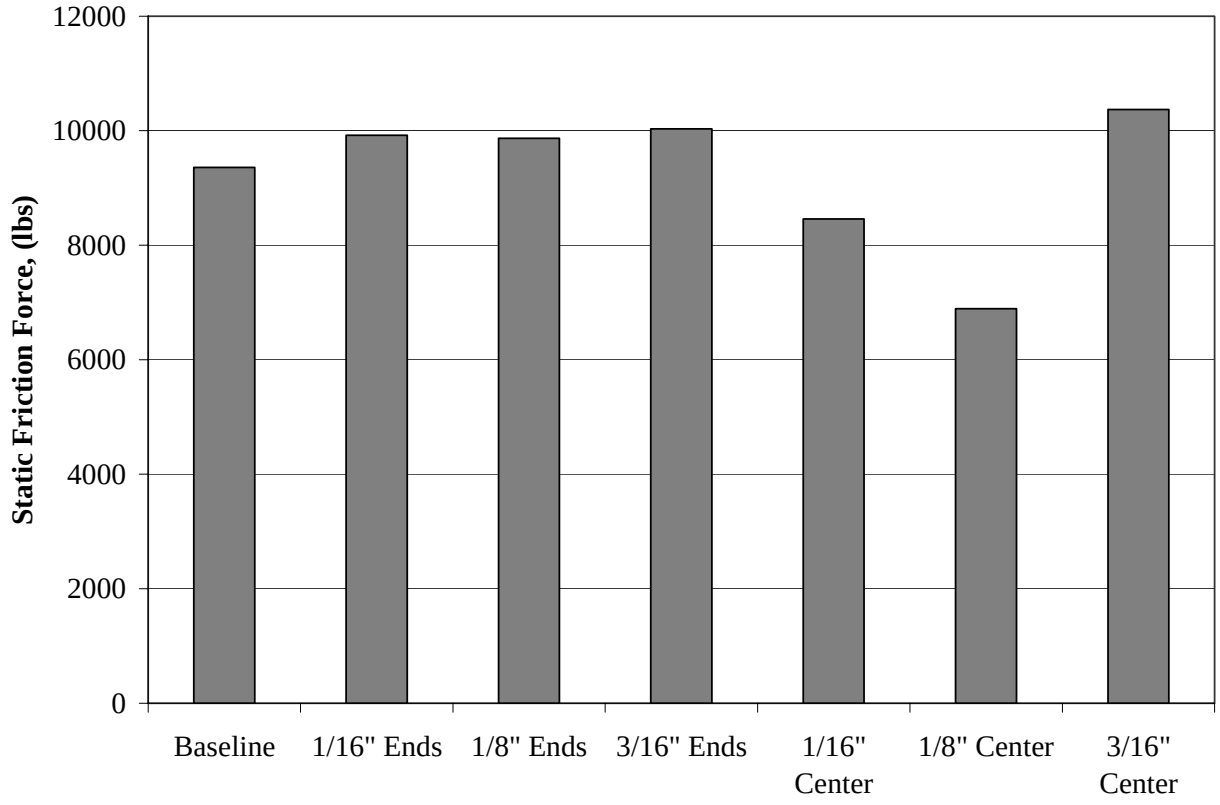


Figure 5-17. The effect of vertical misalignment on the static friction for three bonded plate 4 DF fasteners with common elastic rail clips

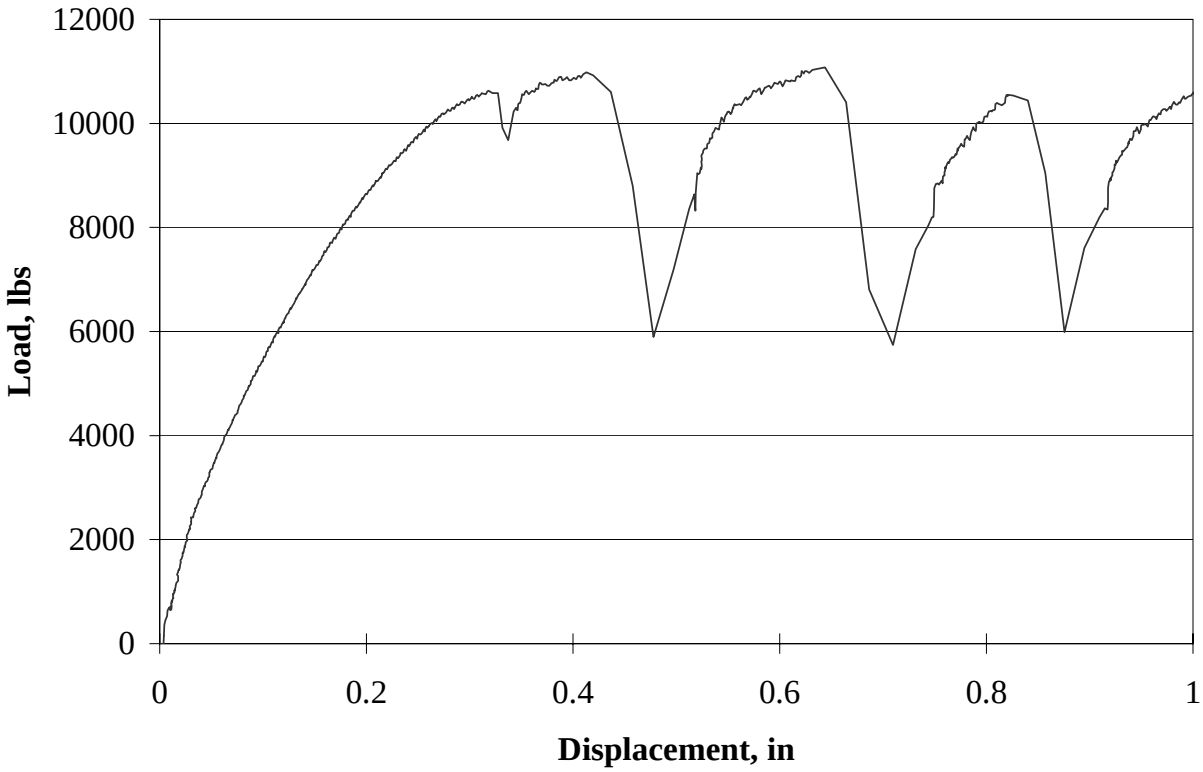
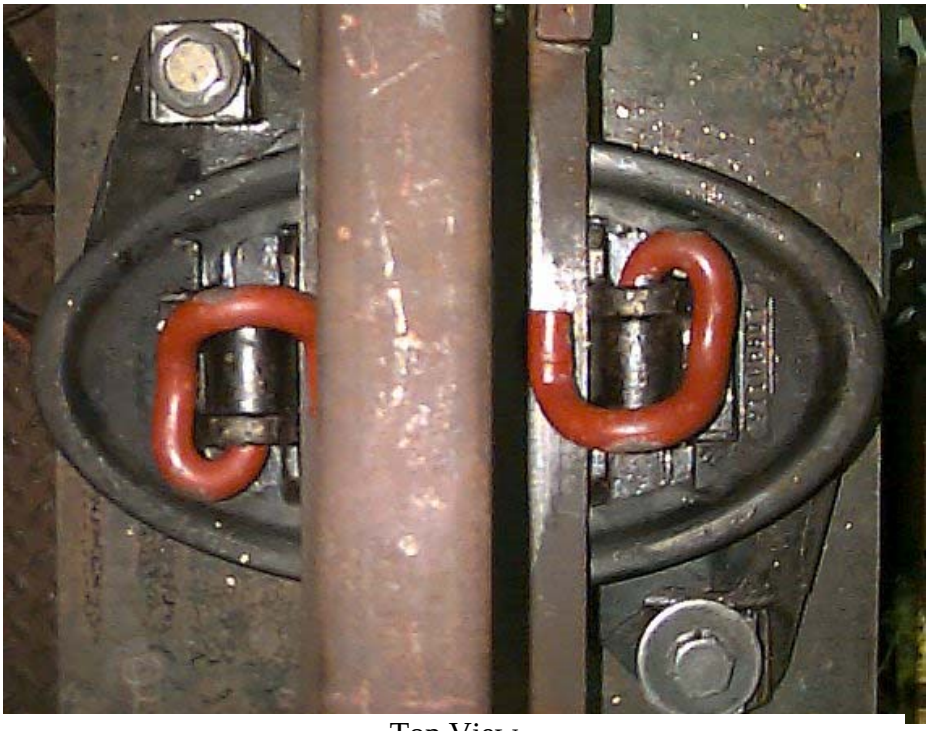


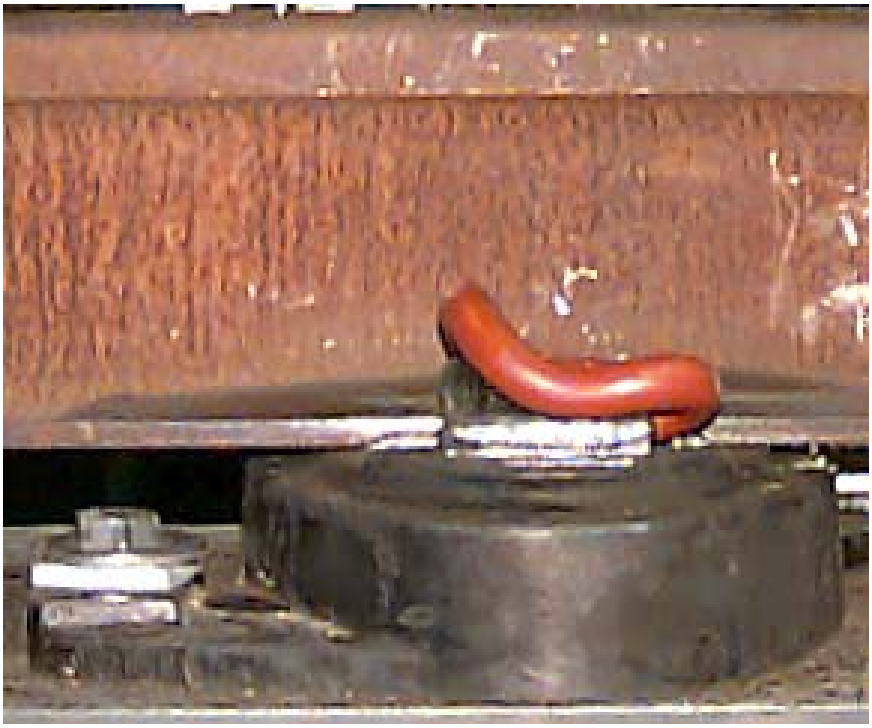
Figure 5-18. Initial load and deflection of three bonded plate 4 fasteners with common elastic rail clips

5.5.3.1 Toe Loads

The testing was completed a minimum of four times with each clip toe and the values were averaged. Table 5-12 shows the average toe load for the fasteners. The normal force due to the six fasteners is 11,713 lbs. (52.1 kN). The weight of the 8-foot rail is approximately 307 lbs., (1.4 kN) giving a total normal force, N, of 12,020 lbs. (53.5 kN). This value is used in the adjoining section to determine the static and dynamic coefficients of friction. During testing, this system was used to determine the rail clamping force for the contamination and loading variation tests.



Top View



Side View

Figure 5-19. Frame fastener 2 rail fasteners with common elastic rail clip

Table 5-12. Average force on frame fastener 2 fastener for contamination tests with the standard clip

	Retraction		Extension	
	Static Friction Force, lbs.	Sliding Friction Force, lbs.	Static Friction Force, lbs.	Sliding Friction Force, lbs.
Dry, Clean	5027	4549	4871	4522
Water, Light	5643	5500	5693	5609
Water, Moderate	5736	5564	5795	5618
Water, Heavy	5848	5696	5840	5717
Sand, Fine	6575	4488	6912	5239
Sand, Course	6175	4551	6398	4731
Grease, Heavy	2557	2492	2641	2583
Grease - Heavy, Sand - Course	2557	2496	2655	2622

5.5.3.2 Friction Force

The longitudinal test was completed on the standard rail fasteners as described in the above sections. Figure 5-20 shows the load and deflection of the "Frame Fastener 2"s for one cycle. Table 5-13 shows the results from three complete cycles of static and kinetic friction force for both retraction and extension.

From the friction force determined above and the normal loads, N, of 12,020 pounds (53.5 kN) determined from the toe load (discussed in the previous section) the coefficients of friction were determined. From the longitudinal testing in a dry, clean environment, the average coefficient of static friction is 0.412 and the average coefficient of kinetic friction is 0.377 for the standard clip.

5.5.3.3 Contamination

Table 5-14 shows the average static friction force and sliding friction force for the contamination tests. Figure 5-21 shows the effects of the contaminant on the static friction force.

5.5.3.4 Push Pull with Misalignment

Table 5-15 shows the average static friction force and sliding friction force for the longitudinal tests with misalignment in the fastener support height. Figure 5-22 shows the effects of the shims on the static friction force.

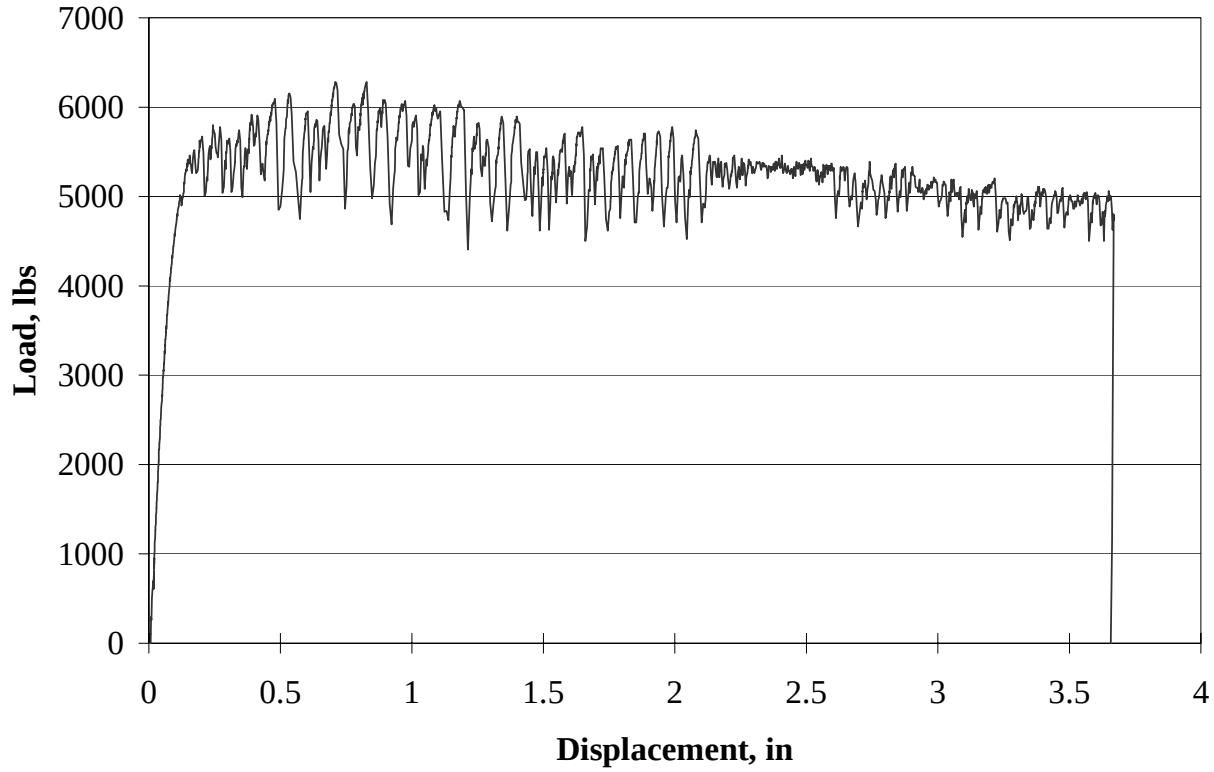


Figure 5-20. Load and deflection of three frame fastener 2 fasteners with common elastic rail clips for one cycle

Table 5-13. Friction force on frame fastener 2 fastener due to longitudinal loading when using the common elastic rail clip

	Cycles			Average
	Friction Force, lbs.	Friction Force, lbs.	Friction Force, lbs.	Friction Force, lbs.
Extension				
Static	4300	4890	5424	4871
Sliding	4164	4524	4878	4522
Retraction				
Static	4394	5051	5637	5027
Sliding	4085	4665	4898	4549

Table 5-14. Average force on frame fastener 2 fastener for vertical misalignment testing with the common elastic rail clip

		Retraction		Extension	
		Static Friction Force, lbs.	Sliding Friction Force, lbs.	Static Friction Force, lbs.	Sliding Friction Force, lbs.
Baseline		5027	4549	4871	4522
Ends	1/16" Shim	6009	5467	6262	5813
	1/8" Shim	6574	5609	6493	5977
	3/16" Shim	6444	4881	6706	5890
Center	1/16" Shim	6365	5636	6306	6071
	1/8" Shim	6647	5360	6625	5904
	3/16" Shim	6903	5135	6792	5402

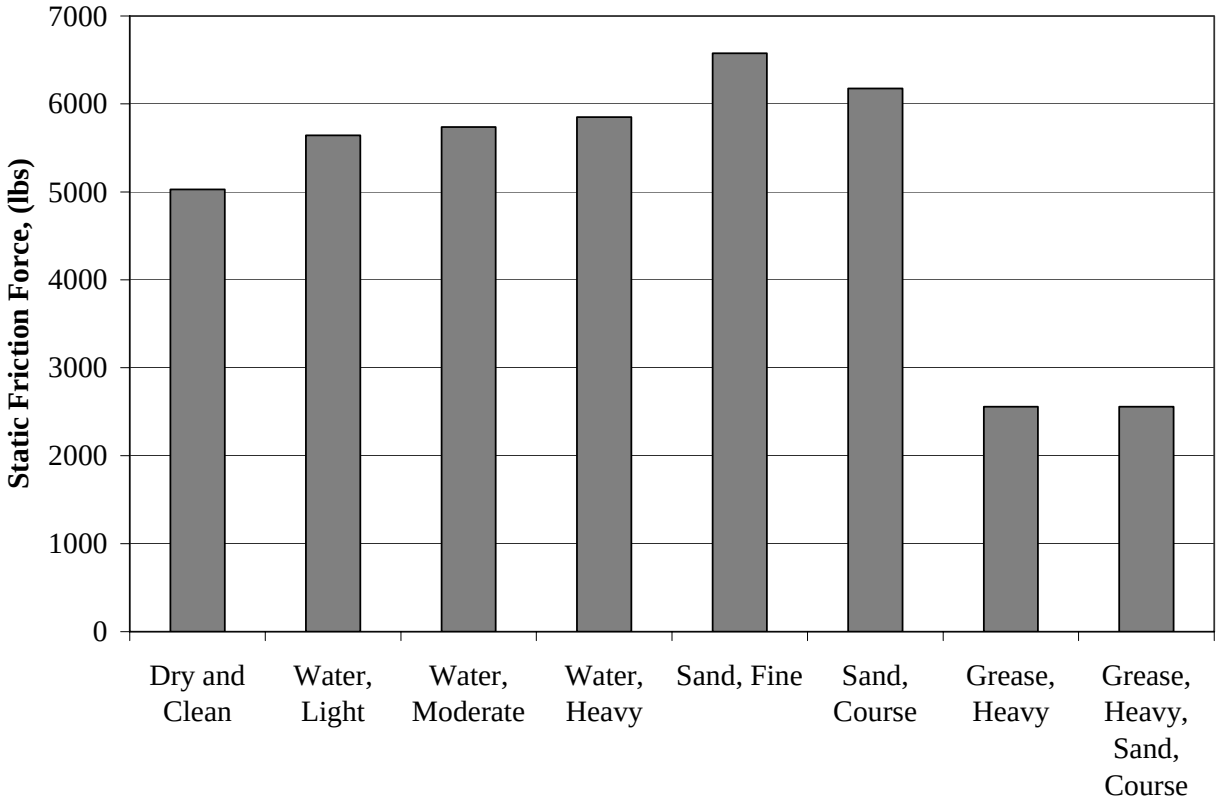


Figure 5-21. The effect of contamination on the static friction force for three frame fastener 2 fasteners with common elastic rail clips

Table 5-15. Average Toe Load for a frame fastener 2 fastener with the common elastic rail clip

Fastener	Average Toe Load Pounds
Fastener 1	2098
Fastener 2	1871
Fastener 3	1967
Fastener 4	1817
Fastener 5	1974
Fastener 6	1985
Average Toe Load for Fasteners	1952

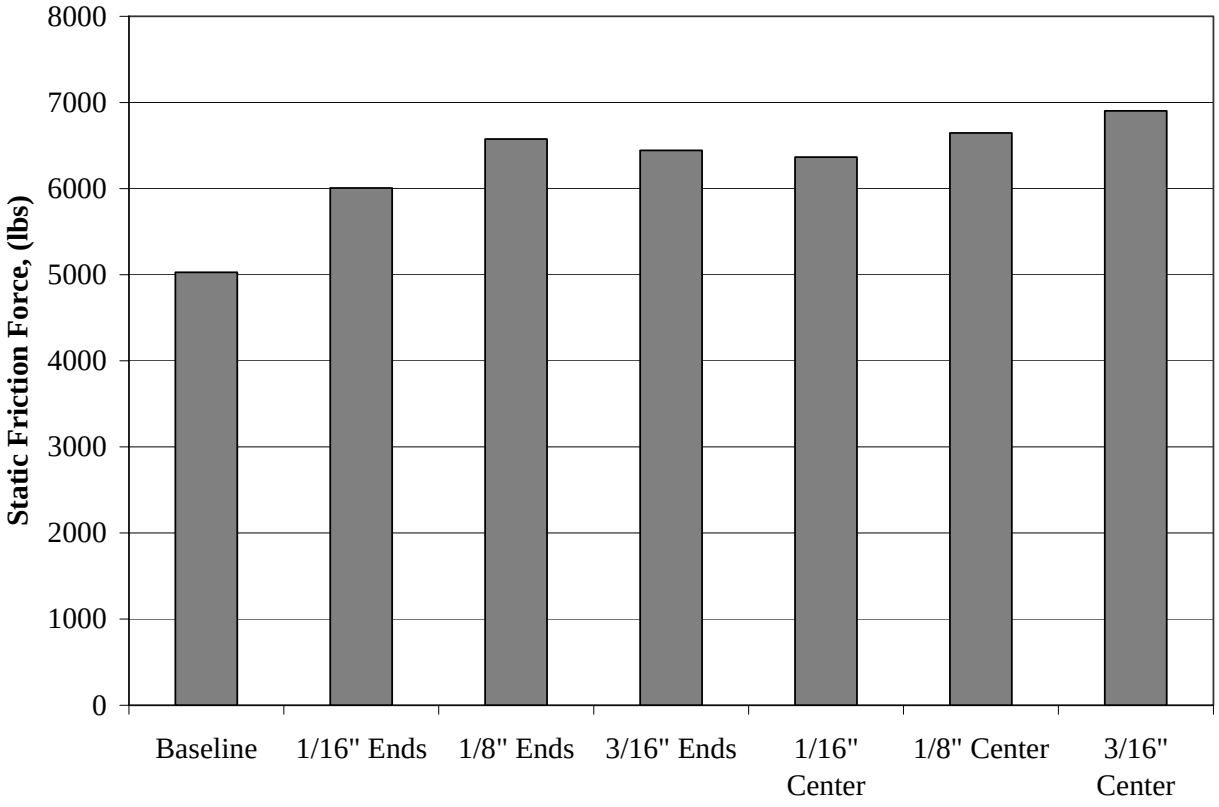


Figure 5-22. The effect of vertical misalignment on the static friction force for three frame fastener 2 fasteners with common elastic rail clips

5.5.3.5 Longitudinal Stiffness

Longitudinal stiffness was determined from the data taken during the longitudinal restraint tests. The initial load and displacement of the three frame fastener 2 is shown in Figure 5-23. The stiffness for the frame fastener 2 with standard clips was 20.1 kips./in (3.5 kN/mm) for a dry and clean rail.

5.5.3.6 Measurement of the Effect of Vibration on Longitudinal Restraint

The dynamic testing was completed on the standard rail fasteners as described in the above sections. Table 5-16 shows the results due to longitudinal and vertical loading for both Retraction and Extension. Figure 5-24 shows the effects of the vertical load on the static friction force. The initial loads and displacements of the three Frame Fastener 2 fasteners with the applied vertical loads are shown in Figure 5-25. This figure shows the effect of the vertical load on the stiffness of the system.

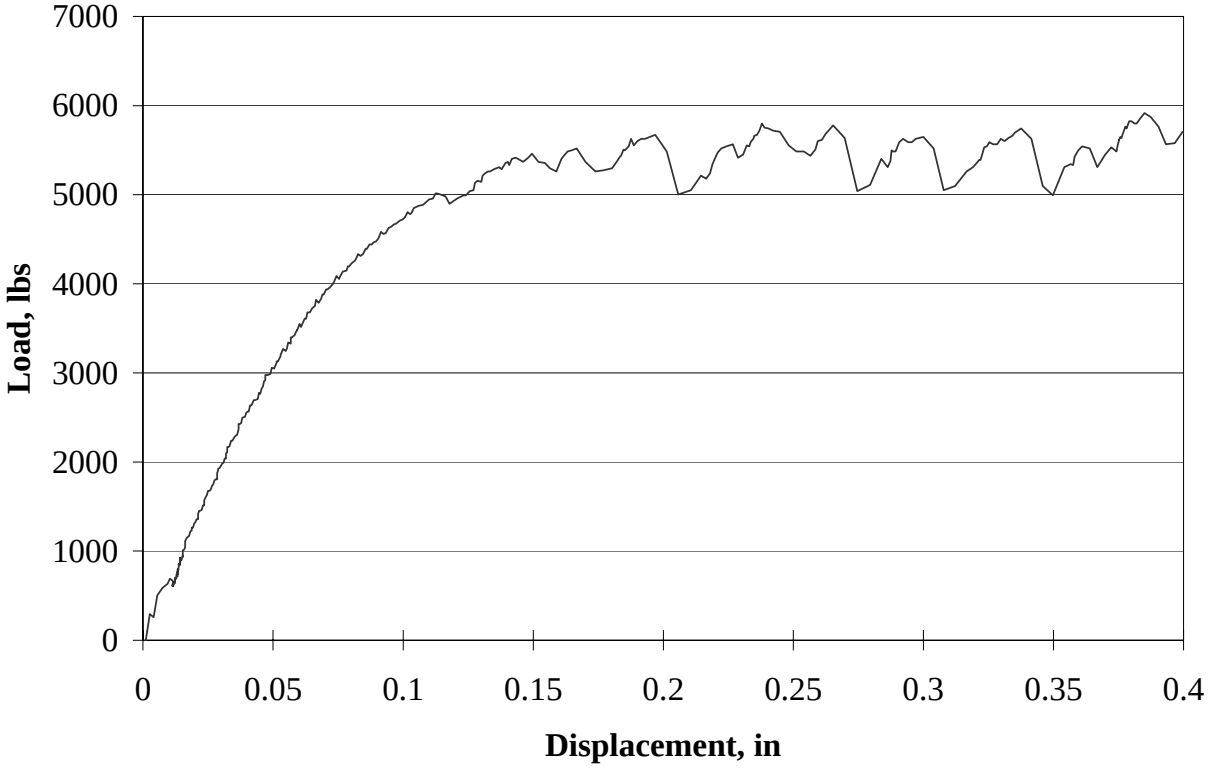


Figure 5-23. Initial load and deflection of three frame fastner 2 fasteners

Table 5-16. Friction force on frame fastener 2 fastener due to longitudinal and vertical loading with the common elastic rail clip

Vertical Load Lb. (kN)	Retraction		Extension	
	Static Friction Force, lbs.	Sliding Friction Force, lbs.	Static Friction Force, lbs.	Sliding Friction Force, lbs.
0 (0)	7826	7045	7419	6880
100 (0.45)	6950	6472	6443	5884
300 (1.33)	6847	6295	6593	5890
500 (2.22)	7404	6772	6953	6665

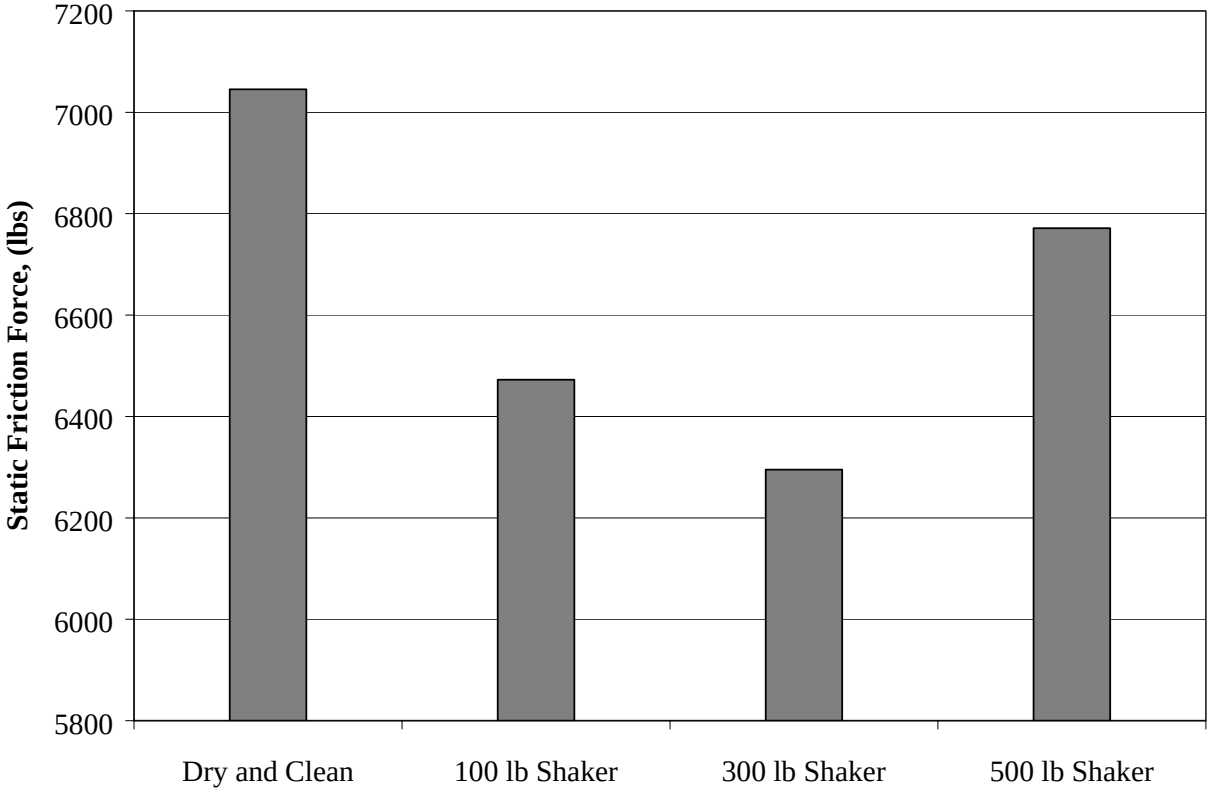


Figure 5-24. The effect of vertical misalignment on the static friction force for three frame fastener 2 fasteners with vertical vibration

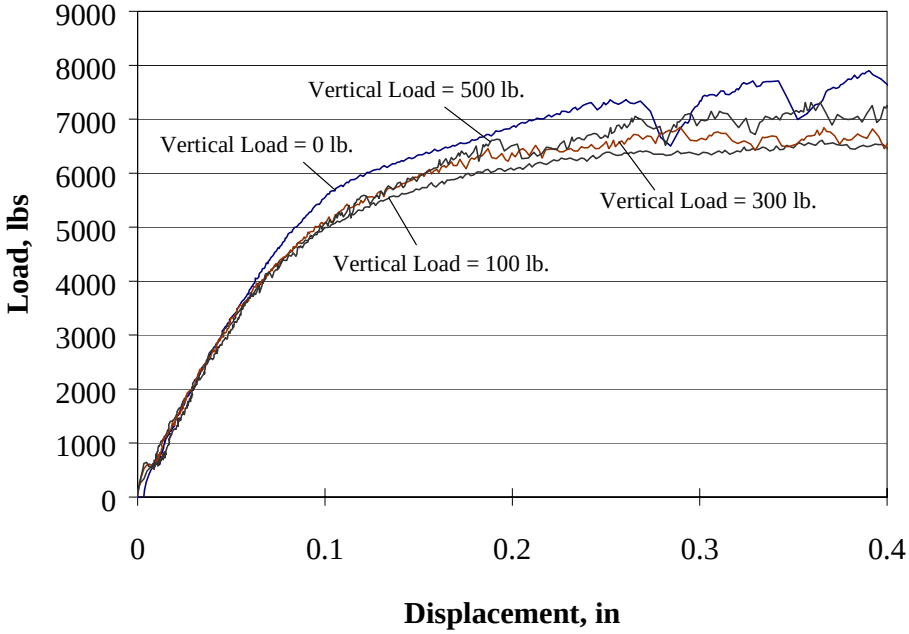


Figure 5-25. Initial loads and deflections of three frame fastener 2 fasteners with varying dynamic vertical loads

5.6 Summary of Longitudinal Restraint Tests

The series of tests to quantify longitudinal restraint values may be summarized in several brief points:

- Contaminants such as water and sand will typically reduce the longitudinal restraint capability of a DF fastener system by 25% especially if the contaminates work between the rail base and the rail seat. The reduction may be as much as 50% in the case of grease type contaminates.

- Vertical misalignment may increase the restraint of a low to medium restraint system by as much as 100%. This is because the forces developed that hold the rail onto the fastener seat may be significant and increase friction. A fastener higher than its neighbors is much worse than a low fastener. (But a single low fastener is worst case on creating clip strain.)

- Vertical misalignment of a full restraint fastener does not have a significant effect on the longitudinal restraint provided by the fastener. The change in restraint due to the added force on the rail seat is typically a 10% increase. (Again a single low fastener is the worst case because of the additional strain experienced by the rail clips.)

- A vibration environment similar to a wheel passage may decrease the longitudinal restraint by 10-15%. The typical decrease in laboratory tests was 14%. This does not include the stick/slip associated the limits of traction/braking force constraint.

6. Direct Fixation Fastener Performance Under Heavy Axle Load

The broad acceptance of the benefits Direct Fixation fasteners brings to transit (less dead load on aerial structures, smaller track envelop, less long-term maintenance demand) is becoming apparent to freight (Channel Tunnel) and even heavy axle load railways (KCRC West Rail, Hong Kong). The latter was in its conceptual engineering when it commissioned Battelle to evaluate Direct Fixation fasteners for use in 40 tonne (44.1 ton) axle load service. Those results are summarized in this section, with permission of that client.

The purpose of the program was "the identification of suitable non-ballasted trackforms," which could fulfill extreme load requirements placed upon the trackform, while fulfilling the requirements of reliability and long life established by the KCRC's operation and maintenance plans.

The test conduct reflects initial presumptions that Heavy axle loading

- Could reduce engineering margins for fatigue,
- Will have a wider range of combination loading (vertical and lateral loads)
- Will have larger load extremes as a percentage of static loads.

The tests also reflect concerns with the testing procedures raised in the remainder of this report on transit level testing.

The work required defining objective criteria for (1) selection of fasteners for evaluation and (2) for acceptance of test results. As an example of the latter, the criteria for elastomer fatigue were developed from elastomeric mechanics. The test results were then able to characterize expected life rather than a simple pass/fail (where pass/fail would have no useful meaning in this context).

The research team developed a load distribution for this railway not yet in existence, based on statistical distributions from robust databases of freight loads.

The original effort examined two different DF track systems and their components in detail. The same techniques were applied to other Direct Fixation systems represented in this report for a total of 16 different DF fasteners and a number of embedded block components. These fasteners represent nine different DF systems, which are listed in Table 6-1 and pictured in Figure 6-1. These samples are representative of the majority of DF fastener designs and types on the market and were used for evaluation, with no particular preferences except an attempt to include DF fasteners of each major type. Each design may be tailored through changes in components. Values presented in this study are representative to give a range of nominal values of components in use today. They are not to be considered as recommendations for use, nor should any fastener be considered until a complete evaluation has been completed to determine the appropriateness of the fastener to the application under consideration.

Table 6-1. Fastener Systems Tested

Fastener Type / Number Tested	Use	Comments
Embedded Block 1 Q	Transit	Fastener originally cast in reaction block. Use as known baseline.
Embedded Block 6 R	Heavy Transit	Prototype dual stiffness boot. Used with existing Embedded Block design
Frame Fastener 1 5 A,B,C,D,E	Heavy Transit/ Locomotives	A large dual stiffness design for passenger and heavy locomotive use.
Frame Fastener 2 3 F,G,H	Transit	Soft fastener claimed to reduce noise.
Unbonded plate with spring preload 2-pad 1 O	Transit	Very soft fastener using microcellular pads and preload spring.
Unbonded plate with spring preload 3-pad 1 P	Transit	Very soft fastener using microcellular pads and preload spring.
Bonded plate 3 1 N	Soft Transit	Soft Fastener used at parts of WMATA
Bonded plate 2 1 M	Nominal Transit	Fastener used for a number of different transit applications
Bonded plate 1 1 L	Heavy Transit	Fastener used for locomotive drawn heavy transit
Frame Fastener 3 2 I,J	Nominal Transit	Fastener from Australia, a very similar design is known in the US as the Alternate I

Figure 6-1. Views of several representative fasteners

6.1 Identify TrackForms for the Design Evaluation Study

The evaluation effort for the KCRC had the directive to identify appropriate track forms for consideration for mixed passenger and heavy freight. The track forms for testing were to be representative of the major classes of non-ballasted track construction. Two track forms were identified for detailed study for the design evaluation, while several others were evaluated under the TCRP program.

It should be noted that the wheel load and axle count used for this fastener evaluation were extreme. This was an actual independent project evaluation performed as part of a preliminary engineering effort for the West Rail Division of the Kowloon-Canton Railway Corporation and reported to them. The two fasteners chosen for detailed fatigue testing were selected to meet a number of specific constraints for the KCRC program. These two fasteners were off-the-shelf products. The fasteners characterized through single fastener tests reported in this Section were selected based upon availability and an attempt to gain data from the major types of fasteners in the market place. The engineering values are representative, but by no means all-inclusive. Variations in elastomer properties provide the ability to tailor fasteners that look identical, but have different characteristics. The methods employed during this evaluation should be valid for all applications.

6.1.1 Criteria for Evaluation of Trackforms

The first step in this process was to construct criteria for selecting fasteners for evaluation. The fundamental requirements, set forth as necessary when considering fasteners for inclusion in the study, were:

1. Prior experience: The fastener design must have some prior experience in revenue applications (there is no expectation that a fastener system will have had significant heavy axle load service exposure). This criterion was placed by KCRC to exclude experimental designs.

2. Multiple designs: The chosen fastener systems should include varying design approaches to ballastless track.

3. Potential competence for the envisioned loads: At least one system is believed to possess capacity for the service. This belief may be established simply as an opinion of the program team or may result from calculations or written statements from the fastener designer/manufacturer.

4. Availability within the program's time frame: Possible candidates must be available either off the shelf or deliverable immediately.

5. The group of fasteners chosen must collectively represent the practical range of fastener designs and fastener design approaches.

While the purpose of the study was to determine design competency of candidate fasteners, the criteria required selection of products either purported to be designed for heavy axle applications, or had some experience in freight service.

The systems chosen to meet these criteria and their salient features were:

- A frame type fastener designated "frame fastener 1"—This fastener is designed as a dual-stiffness system that should balance the high load restraint requirements of freight with the isolation requirements desired for passenger service. This is a large system that the manufacturer believes will meet the service requirements. This system is standard with a common elastic rail clip and no rail pad. A number were delivered for test.

- An embedded.block type system—This system has been adapted to meet the anticipated requirements through the introduction of a dual stiffness boot to provide the same balance of restraint versus isolation as the frame type fastener. Otherwise this system is an off-the-shelf item with modified spring clip isolators to handle RE 136 rail. The block was acknowledged to be of a marginal size for heavy axle loads unless the block spacing is decreased to 550 mm. It is deemed representative of the product line and therefore a good candidate for testing.

- Plate Type Direct Fixation—This general design is the mainstay of North American installations. They consist of two steel plates bonded by a separating elastomer. At least one of the plate type fasteners have an end frame or "hood" similar to the frame designs

  This end hood is believed necessary to provide sufficient restraint against lateral movement. Figure 6-3 shows the end section of two of the bonded plate designs. These fasteners utilize a bottom plate bolt design. Several of the designs have internal interlocking to assure fastener integrity in case of a bond failure. Many other plate designs exist in the market today. Several of the designs rely on springs to provide a preload to the elastomer to enhance the fasteners' dynamic performance. One such variant is being developed and was evaluated as the only un-bonded system tested and is shown in Figure 6-4.

The first two were studied initially. The third was later added for comparison. Several other systems were obtained in limited quantities. Static and dynamic characterization of these other systems was performed although no fatigue testing was performed on these systems.

Examples of several of the plate and frame type designs are shown in Figure 6-5. The top and bottom of each fastener is shown.

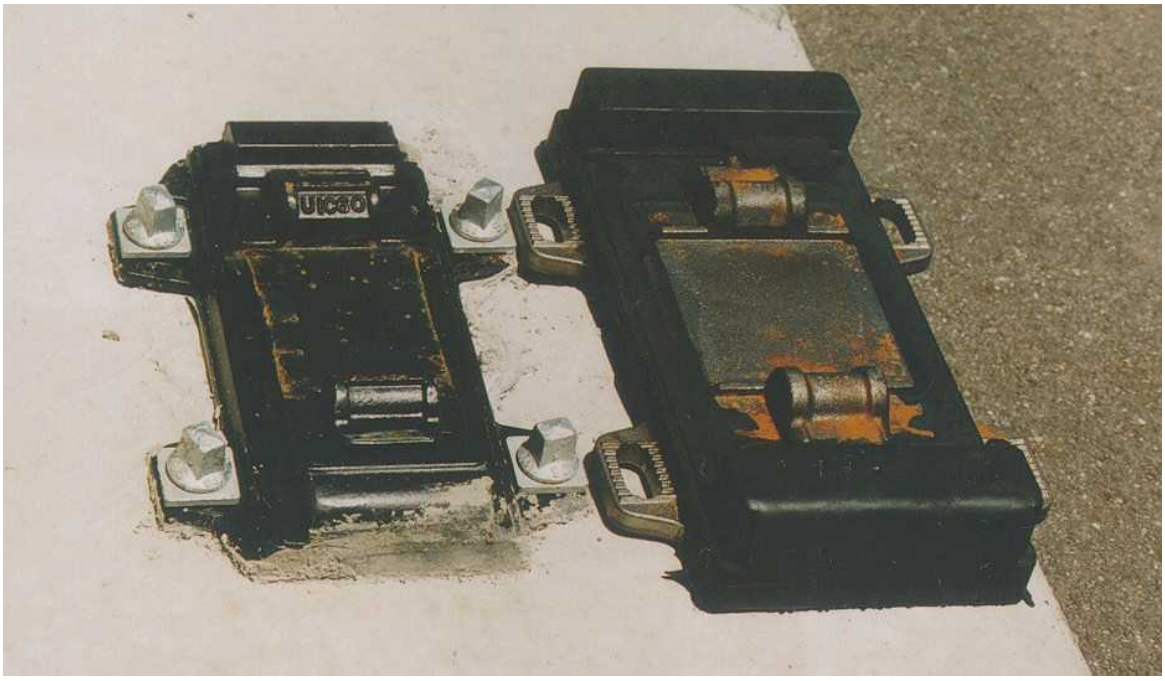


Figure 6-2. Two frame type fasteners, left an Australian design, right, Frame Fastener 1

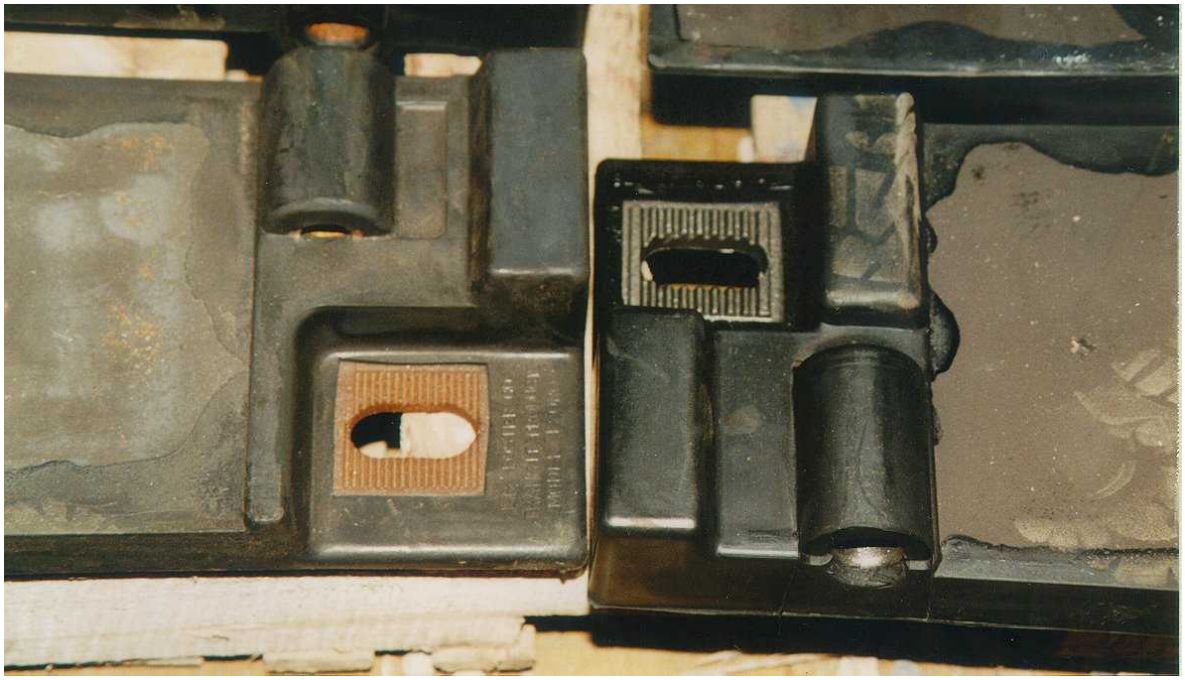


Figure 6-3. Bonded fastener showing end frame "hood"

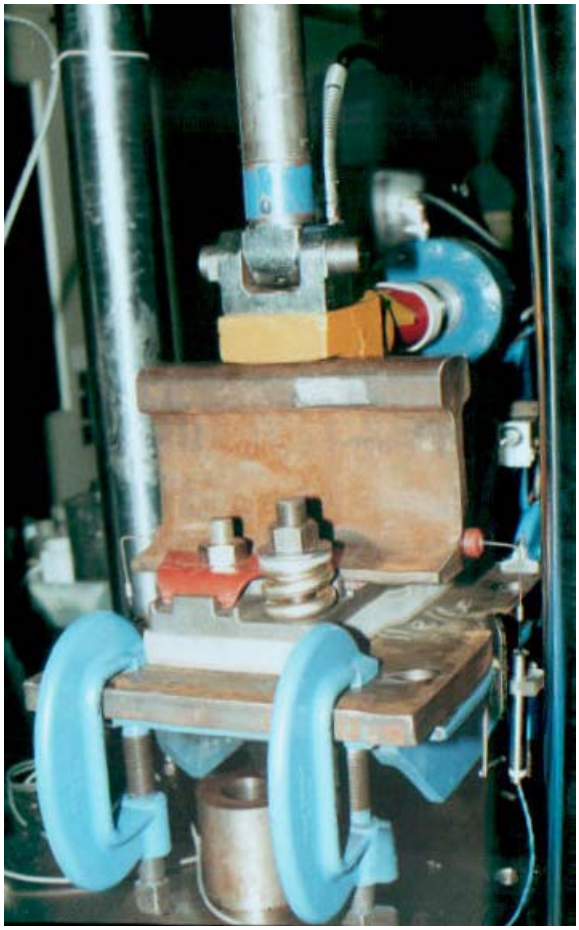


Figure 6-4. Unbonded plate design under test

Figure 6-5. Top and bottom views of several representative direct fixation fasteners

6.1.2 Test Load Determination

Because there was no prior load history for the new heavy axle railroad and to provide an efficient test regimen that allowed confidence in the test results for the new railroad, a representative load distribution was developed and an objective criterion applied to that distribution for selection of test loads. The vertical-loading environment presented in 6.1.2.1 and represented graphically in Figure 6-6, with L/Vs up to 0.8. In several cases the initial static testing uncovered deficiencies in the fasteners at high L/V ratios. The actual fatigue tests were run at a constant L/V of 0.4 or 0.6.

6.1.2.1 Vertical Load Distribution Estimation Procedures

The traditional basis for the fastener vertical design load is the vehicle's static weight, usually the crush load from the vehicle design criteria, increased by a factor for dynamic loads (1.3 to 2 are typical factors) to arrive at a design load for the rail head load. These rail loads are then reduced due to the load sharing that occurs between fasteners to a load for each fastener. The load sharing is given by the Zimmerman Distribution Factor[11]:

$$F_z = (d/\sqrt{8}) * (K_s / dEI)^{1/4} = 0.41$$

where with typical values

d = fastener spacing = 24 inches (610) mm

K_s = fastener stiffness = 250,000 lb/in (44 kN/mm)

E = modulus of steel = 30×10^6 lb/in^2 (210 kN/mm^2)

I = 65.9 in^4 (2743×10^4 mm$^{4)}$ for RE 115 Rail)

and

L_f = F_z*wheel-load*impact factor.

This factor is the same as the Timoshenko Beam-on-Elastic Foundation formula's in a slightly different format.

The fastener is then designed or selected based upon this load. This is an approach that works well for the majority of applications. When dealing with complex loadings, high speed systems, mixed traffic, and or heavy traffic densities, it is beneficial to better quantify the loading environment. During the course of this work an approach was developed to address those more complex loading scenarios. As an example of this approach, the static vertical loads to be encountered during operation of a shared right-of-way mixed passenger/freight operation were defined by review of various operational documents. This information is typically presented as a static load profile. Using this information it is possible to develop an assumed load profile representative of a vehicle population that might make up a mixed freight-

[11] Originally stated by Timoshenko & Langer, "Stresses in Railroad Track", APM-54-26, Proceedings of the American Society for Mechanical Engineers, Nov.30 to Dec. 4, 1931, pg. 279, eqn. 9.

passenger system. This baseline population was used for additional characterizations and is shown in Figure 6-6.

These histograms represent only the static load of vehicles over the track as defined by marketing and planning projections of the KCRC West Rail. The actual dynamic loads encountered by the track and fasteners will be considerably different from the static loads. A number of factors affect the actual dynamic loads. These factors have been described in detail in the literature. The major factors are:

- Track stiffness, geometry, and condition
- Wheel and rail running surface condition
- Vehicle suspension parameters and vehicle design
- Vehicle operating parameters.

There are also a large number of variables that affect each of these factors. The end result is that the final dynamic load distribution assumes a nearly Gaussian distribution for the majority of the axle load events, the distribution is not purely Gaussian. There is a sub-population of extreme value events that follow an exponential distribution.

At the present time there is no widely defined, accepted, or used parameter for predicting service loads for wheel loading, such as the ones used in the Davis equations for train drag. Most of the wheel load characterization measurements in this country have included wheel populations where the wheel condition is considerably worse than would be allowed on a well-maintained system, at least those studies available to the researchers. This assumption is based upon the measurements and observations during the various property visits both on this program and on previous endeavors. The desire is to develop procedures and parameters for a well maintained system. Measured data captured by a Wheel Impact Load Detector (WILD) system on VIA Rail Canada is an example, presented in Figure 6-7 in histogram form and in Figure 6-8 in an exceedance plot. These passenger vehicles have nominal wheel loads and typical operating conditions for the passenger vehicles. The wheel loads are typically 16 to 18 kips (71 to 80 kN) and the vehicles are operated at speeds up to 100 mph (160 km/h).

These data represent the best available known distribution for characterizing the wheel loads likely to be generated by a system with good maintenance practices, an assumed condition for this study. With these issues in mind, the VIA Rail data was chosen to represent a basis for determining the factors necessary to transform static wheel loads into a dynamic wheel load distribution as an estimate of actual service loads.

The developed analytical representation transformed a population of 16 kip wheel loads (14.52 tonne axle load) presented in Figure 6-9. A set of these curves was then constructed for the assumed KCRC static loading histogram. These are presented in Figure 6-10. These curves were then used to transform the assumed static loading histogram.

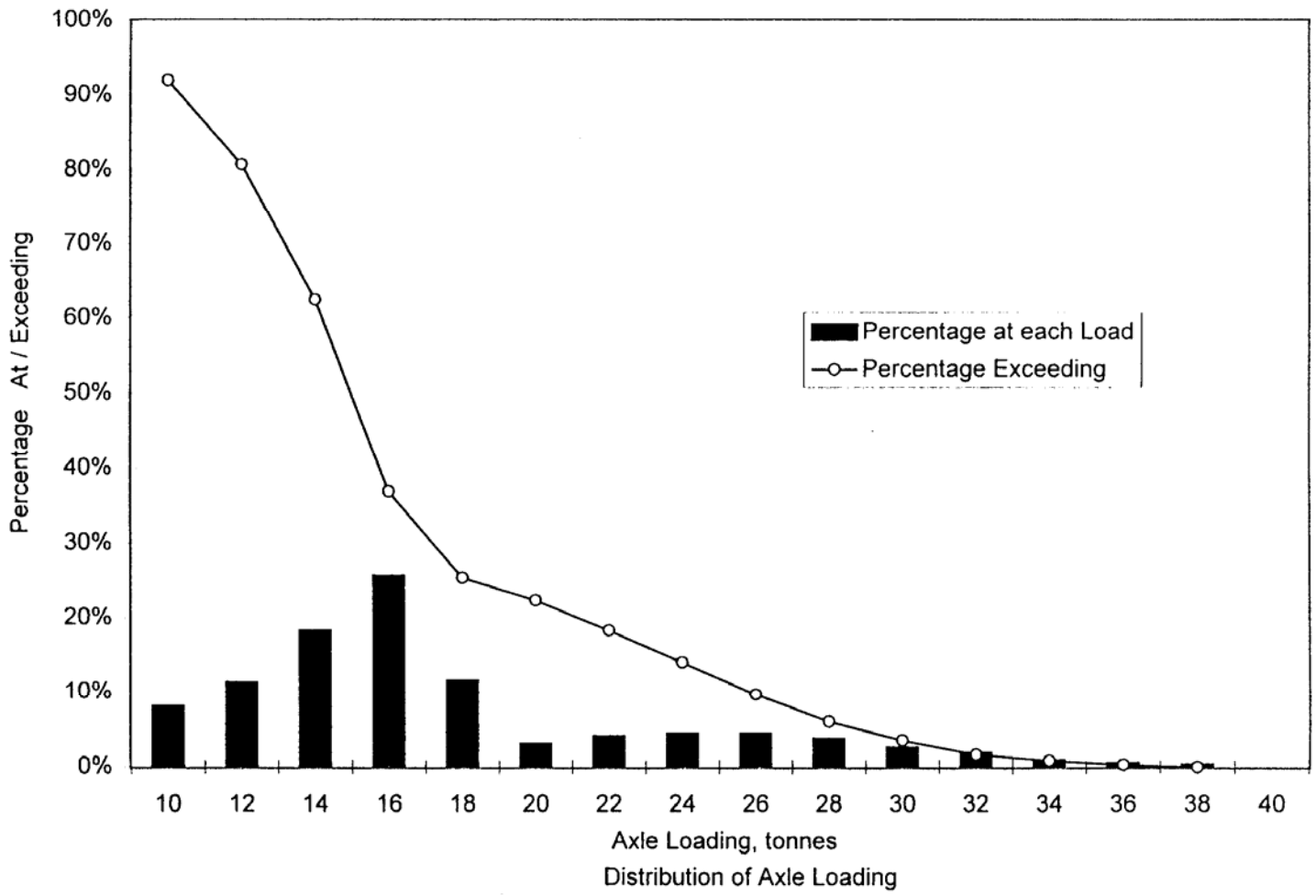


Figure 6-6. Static axle load for mixed freight and passenger operation

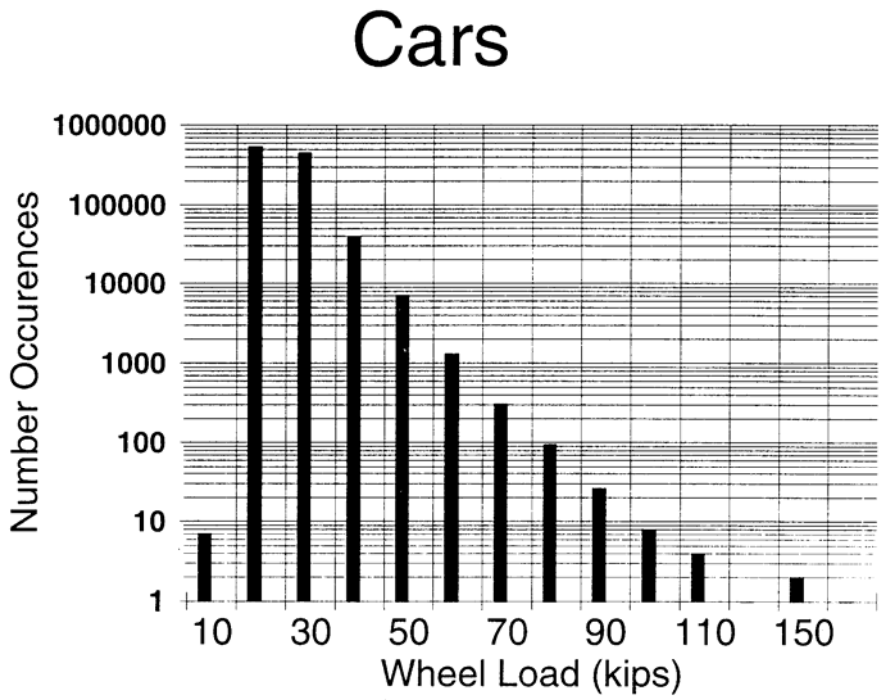


Figure 6-7. Example of "clean" wheel vertical loading distribution

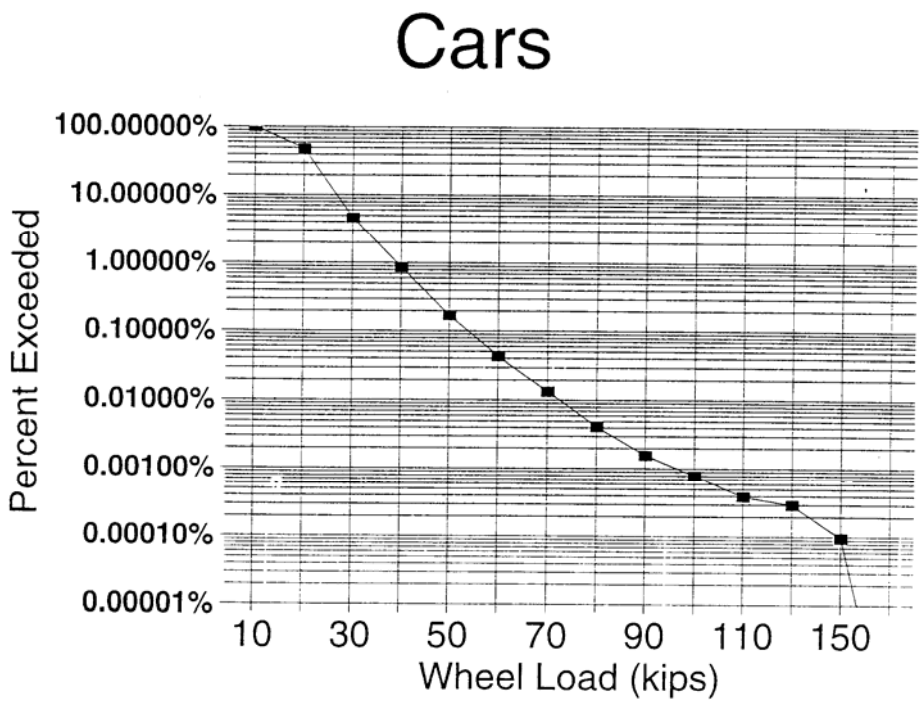


Figure 6-8. Vertical load exceedance distribution for "clean" wheels

The transformed load histogram is presented in Figures 6-11 and 6-12. Figure 6-11 shows the nominal overall distribution as a percent of the wheel population. Figure 6-12 shows the high load end of the distribution on an expanded scale in actual number of events. The rationale and benefits of this scale will be more apparent as modified fastener testing procedures are developed later in this report.

The importance of Figure 6-12 is to show that the number of occurrences of very large axle loads can be significant even with the very small percentages represented by these loads. This is important to consider when specifying safety and loading factors for an operation where the reliability requirements are very high. Factors must be assumed to assure no catastrophic failures occur due to these extreme events.

Actually, the large loads tend to occur as single wheel events so the better parameter to use is wheel load, not axle load, when specifying component performance.

The Excel worksheet used to construct the transformed loading histograms in the previous figures is available on request. The practitioner can use these worksheets to construct appropriate histograms of projected loading for different input populations using these worksheets with new input histograms.

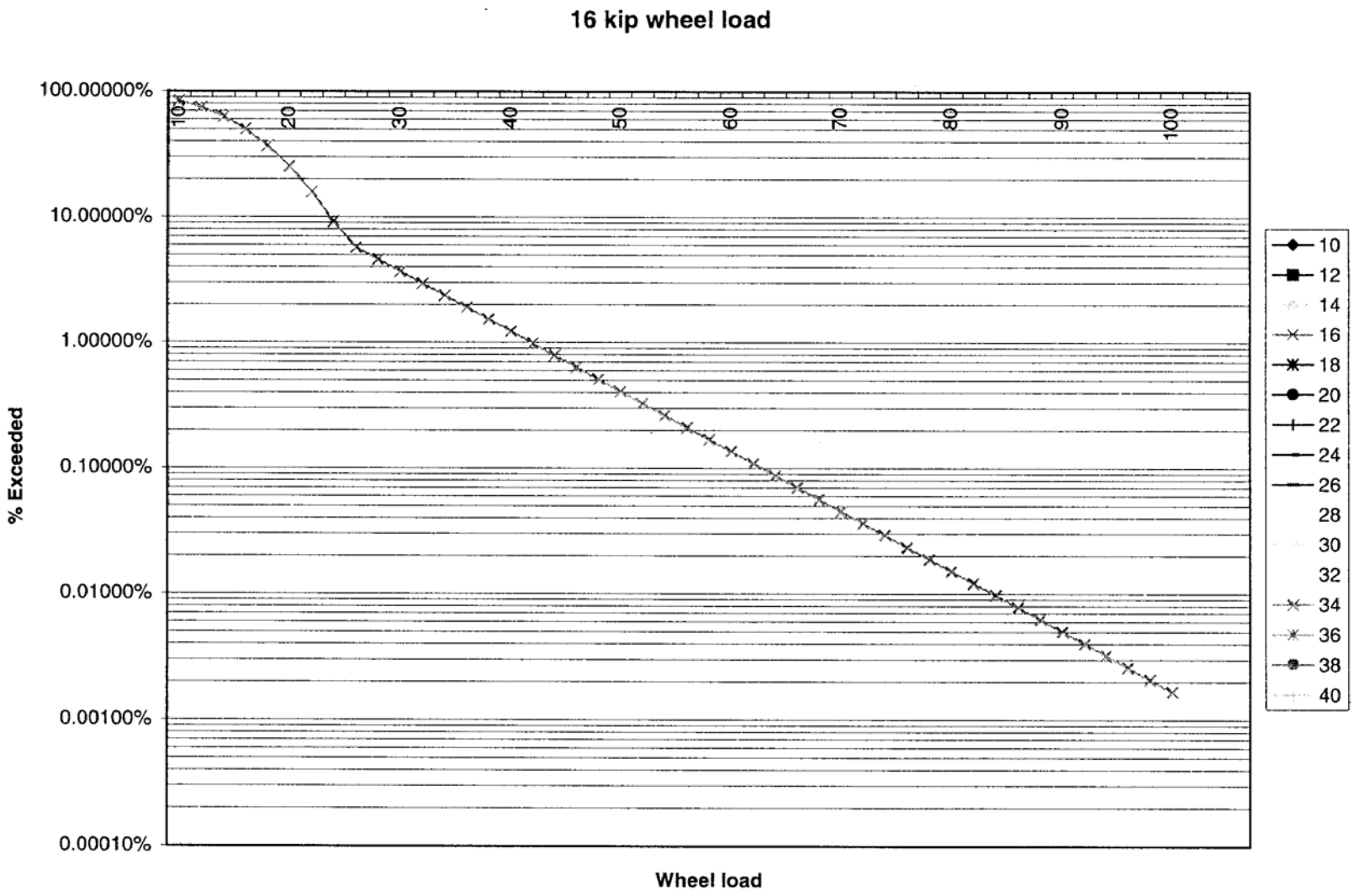


Figure 6-9. Analytical vertical wheel load exceedance for 16 kip wheel load

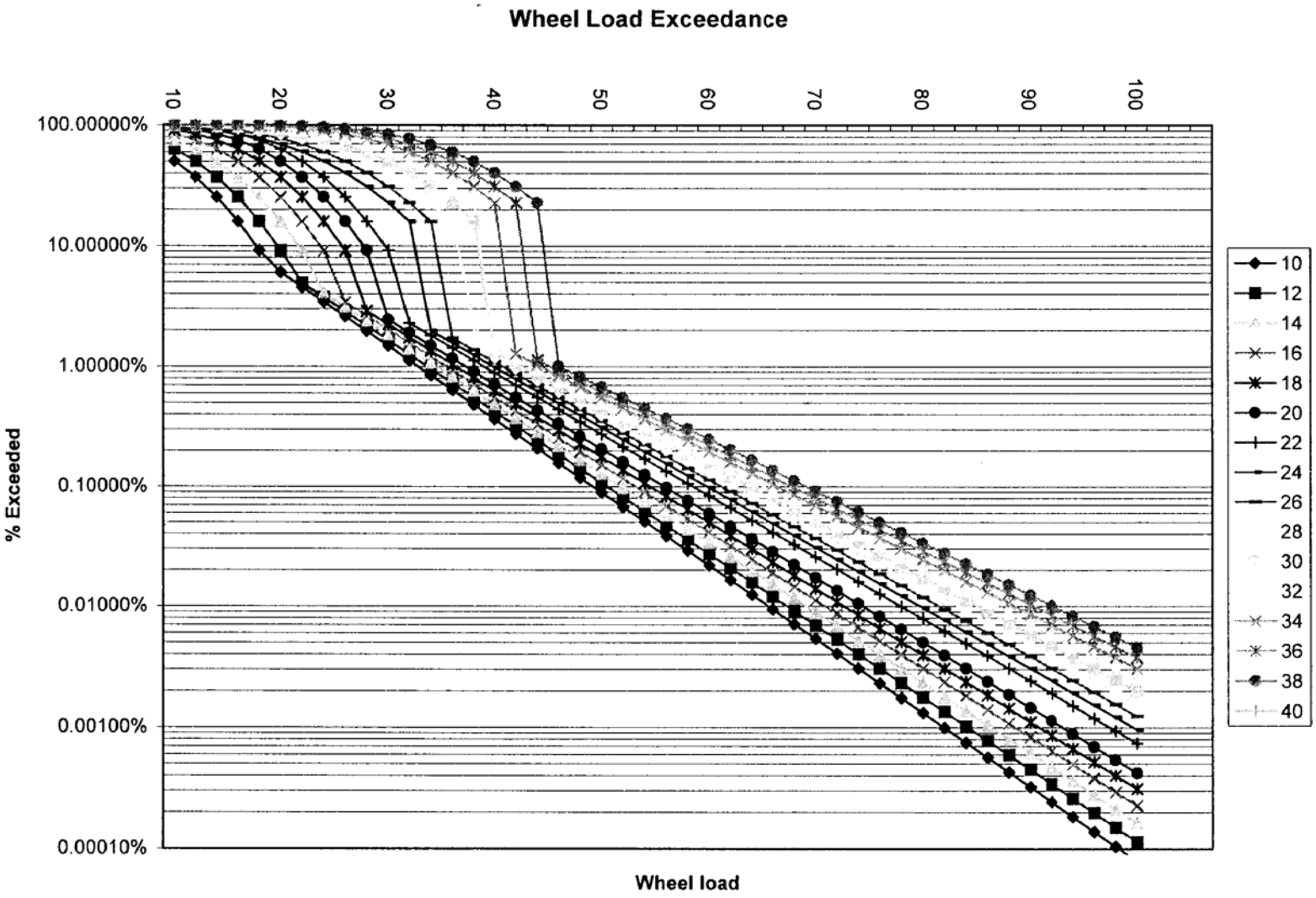


Figure 6-10. Analytical vertical wheel load exceedance curves for binned wheel loads

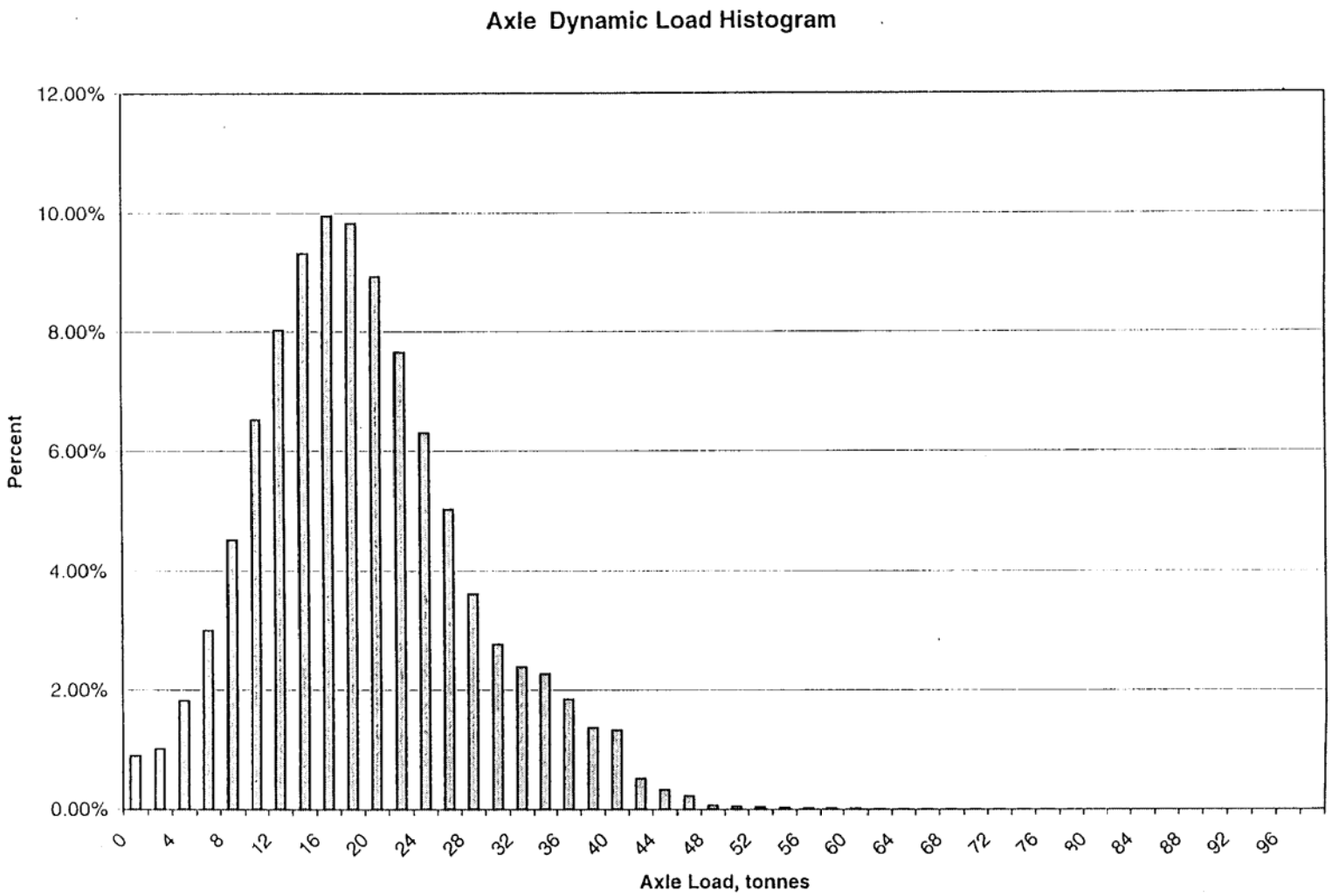


Figure 6-11. Dynamic vertical wheel load distribution after transformation

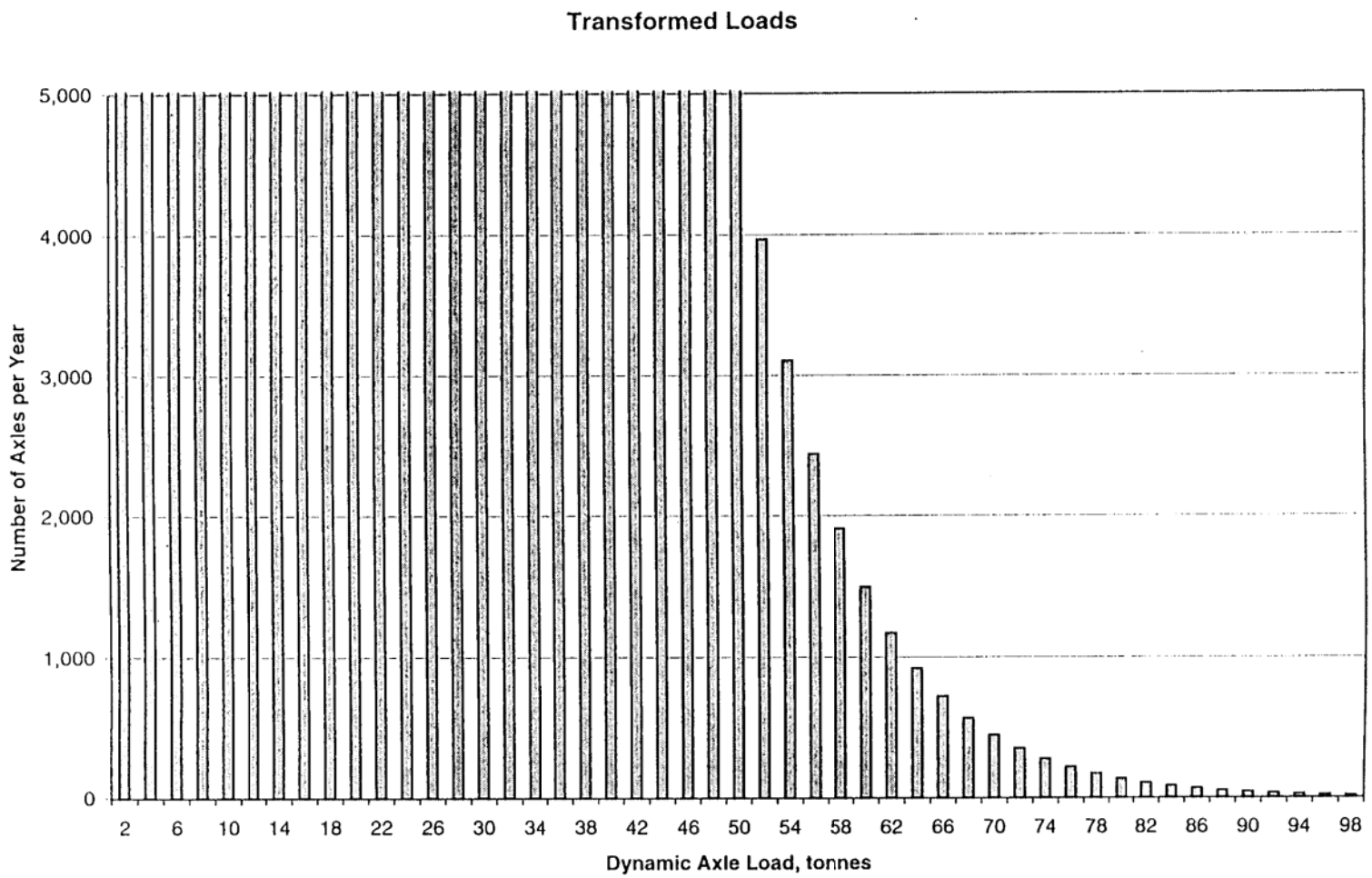


Figure 6-12. Dynamic vertical wheel load distribution after transformation

This figure represents the total loading environment. The desire is to test only at those loads that will cause damage to the material in order to accelerate testing. The highest 5% loadings were selected for testing. The load cycles then were comprised of the selected top loadings, and for the number of occurrences predicted in a single year for each load level. The yearly load cycles were then repeated to test for subsequent years. The results then provide a measure of damage/fatigue by year throughout a fastener's life cycle.

6.1.2.2 Elastomer Fatigue Acceptance Criteria

An issue was to determine the damage threshold for elastomers in the different fastening systems. The strains, and therefore damage potential, are highest in the microcellular pad. The stress versus strain curve for the microcellular pad is given in Figure 6-13. The load versus deflection curve for a pair of Embedded Block blocks is given in Figure 6-4. The damage threshold for an elastomer is given as:

$$G = 0.25hE_c\varepsilon_c\ 2$$

where

G = 40 J/m^2 for the EPDM material

h = 12 mm = pad thickness

E_c = 0.9kN/mm^2 = Compressive modulus determined from the stress/strain curve in Figure 4-103

ε_c = Compressive strain = pad deflection/thickness

Pad deflection at damage threshold

$$= \sqrt{G * h/(0.25 * E_c)}$$

$$= \sqrt{40 * .012/(0.25 * 0.9)}$$

= 1.41 mm (0.056 inch).

This is the approximate deflection at which fatigue damage to the microcellular pad would begin to accumulate. This deflection corresponds to a load on the pad of 115.6 kN (26 kips). The tangent stiffness of the embedded block system at 115 kN is 41 kN/mm.

Then using this stiffness to calculate a Zimmerman Distribution Factor:

$$F_z = (d/\sqrt{8}) * (K_s / dEI)^{1/4} = 0.34$$

where

d = fastener spacing = 550 mm

K_s = fastener stiffness = 41 kN/mm

E = modulus of steel = 210 kN/mm^2

I = 3950 x 104 mm4(for RE 136 Rail)

and

Lf = Fz*Wheel load.

This distribution factor can then be used to calculate the single wheel load that would impart a 115 kN load to a single support block, in track.

Wheel load

= Lf/Fz = 340 kN (76 kips)

Therefore, all loads for testing should be above the 340 kN (76 kip) load threshold (in this manner, all non-damaging load cycles are ignored). This cuts the number of loading cycles per month from over 86,000 to less than 300. To provide a 33 percent margin of testing safety the load threshold was set at 204 kN (46 kips). At that threshold approximately 7,000 loading cycles are accumulated for each month of simulated service. This was the basic loading threshold used for both of the fatigue evaluations. The same profile was used for both to provide directly comparable results. As will be shown elsewhere, the strain percentages for the two systems are very similar.

Table 6-2. Fastener test dynamic loading schedule

Vertical Wheel Load, Kips	Axle Load Tonnes	Lateral Wheel Load, Kips	Number of Occurrences per year	Number of Occurrences per month		Vertical Wheel Load, Kips	Number of Occurrences per month
46	**42**	**18**	47,663	3972		46	3972
49	**44**	**20**	30,534	2545		49	2545
51	**46**	**20**	21,226	1769		51	1769
53	**48**	**21**	6,529	544		53	544
55	**50**	**22**	5,123	427		55	427
57	**52**	**23**	4,024	335		57	335
60	**54**	**24**	3,167	264		60	264
62	**56**	**25**	2,496	208		62	208
64	**58**	**26**	1,972	164		64	164
66	**60**	**26**	1,562	130		66	130
68	**62**	**27**	1,241	103		68	103
71	**64**	**28**	990	83		71	83
73	**66**	**29**	794	66		73	66
75	**68**	**30**	640	53		75	53
77	**70**	**31**	520	43		77	43
79	**72**	**32**	427	36		79	36
82	**74**	**33**	353	29		82	29
84	**76**	**34**	296	25		84	25
86	**78**	**34**	251	21		86	21
88	**80**	**35**	217	18		88	18
90	**82**	**36**	190	16		90	16
93	**84**	**37**	169	14		93	14
95	**86**	**38**	153	13		95	13
97	**88**	**39**	141	12		97	12
99	**90**	**40**	132	11		99	11
101	**92**	**40**	125	10	Total		6929
104	**94**	**42**	120	10			
106	**96**	**42**	117	10	Use lateral load of constant L/V of 0.4 or 0.6		
108	**98**	**43**	115	10	At 3 hz = 1 month per hour		

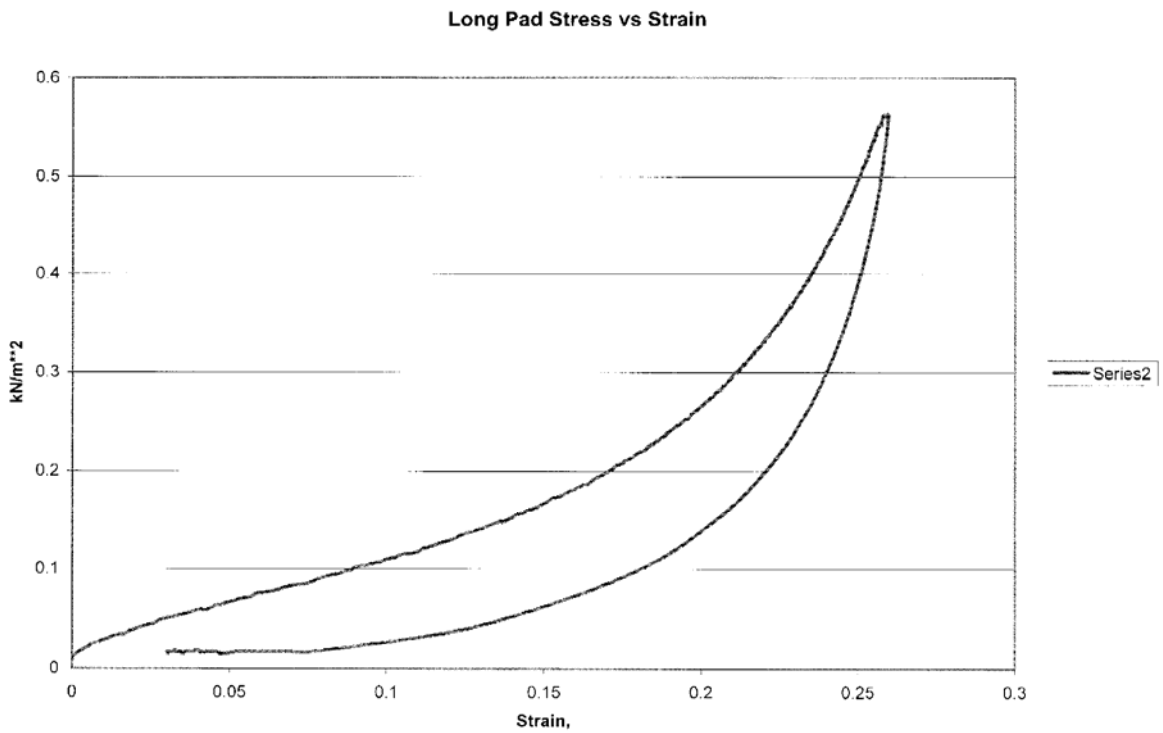


Figure 6-13. Series 2 long pad stress vs strain

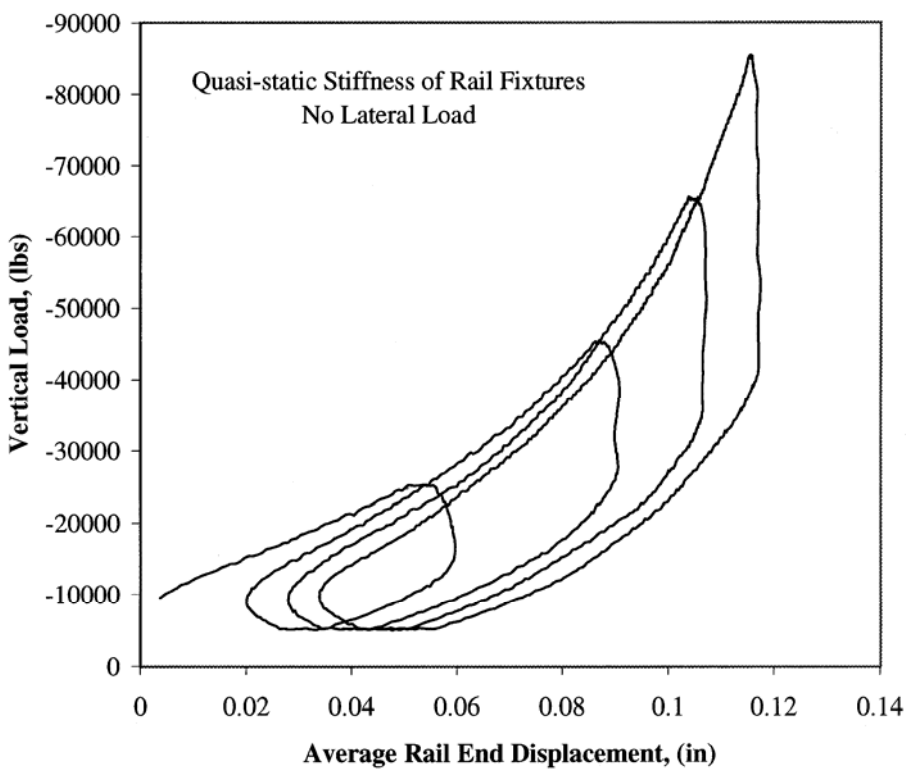


Figure 6-14. Quasi-static stiffness of rail fixtures, no lateral load average rail end displacement (in)

6.2 Stress or Strain Evaluation for Each Component

After the components were tested to determine their force vs. deflection characteristics for anticipated loads, reported in Section 3, it was then necessary to relate these deflections to actual stress or strain in the materials within the components. This evaluation was necessary in order to relate the loads to an allowable stress or strain. A simplified approach has been used to obtain this stress or strain condition. Simple P/A or delta-L/L type analysis to get values for the material states in the test items has been performed. This method is somewhat limited, but will be adequate for the majority of the loading cases. While FEA evaluations could be performed, it was considered outside the scope of the effort. The detailed evaluation is judged to be the responsibility of the vendor during final track design.

As an example, the strain in the Embedded Block microcellular pad and most pronounced frame fastener 1 support areas were calculated. Table 6-3 shows these values. For typical loading the elastomer strain is below the recommended level of 15 to 20 percent strain. The strain in the rail pads and in the Embedded Block boot are even lower due to their higher stiffnesses.

Table 6-3. Strain and deflection of fasteners

	Deflections	Strain
Embedded Block	3.5 mm max	31%
	1.0 to 2mm typical	8% to 16%
Frame fastener 1	5.0 mm max	30%
	2.0 to 3mm typical	12% to 18%

The consistency of the values is remarkable given that there has been no attempt by the manufacturer to standardize on this strain value. The thickness of the Embedded Block pad is 12 mm, and the thickness of the frame fastener 1 pad is 16.5 mm.

6.3 Dual Fastener Fatigue Experiments

6.3.1 Test Configuration

After an evaluation of a broad range of available DF fasteners, samples from two suppliers were sent to Battelle to be installed and tested to determine their fatigue life under the extreme loading conditions developed in Section 6.1.2. The full scale tests required that the specimens be assembled into a large support frame to allow for testing using two fasteners loaded by a single rail. This configuration duplicated the loading that occurs in actual field use. A number of test specimens using two Embedded Block ties were assembled for testing. Assembly was completed at the Battelle facility at West Jefferson. For the Embedded Block system, the assembly of the two tie blocks began by cleaning boots and attaching the boots to the blocks using tape. Welded steel containers were used to strengthen the concrete and as forms for the concrete pour. Reinforcing steel was also placed approximately 75 mm (3 inches) from the top of the steel forms. The tie blocks were positioned in the form using the rail and angled at 1:40. The precast concrete ties and fasteners were installed on 750 mm (30 inch) centers. The required clearance around the blocks was checked before the second pour of concrete.

While this spacing is wider than in a normal installation, the test is independent of the spacing because a short segment of rail is used. There is no moment from outside the two-tie zone.

For the Frame fastener 1 assembly, the tie blocks were positioned in the form using the rail and angled at 1:40 and installed on 750 mm (30 inch) centers. Shims were placed under the fixtures. The concrete pour was placed into similar welded steel containers with reinforcing steel. The top surface was finished with fasteners in place and the shims under the fasteners were removed after the concrete set.

After assembly, specimens were positioned into the 2,224 kN (500 kip) load frame and strong back. The setup is shown schematically in Figure 6-15. The large base fixture and lateral support were manufactured from steel wide flange beams and plate, as shown in Figure 6-16. The 2,224 kN (500 kip) actuator and load cell provided the vertical load, and a 445 kN (100 kip) actuator and load cell furnished the lateral load. The vertical load was applied at the center of the rail on the railhead. The lateral load was applied at the midpoint of the railhead, midway between the block ties. As seen in Figures 6-17 and 6-18, the fixture applying the load allowed rotation and deflection of the rail. The loading point was not fixed to the rail, but was a special designed loading head with an AAR wheel rim segment providing the final load contact point. This provides a realistic loading on the railhead.

Vertical deflection was measured at the ends of the rail using two calibrated direct current displacement transducers (DCDTs). Lateral deflection was measured at the top and bottom of the rail midway between the ties and normal to the rail using two other calibrated DCDTs. The large vertical column was required to allow the lateral displacement of the rail without damaging the vertical load cell. The qualification testing used calibrated equipment traceable to the National Institute of Standards and Technology (NIST).

A programmable single output waveform generator controlled the system for the static and dynamic tests. Data were acquired using a computer controlled data acquisition system. Loads, displacements, cycle count, and the input function were recorded during testing.

Baseline static and dynamic testing was completed on specimens before and after the repeated load testing. This was used to measure the damage that accrued during testing.

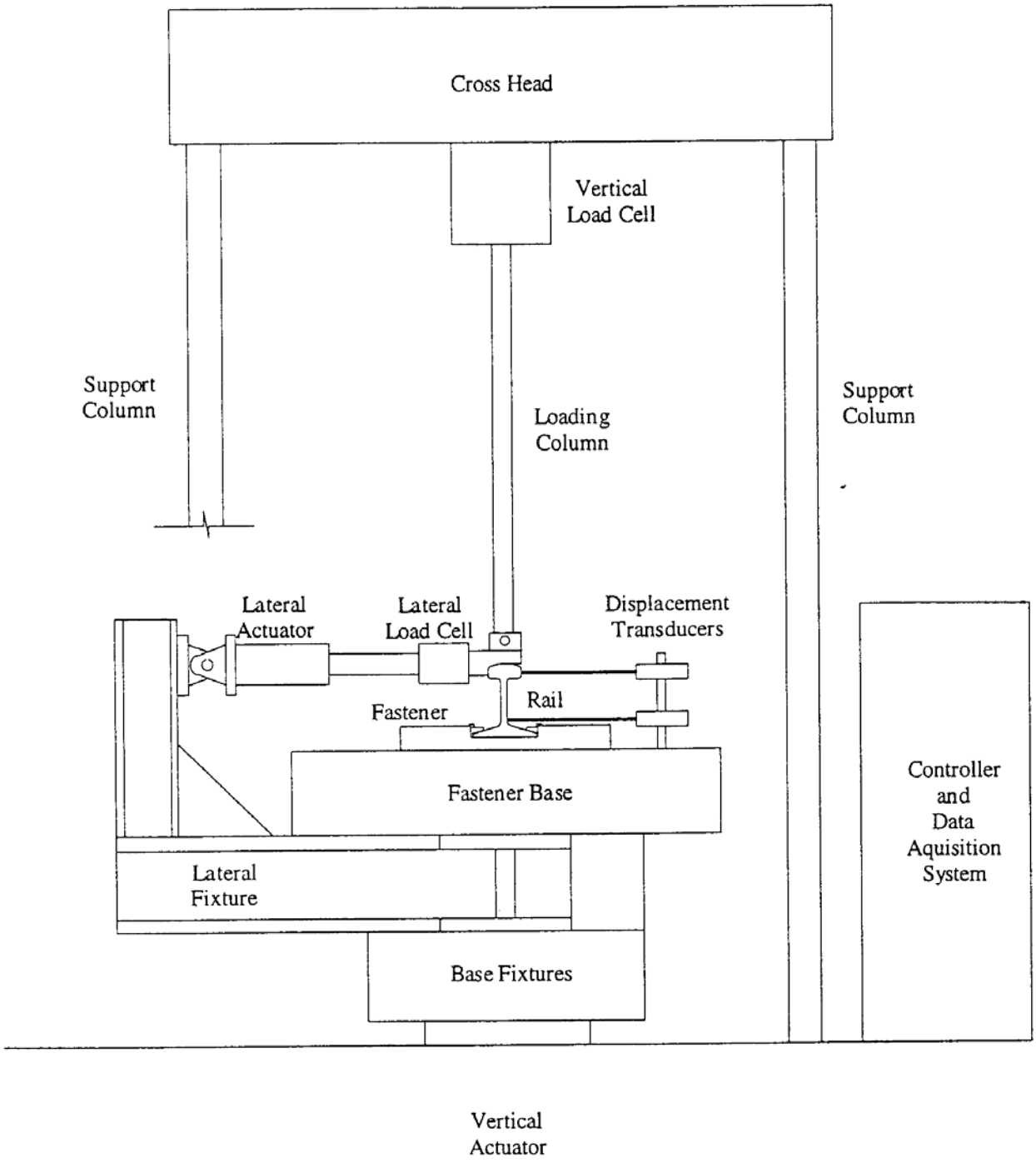


Figure 6-15. Schematic of duel fastener layout

Figure 6-16. Photo of duel fastener layout

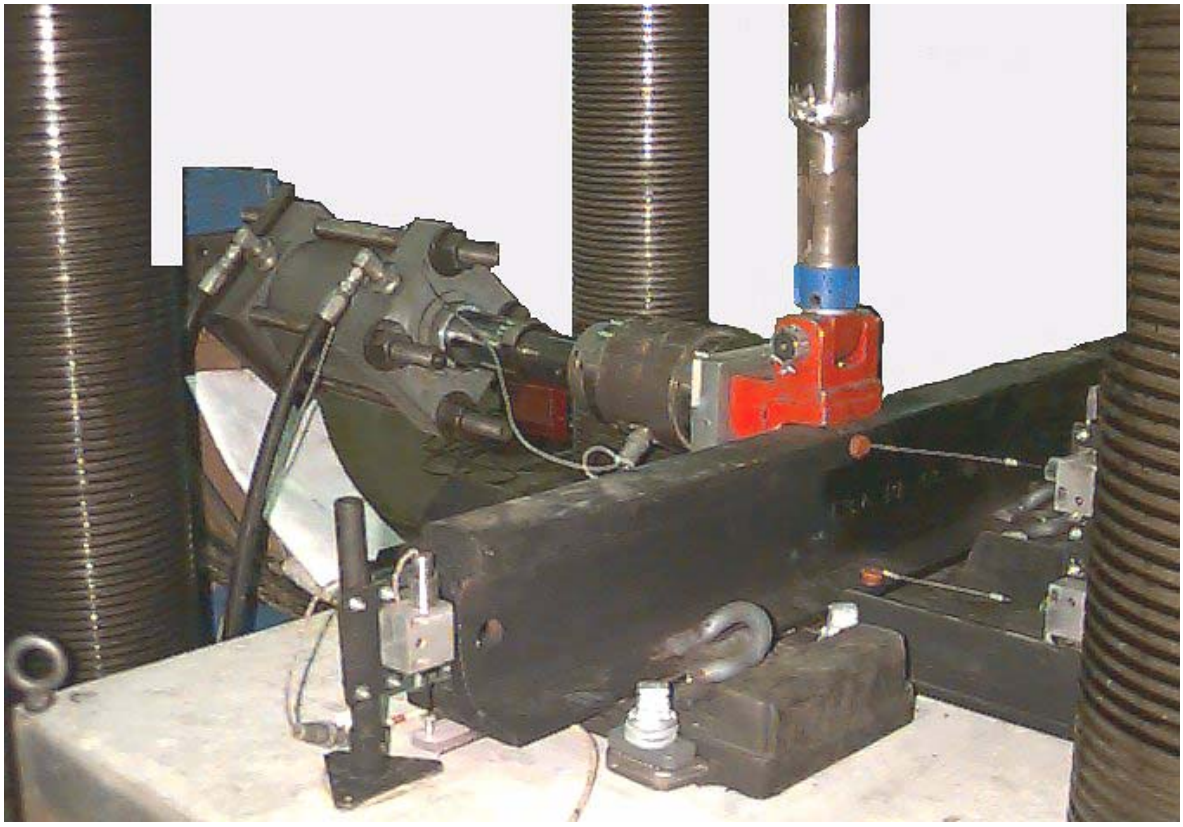


Figure 6-17. Photograph of duel fastener layout

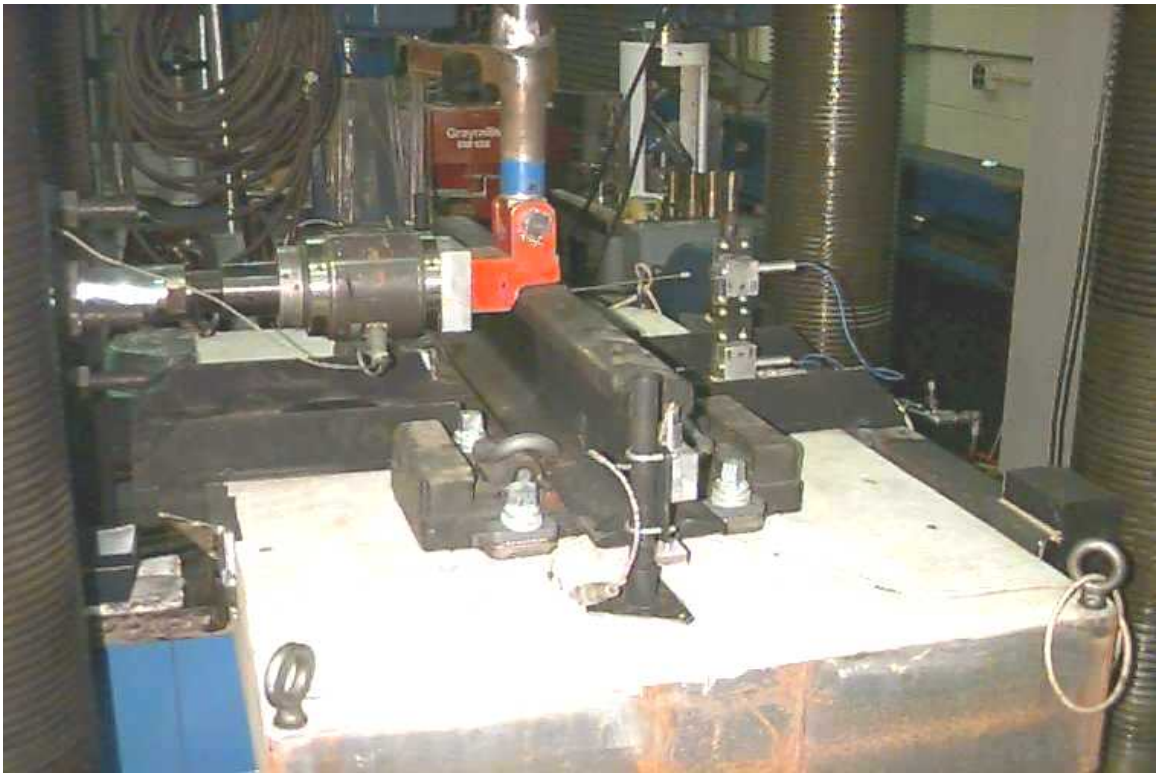


Figure 6-18. Closeup photograph of dual fastener layout

6.3.2 Baseline Static Testing

6.3.2.1 Vertical Load Test

The vertical load test evaluates the deflection of the rail due to compressive vertical loads. Loads ranged from 0 to 445 kN (0 to 100 kip) for the two-block tie assembly. Deflection was measured at the center and both ends of the rail. From this test, the static stiffness of the system was determined.

6.3.2.2 Lateral Load Test

The lateral load test evaluates the deflection of the rail due to lateral loads on the railhead when a vertical load is applied. The vertical loads ranged from 0 to 445 kN (0 to 100 kip) for the two-block tie assembly, and the lateral loads varied from 0 to 20 percent, 0 to 40 percent, and 0 to 60 percent of the vertical loads. Table 6-4 shows the constant vertical loads and lateral loads during each test. This test determined the lateral static stiffness of the fasteners.

Table 6-4. Lateral load test matrix

Constant Vertical Load, kN (kips)	Maximum Lateral Load, kN (kips)		
	Loading Cycle 1	Loading Cycle 2	Loading Cycle 3
44 (10)	9 (2)	18 (4)	27 (6)
89 (20)	18 (4)	36 (8)	53 (12)
133 (30)	27 (6)	53 (12)	80 (18)
178 (40)	36 (8)	71 (16)	107 (24)
267 (60)	53 (12)	107 (24)	160 (36)
356 (80)	71 (16)	142 (32)	214 (48)
445 (100)	89 (20)	178 (40)	267 (60)

6.3.3 Dynamic Testing

6.3.3.1 Dynamic Load Test

The dynamic vertical load test evaluates the deflection of the rail due to compressive dynamic vertical loads. The dynamic loads were applied for a range of 45 to 445 kN (10 to 100 kip) at 1 Hz. There was no lateral load placed on the system. From this test, the dynamic stiffness of the system was determined by calculating the tangent stiffness at each load value.

6.3.3.2 Dynamic to Static Stiffness

The purpose of this test is to determine the vertical dynamic stiffness to the vertical static stiffness values. Data from the dynamic and static stiffness tests were used. There was no lateral load placed on the system. The ratio of the dynamic to static stiffness is calculated from the loads and deflections from the previous tests.

6.3.4 Vertical and Lateral Life Test

The purpose of this test is to evaluate the effects of repeated loads on fastening components. Before the testing, the specimens were carefully inspected, noting any cracking of the concrete or damage to the fastener or pads. During the testing, the vertical and lateral loads were applied simultaneously in phase to the rail. Loads were determined based on life estimates completed by Battelle and summarized in Table 6-5. The cyclic loads were divided into 22 kN (5 kip) increments and the lateral load was 40 percent of the vertical load unless otherwise stated. The frequency of the loads varied between 1 and 2.5 Hz and is shown in Table 6-5.

Table 6-5. Dynamic loading schedule for one month's damage

Vertical Load Pounds (kN)	Lateral Loads Pounds (kN)	Frequency of Loading (Hz)	Number of Cycles
50,000 (222)	20,000 (89)	2.5	4314
55,000 (245)	22,000 (98)	2	1306
60,000 (267)	24,000 (107)	1.75	472
65,000 (289)	26,000 (116)	1.5	294
70,000 (311)	28,000 (125)	1.25	186
75,000 (334)	30,000 (133)	1	162
80,000 (356)	32,000 (142)	1	65
85,000 (378)	34,000 (151)	1	46
90,000 (400)	36,000 (160)	1	34
95,000 (423)	38,000 (169)	1	39
100,000 (445)	40,000 (178)	1	51

6.3.5 Results of Dual Fastener Testing

The Embedded Block system and the "Frame Fastener 1" direct fixation fastener were subjected to repeated load testing to determine the life expectancy of the fasteners. Baseline static and dynamic testing was completed on specimens before, after, and at approximately 10-year intervals during the repeated load testing. This was used to measure the damage that accrued during testing. Table 6-6 shows the number of cycles for each repeated load test. The number of cycles is converted into length of years based on the dynamic loading schedule. Also, static and dynamic testing times for the baseline testing are shown in Table 6-6.

Table 6-6. Repeated load testing summary

	Number	Total Life, Years (cycles)	Baseline Testing, Years	L/V
Embedded Block	Specimen Pair 1	2.5 (211,376)	0, 2.5	0.4
	Specimen Pair 2	24 (2,010,630)	0, 10, 16, 24	0.4
	Specimen Pair 3	10.4 (867,911)	0, 10.4	0.6
Frame Fasterer 1	Specimen Pair 1	23.25 (1,942,830)	0, 10, 20, 25	0.4
	Specimen Pair 2	3.25 (274,784)	0, 3.25	0.6

6.3.5.1 Embedded Block System

Three two-block assemblies were tested with the Embedded Block fastening system. Initial baseline testing of the fastening system included dynamic and static vertical loads. After baseline testing, vertical and lateral life tests were begun. During the first set of tests, the concrete around the precast block assemblies failed in tension at approximately 2.5 years. The failure of the Battelle cast concrete was due to higher then expected tension loads in the cast concrete. A tension strap was manufactured to control the tension for subsequent tests. The failure of the cast concrete block did not occur in later tests, although minor cracking did occur. Final baseline tests were not completed due to the failure of the concrete base.

For the second Embedded Block two-block assembly, the baseline testing was completed and the vertical and lateral life testing was begun. The Embedded Block system was tested for 696,900 cycles or approximately 10 years with an L/V ratio of 0.4. The dynamic and static vertical stiffness and static lateral stiffness with constant vertical loads were completed after the life test.

After the equivalent of 10 years of testing, the tie blocks were also removed from the concrete base for inspection. Figure 6-19 shows the base Embedded Block pads. The condition of the block-tie assembly after completion of the repeated load test was excellent. Cracking was not seen in the pre-cast concrete and the boot had minimal visual damage. The pad between the rail and the fastener was slightly deformed and damaged.

The specimens were replaced into the two-block system and testing continued until 24 years of simulated service. Figures 6-20 and 6-21 show the static and dynamic stiffness during the testing. Table 6-7 shows the static stiffness and Table 6-8 shows the dynamic stiffness of the Embedded Block system. Table 6-9 shows the dynamic/static stiffness ratio for the testing.

For the third Embedded Block two-block assembly, the baseline testing was completed and the vertical and lateral life tested was begun. After 163,756 cycles or approximately 2 years with an L/V ratio of 0.6, the bolts holding the clips in position failed due to fatigue. There was no visual damage to the blocks. The bolts and clips were replaced and testing continued until 867,911 cycles or 10.4 years. The dynamic and static vertical stiffness and static lateral stiffness with constant vertical loads were completed after the life test.

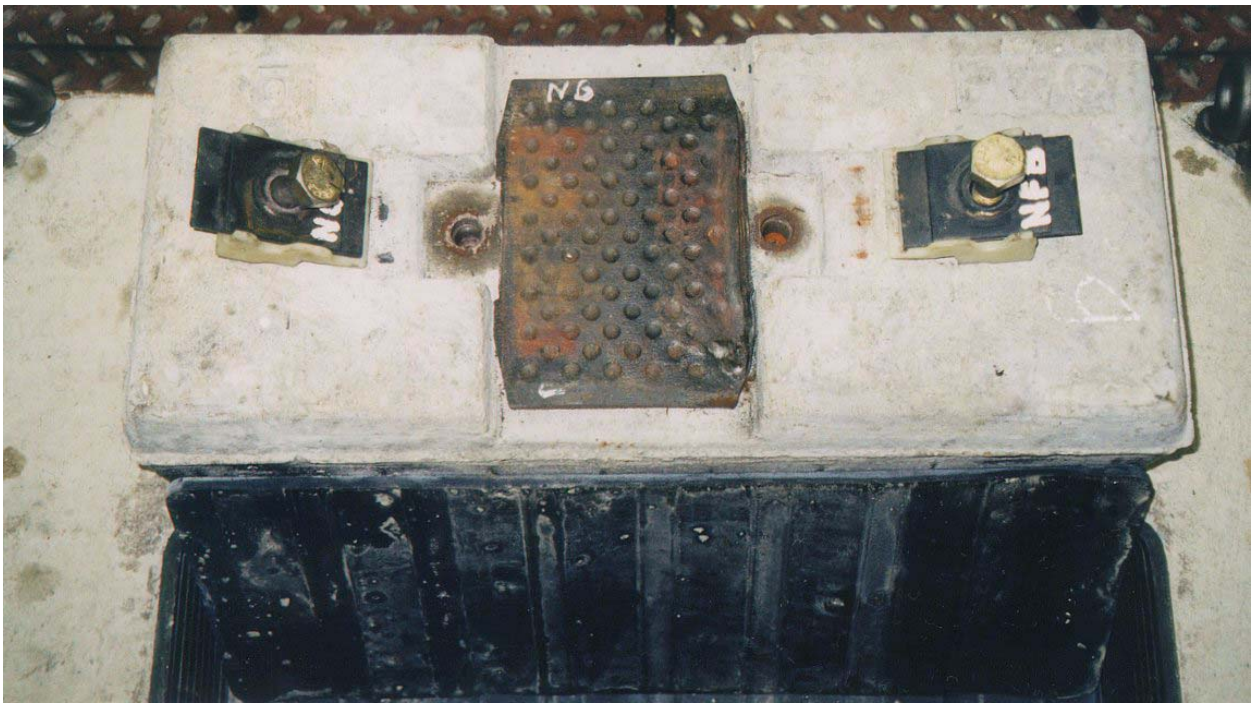


Figure 6-19. Embedded Block system pads after testing

Figures 6-22 and 6-23 show the static and dynamic stiffness during the testing. Table 6-10 shows the static stiffness and Table 6-11 shows the dynamic stiffness of the Embedded Block third system. Table 6-12 shows the dynamic/static stiffness ratio for the testing over time as the simulated age of the system accumulated.

6.3.5.2 "Frame Fastener 1" System

Two each, two-fastener assemblies were tested with the "Frame Fastener 1" system. Initial baseline testing of this fastening system included dynamic and static vertical stiffness and static lateral stiffness with constant vertical loads. For the initial tie-block assembly, the baseline testing was completed and the vertical and lateral life testing was begun. The "Frame Fastener 1" was tested for 1,942,830 cycles or approximately 23.25 years with an L/V ratio of 0.4. The dynamic and static vertical stiffness with varying lateral loads and static lateral stiffness with constant vertical loads were completed after the life test.

Table 6-7. Static stiffness at varied lives for the second Embedded Block system

Vertical Load kN (kips)	Quasi-Static Stiffness, kN/mm (kip/in)			
	Baseline	10 Years	16 Years	24 Years
12.5 (3)	30 (170)	13 (76)	72 (410)	26 (149)
25 (6)	31 (174)	14 (79)	62 (353)	31 (178)
37.5 (8)	41 (233)	17 (97)	77 (441)	38 (217)
50 (11)	56 (321)	23 (133)	77 (441)	44 (251)
75 (17)	101 (579)	41 (234)	122 (696)	72 (412)
100 (22)	86 (490)	47 (267)	142 (810)	92 (527)
125 (28)	121 (691)	84 (481)	185 (1057)	121 (690)
150 (34)	237 (1354)	145 (825)	218 (1242)	156 (891)
175 (39)	258 (1473)	176 (1007)	225 (1284)	184 (1053)
200 (45)	360 (2054)	214 (1223)	284 (1619)	223 (1275)

Table 6-8. Dynamic stiffness at varied lives for the second Embedded Block system

Vertical Load kN (kips)	Dynamic Stiffness, kN/mm (kip/in)			
	Baseline	10 Years	16 Years	24 Years
12.5 (3)		47 (266)		
25 (6)	109 (625)	61 (347)	119 (678)	147 (842)
37.5 (8)	95 (542)	61 (347)	84 (481)	107 (614)
50 (11)	100 (572)	63 (362)	87 (494)	103 (586)
75 (17)	116 (663)	71 (403)	97 (551)	113 (646)
100 (22)	145 (829)	81 (465)	110 (629)	126 (720)
125 (28)	297 (1693)	94 (535)	134 (767)	146 (835)
150 (34)		121 (691)	171 (979)	183 (1046)
175 (39)		151 (864)	202 (1155)	229 (1308)
200 (45)		164 (934)	195 (1116)	233 (1333)

Table 6-9. Dynamic/static stiffness ratios at varied lives for the second Embedded Block system

Vertical Load kN (kips)	Dynamic/Static Stiffness Ratio			
	Baseline	10 Years	16 Years	24 Years
12.5 (3)		3.51		
25 (6)	3.58	4.41	1.92	4.73
37.5 (8)	2.33	3.59	1.09	2.83
50 (11)	1.78	2.72	1.12	2.34
75 (17)	1.15	1.72	0.79	1.57
100 (22)	1.69	1.74	0.78	1.37
125 (28)	2.45	1.11	0.73	1.21
150 (34)		0.84	0.79	1.17
175 (39)		0.86	0.90	1.24
200 (45)		0.76	0.69	1.05

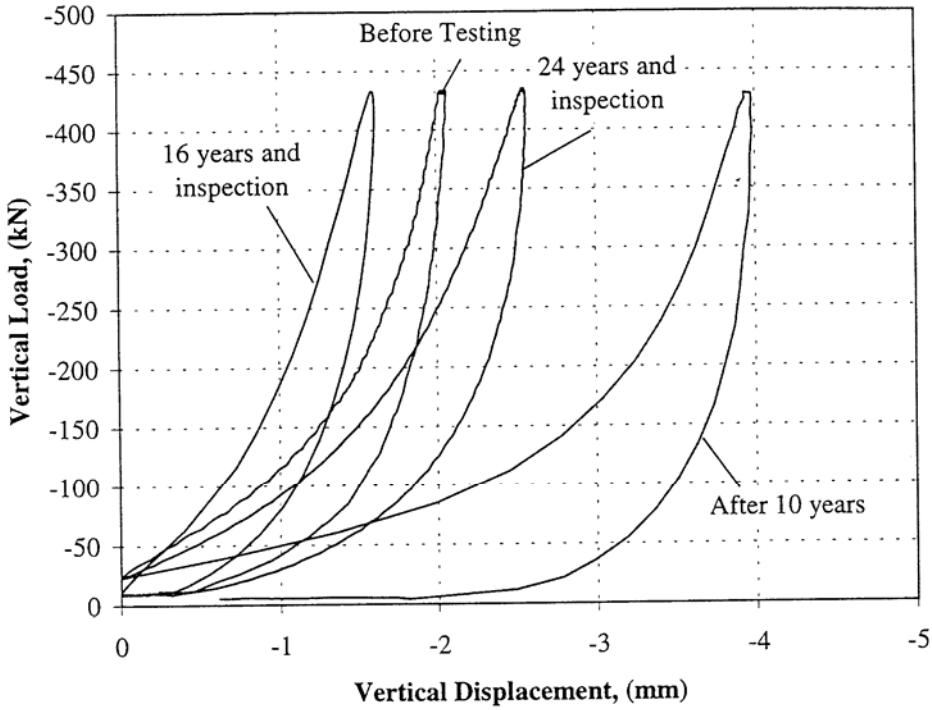


Figure 6-20. Quasi-static testing of second Embedded Block system

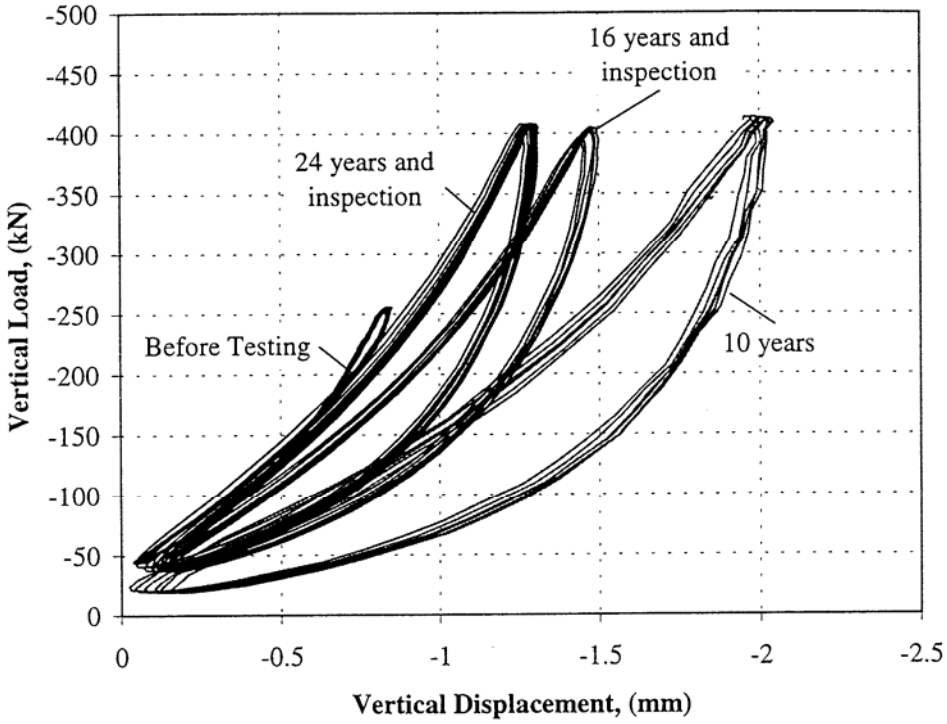


Figure 6-21. Dynamic testing of the second Embedded Block system

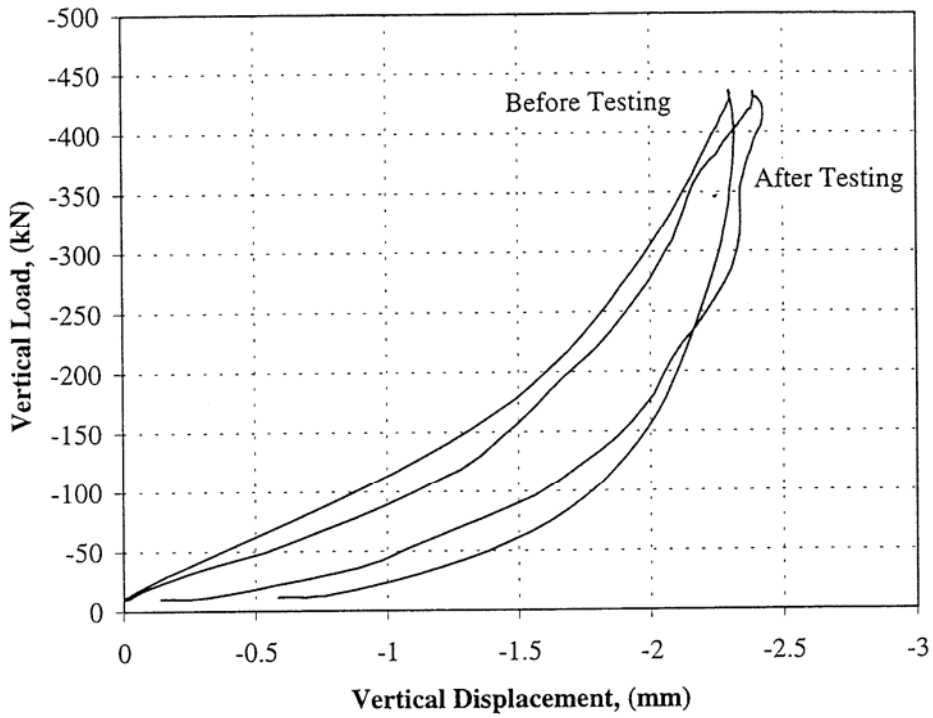


Figure 6-22. Quasi-static testing of the third Embedded Block system

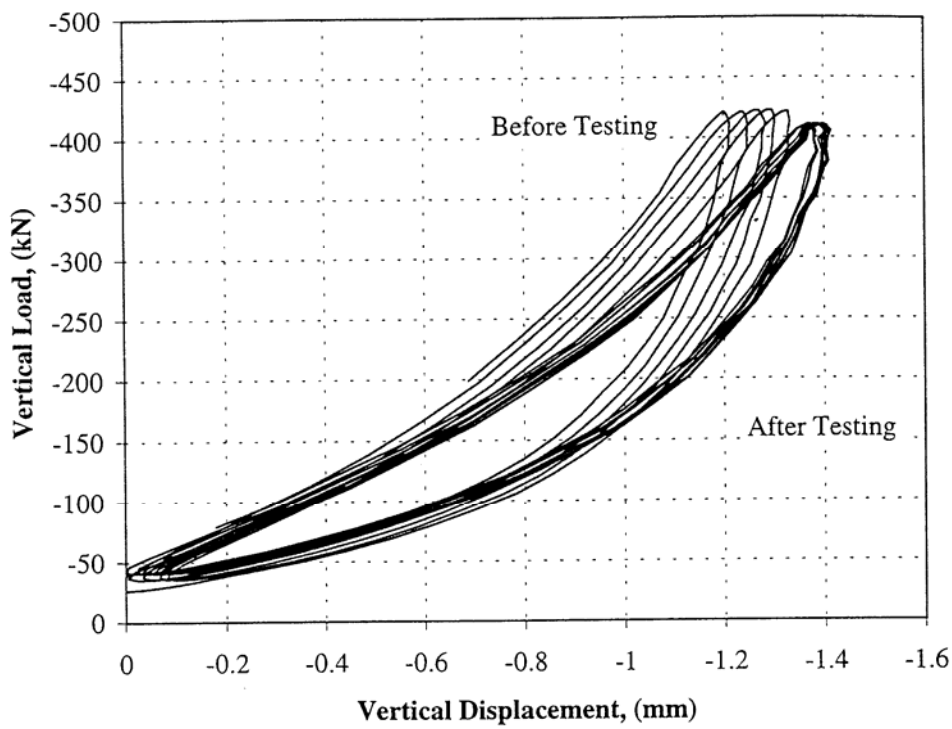


Figure 6-23. Dynamic testing of the third Embedded Block system

Table 6-10. Static stiffness at varied lives for the third Embedded Block system

Vertical Load kN (kips)	Quasi-Static Stiffness, kN/mm (kip/in)	
	Baseline	10 Years
12.5 (3)	53 (303)	42 (241)
25 (6)	49 (279)	35 (201)
37.5 (8)	49 (283)	43 (247)
50 (11)	52 (297)	52 (297)
75 (17)	62 (354)	91 (518)
100 (22)	85 (483)	108 (616)
125 (28)	122 (696)	126 (722)
150 (34)	156 (890)	170 (970)
175 (39)	189 (1082)	246 (1405)
200 (45)	219 (1249)	146 (835)

Table 6-11. Dynamic stiffness at varied lives for the third Embedded Block system

Vertical Load kN (kips)	Dynamic Stiffness, kN/mm (kip/in)	
	Baseline	10 Years
12.5 (3)		
25 (6)	113 (645)	126 (720)
37.5 (8)	98 (561)	87 (496)
50 (11)	101 (579)	86 (492)
75 (17)	113 (647)	97 (556)
100 (22)	128 (732)	112 (637)
125 (28)	155 (885)	130 (743)
150 (34)	199 (1135)	166 (949)
175 (39)	237 (1353)	206 (1178)
200 (45)	245 (1401)	219 (1253)

Table 6-12. Dynamic/static stiffness ratios at varied lives for the third Embedded Block system

Vertical Load KN (kips)	Dynamic/static Stiffness Ratio	
	Baseline	10 Years
12.5 (3)		
25 (6)	2.31	3.58
37.5 (8)	1.98	2.01
50 (11)	1.95	1.65
75 (17)	1.83	1.07
100 (22)	1.52	1.04
125 (28)	1.27	1.03
150 (34)	1.28	0.98
175 (39)	1.25	0.84
200 (45)	1.12	1.50

After 10 years of testing, the fasteners were also removed from the concrete base for inspection. The condition of the fasteners after completion of the repeated load test was excellent. Visual scraping of the concrete base was seen, as shown in Figure 6-24.

The specimens were replaced into the two-fastener system and testing continued until 23.25 years. At that time, the base plates of both fasteners failed due to fatigue. Cracking had occurred on both sides of the base plate. Figure 6-25 shows the failure of one side of the base plate. Failure of the fasteners occurred within hours of each other. This was somewhat expected given the load scenario.

Figures 6-26 and 6-27 show the static and dynamic stiffness during the testing. Table 6-13 shows the static stiffness and Table 6-14 shows the dynamic stiffness of the frame fastener 1 system. Table 6-15 shows the dynamic/static stiffness ratio for the testing.

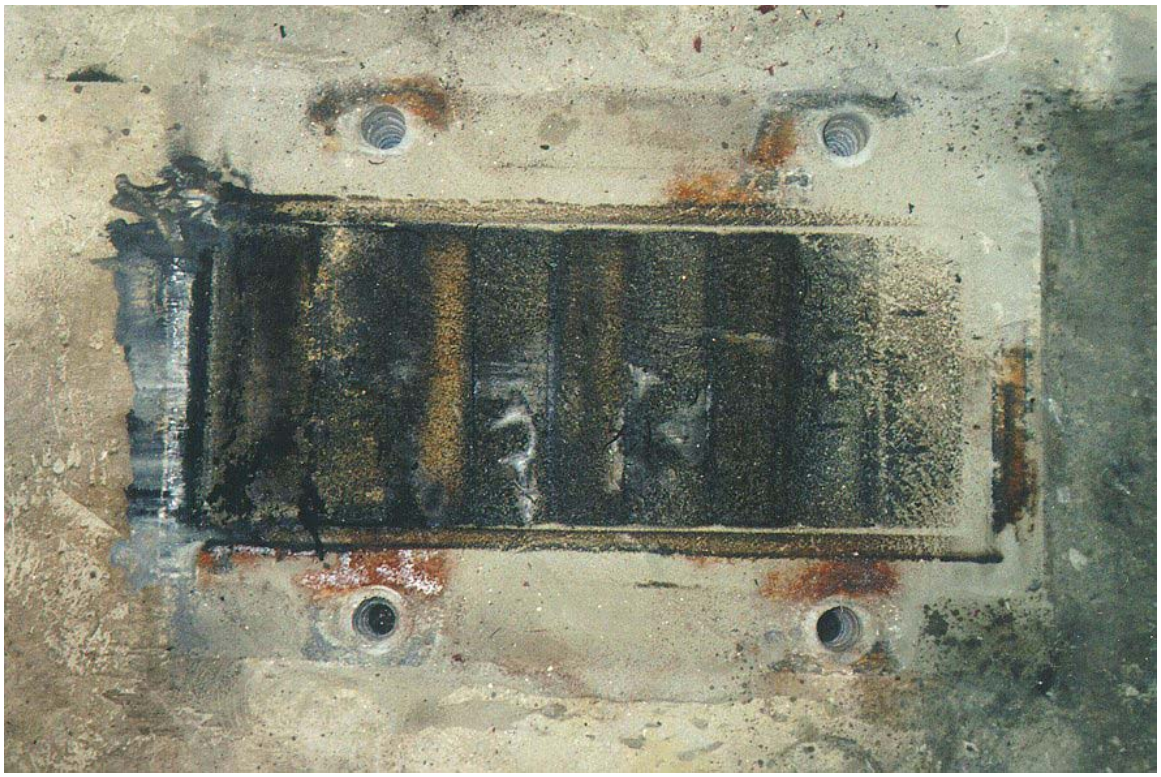


Figure 6-24. Scraping from the Frame fastener 1 after the equivalent of 10 years of testing

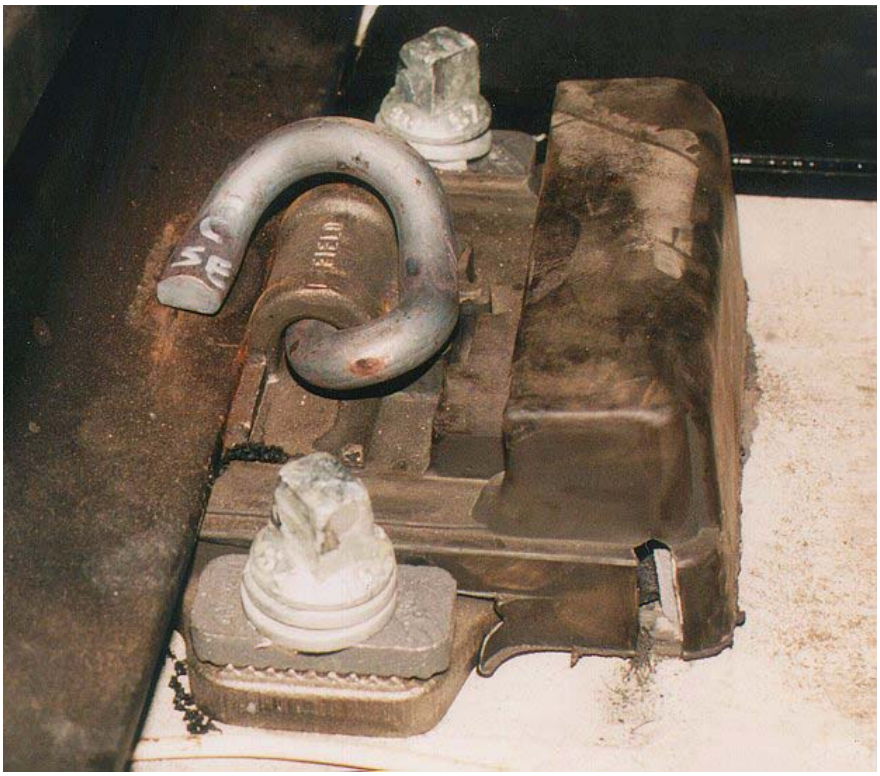


Figure 6-25. Fatigure failure of the base plate from the frame fastener 1 after the equivalent of 23.25 years of testing

For the second Frame fastener 1 two-fastener assembly, the baseline testing was completed and the vertical and lateral life tested was begun. After 141,314 cycles or approximately 1.75 years with an L/V ratio of 0.6, the base plates of both fasteners failed due to fatigue. Cracking had occurred on both sides of the base plate. Testing continued until 274,784 cycles or 3.25 years. The dynamic and static vertical stiffness and static lateral stiffness with constant vertical loads were completed after the life test.

Figures 6-25 and 6-26 show the static and dynamic stiffness during the testing. Table 6-16 shows the static stiffness and Table 6-17 shows the dynamic stiffness of the second frame fastener 1 system. Table 6-18 shows the dynamic/static stiffness ratio for the testing.

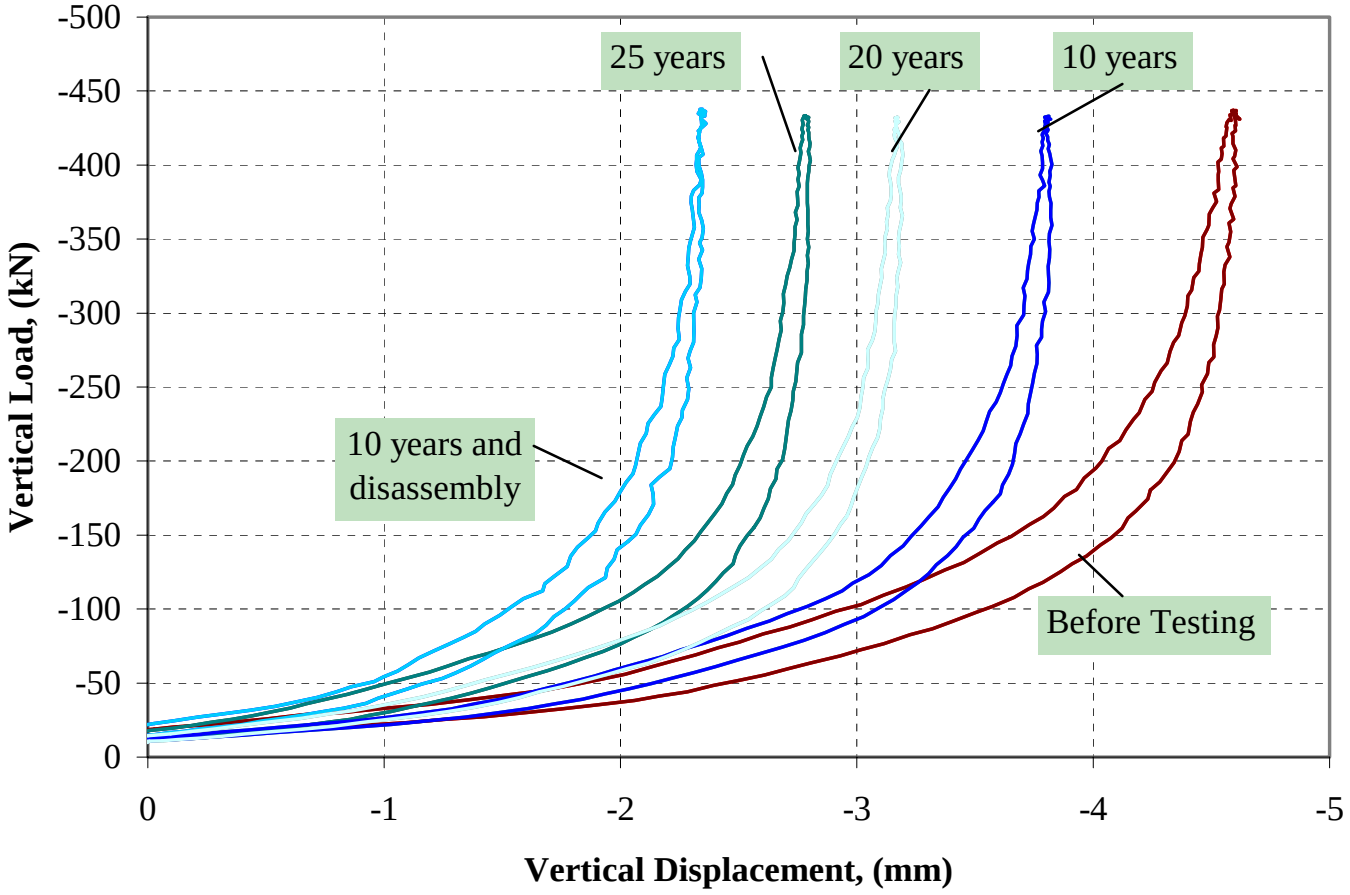


Figure 6-26. Quasi-static testing of the first fastener 1 system

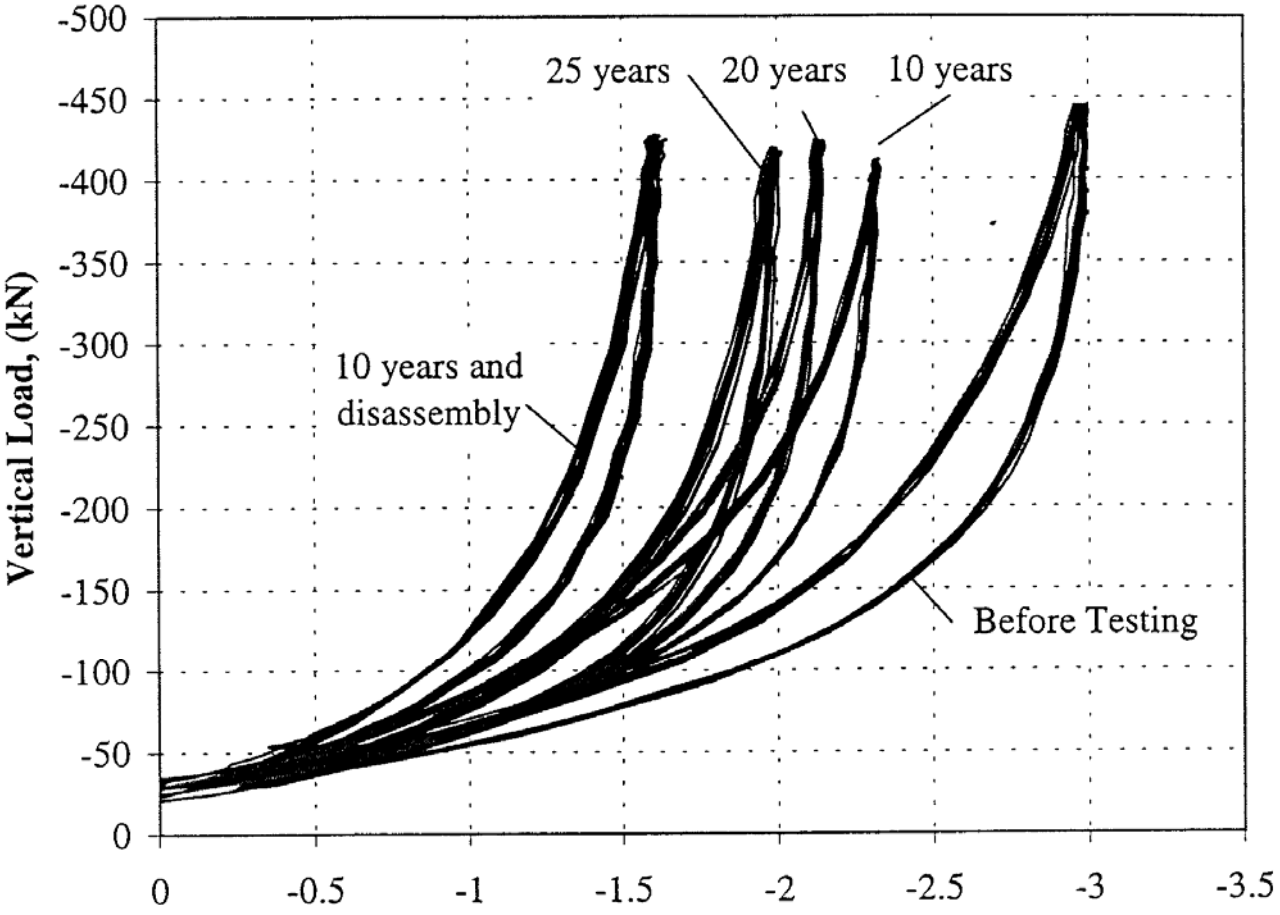


Figure 6-27. Dynamic testing of the first frame fastener 1 system

Table 6-13. Static stiffness at varied lives for the first frame fastener 1 system

Vertical Load kN (kips)	Quasi-Static Stiffness, kN/mm (kip/in)				
	Baseline	10 Years	10 Years	20 Years	23.25 Years
12.5 (3)	8 (43)	8 (46)	12 (69)	9 (52)	12 (69)
25 (6)	16 (90)	20 (116)	22 (124)	22 (127)	22 (124)
37.5 (8)	23 (134)	26 (146)	37 (212)	26 (149)	24 (138)
50 (11)	25 (141)	31 (175)	52 (295)	40 (227)	37 (214)
75 (17)	45 (259)	79 (450)	80 (456)	95 (540)	92 (526)
100 (22)	95 (545)	133 (758)	155 (886)	190 (1,083)	185 (1,056)
125 (28)	138 (787)	166 (947)	169 (966)	292 (1,669)	245 (1,397)
150 (34)	247 (1,408)	332 (1,895)	461 (2,635)	369 (2,104)	540 (3,081)
175 (39)	341 (1,944)	480 (2,738)	493 (2,813)	669 (3,818)	545 (3,111)
200 (45)	400 (2,287)			312 (1,779)	622 (3,549)

Table 6-14. Dynamic stiffness at varied lives for the first frame fastener 1 system

Vertical Load KN (kips)	Dynamic Stiffness, kN/mm (kip/in)				
	Baseline	10 Years	10 Years	20 years	23.25 Years
12.5 (3)	10 (58)	15 (85)	0 (0)	15 (87)	26 (148)
25 (6)	19 (109)	29 (166)	40 (230)	28 (161)	31 (178)
37.5 (8)	27 (152)	35 (197)	53 (304)	36 (206)	39 (224)
50 (11)	32 (182)	43 (248)	67 (382)	45 (257)	53 (304)
75 (17)	51 (291)	60 (344)	100 (569)	65 (371)	79 (451)
100 (22)	63 (358)	70 (401)	117 (666)	80 (459)	97 (556)
125 (28)	87 (498)	104 (597)	156 (893)	121 (692)	156 (890)
150 (34)	130 (742)	163 (933)	258 (1,475)	185 (1,055)	243 (1,390)
175 (39)	178 (1,015)	290 (1,658)	368 (2,103)	334 (1,907)	396 (2,263)
200 (45)	238 (1,360)	479 (2,738)	511 (2,916)	606 (3,459)	600 (3,426)

Table 6-15. Dynamic/static stiffness ratios at varied lives for the first frame fastener 1 system

Vertical Load KN (kips)	Dynamic/Static Stiffness Ratio				
	Baseline	10 Years	10 Years	20 Years	23.25 Years
12.5 (3)	1.34	1.88		1.66	2.16
25 (6)	1.21	1.43	1.86	1.26	1.44
37.5 (8)	1.13	1.35	1.43	1.39	1.62
50 (11)	1.30	1.42	1.30	1.13	1.42
75 (17)	1.12	0.76	1.25	0.69	0.86
100 (22)	0.66	0.53	0.75	0.42	0.53
125 (28)	0.63	0.63	0.93	0.41	0.64
150 (34)	0.53	0.49	0.56	0.50	0.45
175 (39)	0.52	0.61	0.75	0.50	0.73
200 (45)	0.59			1.94	0.97

7. Discussion of Fastener Stiffness

A Direct Fixation fastener functions as a rail restraint device, as a mechanical filter for impacts and vibrations, and as an insulator. The ability of the fastener to provide restraint and to provide impact and vibration attenuation is governed by the stiffness of the fastener. The restraint properties are defined by the static stiffness and the vibration and impact attenuation properties are governed by the dynamic stiffness. These two properties are addressed via different methods and they will be discussed separately. Railroads are a continual mix of static and dynamic loading events. The majority of static events are due to alignment or due to thermally induced loads. Dynamic loading events are typically due to wheel passage events. Both the static and dynamic properties are equally important, although they are important to different interests. The only separation between the civil (primarily static) and mechanical (primarily mechanical) loadings are the frequency of interest.

7.1 Static Stiffness

The key fastener properties for mechanical performance are vertical and lateral stiffness. The two stiffnesses are interrelated because of the complex interaction between a wheel, rail, and the rail support, which in this discussion, is a Direct Fixation Fastener. As a result of rubber nonlinearity, Direct Fixation fasteners have inherently non-linear load-deflection curves, which result in a static stiffness value that is load dependent. That is, the static stiffness varies with applied load. Different designs have different characteristics. An example of a vertical deflection curve for a representative fastener during loading and unloading is shown in Figure 7-1. This fastener is designed to be linear and does so up to a load of approximately 100 kN. In contrast the fastener in Figure 7-2 is designed to have a “stiffening” characteristic. The greater the load, the “stiffer” the fastener, or the lower the deflection per unit load. In this case a 50 kN load results in a 3.5 mm deflection, while a 100 kN load results in only a 4.6 mm deflection. Twice the load produces only 30% additional deflection. Because of the non-linearity the preferred definition of fastener stiffness is the “tangential stiffness” at a stated load. Figure 7-3 illustrates the definition. This definition is especially important when considering any dynamic properties.

Care must be exercised when using the tangential stiffness if the desired calculation is being used to determine overall rail deflections. Fastener non-linearity’s and any “looseness” or play in the fastener system will introduce errors in the calculated versus actual displacements.

Typical lateral loads for a given deflection with a standard representative fastener are shown in Figure 7-4. This fastener is the same one for which the vertical load/deflection characteristics are presented in Figure 7-1. Similarly the lateral load/deflection characteristics for the non-linear fastener represented by Figure 7-2 are presented in Figure 7-5. While the characteristics are similar in both cases, the vertical load distinctly influences the lateral deflection, and the actual values and characteristics are very different. The useful specification of the lateral stiffness for a fastener is very difficult because an exact manner of both vertical and lateral loading must be carefully specified. The interactions of the loads, the rail and wheel profiles, and the fastener system are complex and defy simple specification. The more pragmatic approach is to assure that the fastener system will fall into a broad range of allowed performance that is representative of in-service loads.

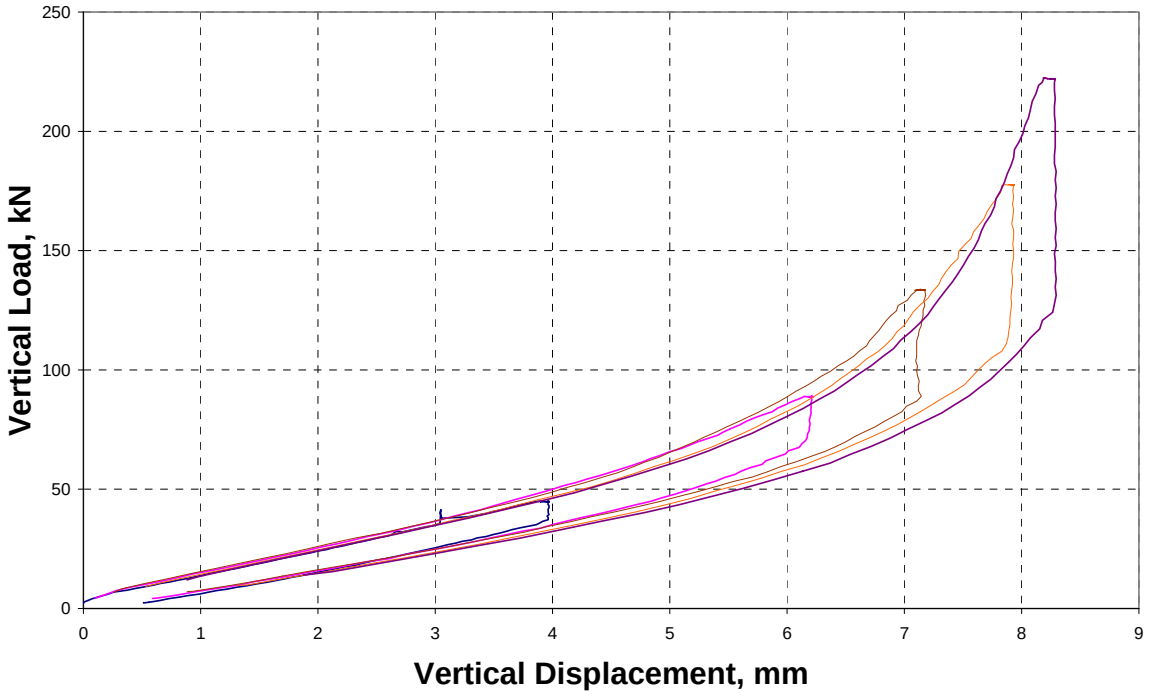


Figure 7-1 Quasi-Static Vertical Load and Displacement

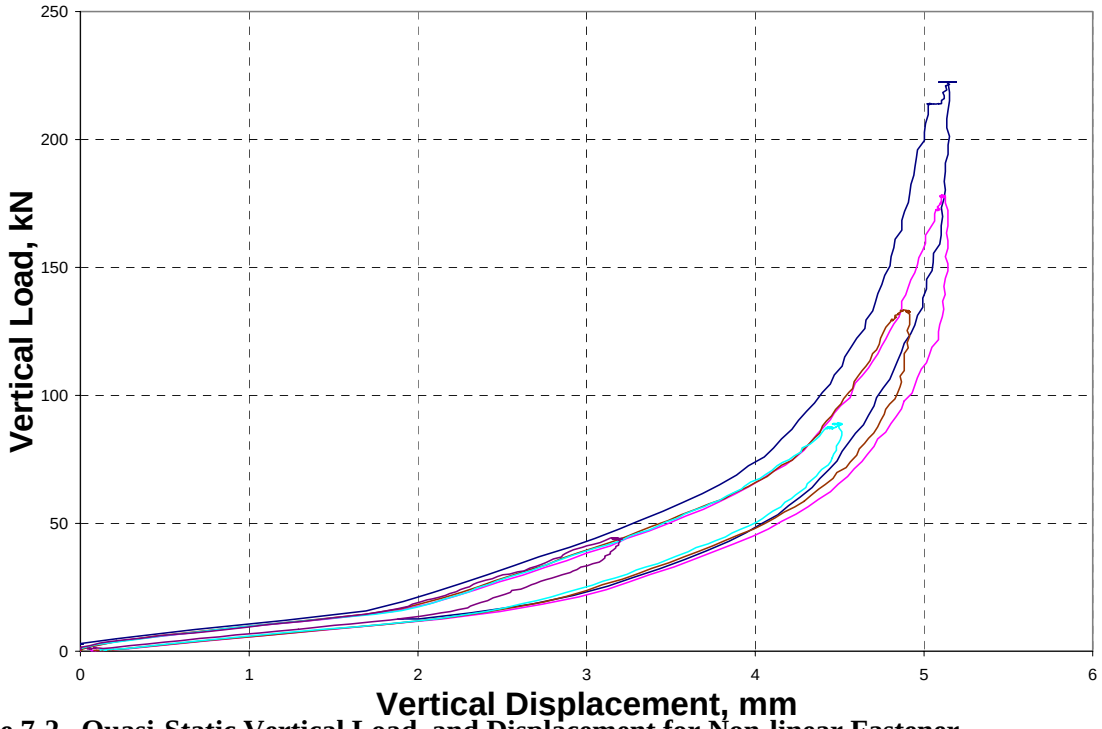


Figure 7-2 Quasi-Static Vertical Load and Displacement for Non-linear Fastener

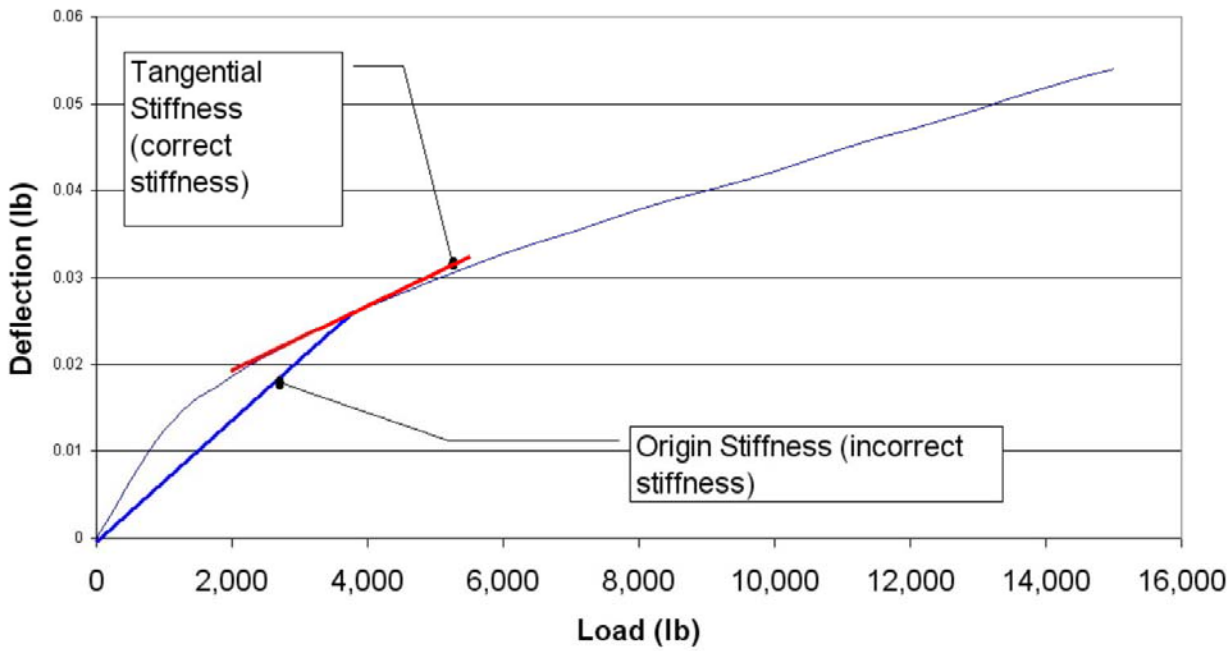


Figure 7-3 Methods for Calculation of Fastener Stiffness

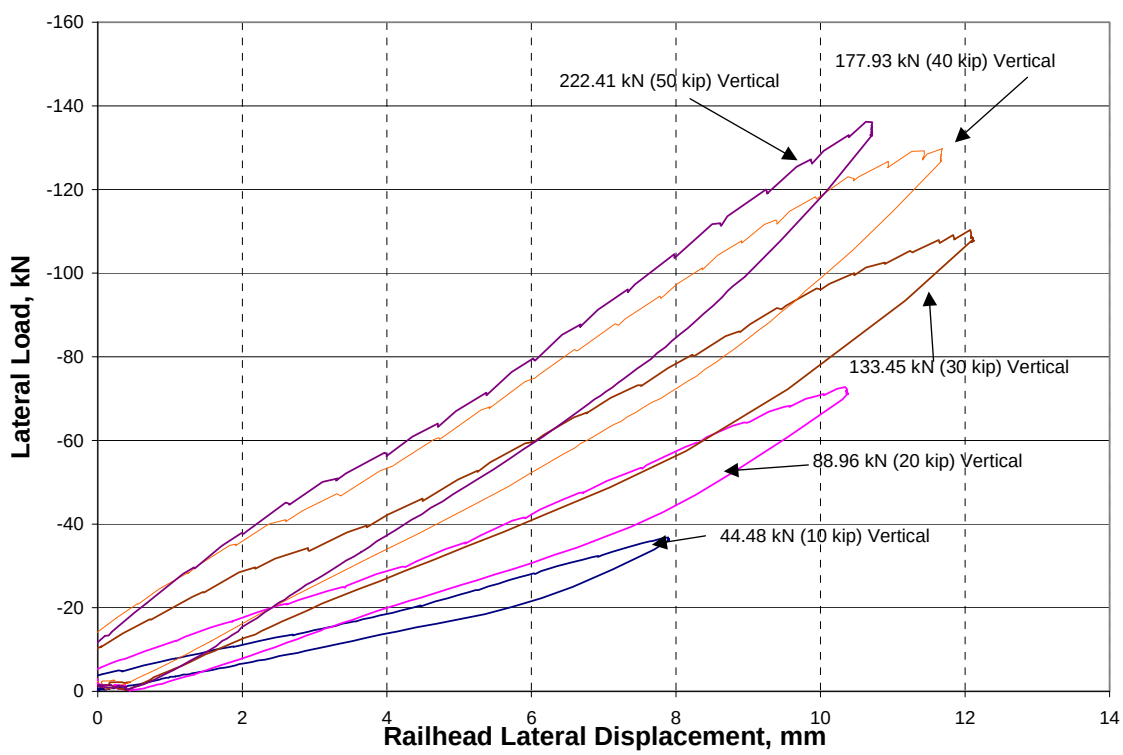


Figure 7-4. Quasi-static Lateral Railhead Load Deflection Characteristics with Different Vertical Loads for a Very Linear Fastener

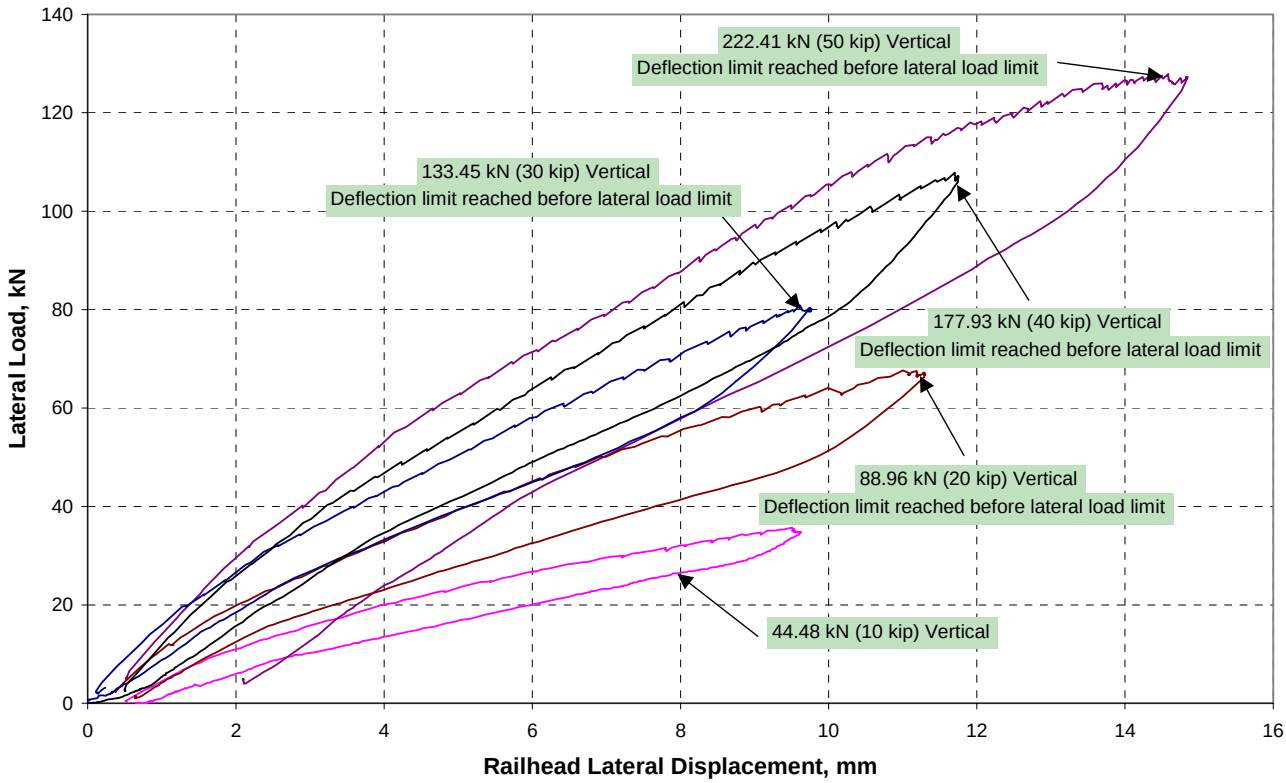


Figure 7-5. Quasi-static Lateral Railhead Load Deflection Characteristics with Different Vertical Loads for a Non-Linear Fastener

7.2 Fastener Stiffness Variability

There is a significant difference between measured load-deflection characteristics of similar fasteners. Using the test setups ands procedures presented in Section 3, a number of different fasteners of the same type were tested in order to characterize their performance. Figure 7-6 is the load-deflection curves of 17 fasteners of the identical design. In this figure it is clear that this fastener has a non-linear characteristic that is very different at transit loading levels, producing a wide range of tangential stiffness values shown in Figure 7-7. The range of available fastener stiffnesses for the products tested is shown in Figure 7-8, excluding the fastener model in Figures 7-6 and 7-7.

The result is the natural frequency (the vibration filtering frequency) variation between fastener models may be as large as the natural frequency variation between fasteners of the same model, shown in Figure 7-9, which includes all manufactures and models tested.

For loads important to transit, the vibration attenuation of all fasteners should be considered to be in the same range, with variations expected in the range between fasteners of the same make and model.

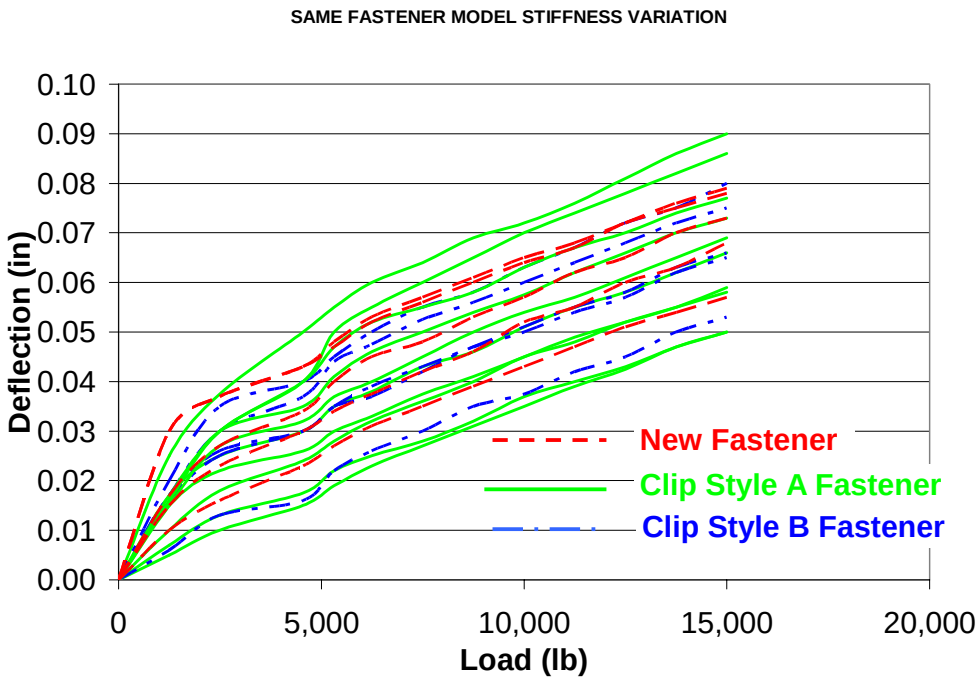


Figure 7-6. Quasi-static Vertical Load Deflection Variation with Different Fasteners of the Same Model

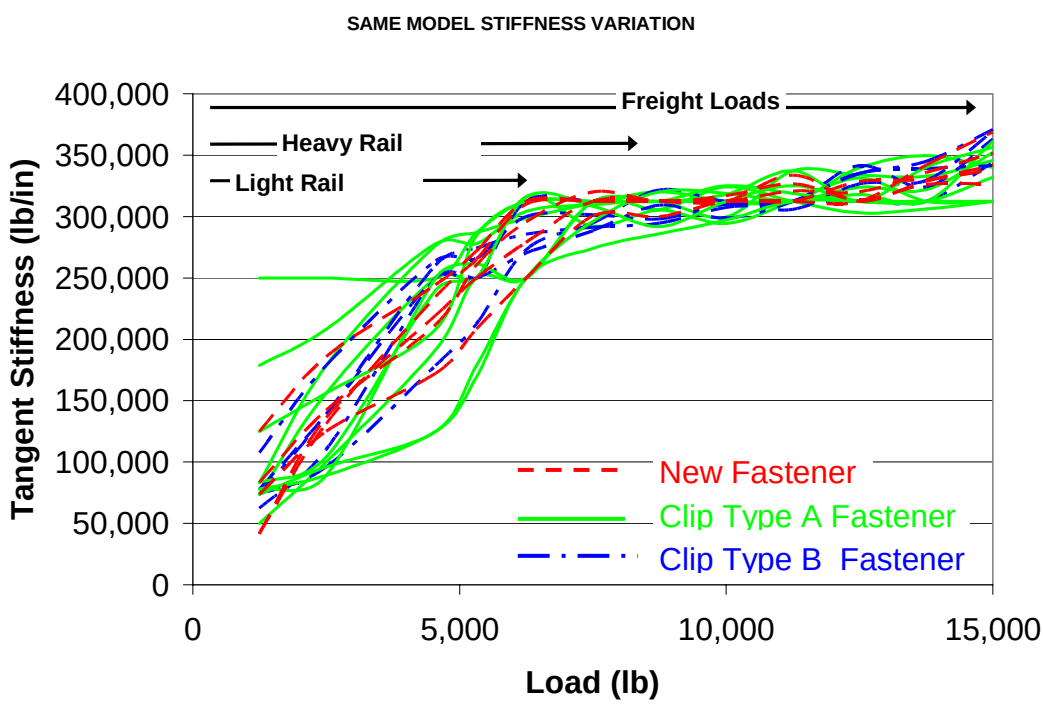


Figure 7-7. Tangential Stiffness for Different Fasteners of the Same Type

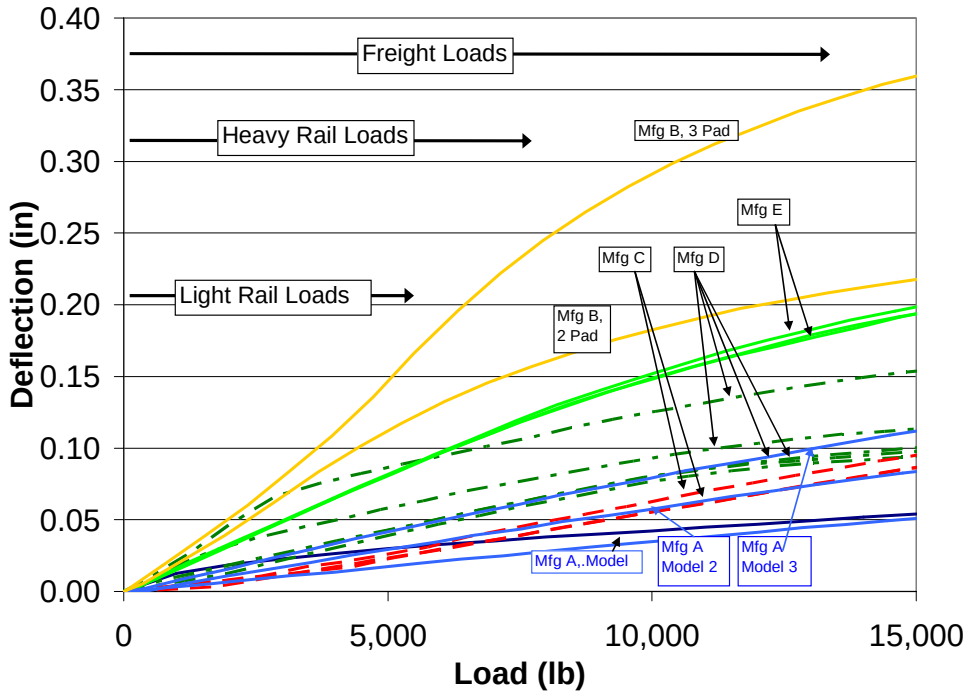


Figure 7-8. Load-Deflection Characteristics of All Fasteners (not including the fastener in Figures 7-6 and 7-7)

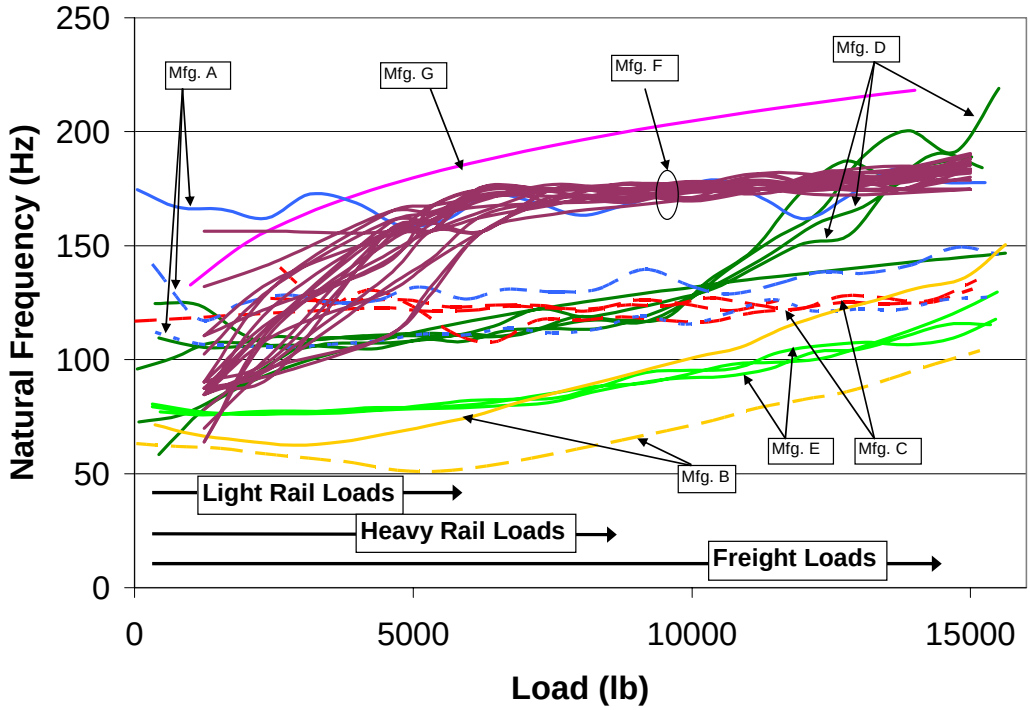


Figure 7-9. Natural Frequency of All Fasteners Versus Load for All Fasteners

8. Guidelines for the Application of Dynamic Modeling and Simulation Tools to Support Direct Fixation (DF) Track Design

8.1 Objective

The objective of this activity was to develop computer analysis procedures that will allow a practitioner to determine track and vehicle stiffness properties that collectively achieve the lowest wheel/rail L/V ratios.

8.2 Expected Results

The result of this activity is a guideline on the procedures needed to analyze ranges of fastener and vehicle stiffness and damping values to determine fastener properties that are compatible with the vehicle (i.e., produce the least L/V forces for the vehicle/track system).

8.3 Approach

The approach to this activity was to catalog and define procedures that use existing computer models to analyze wheel/rail loads as a function of track and vehicle stiffness properties. No specific model was chosen, rather a discussion on the appropriate model to use for various analyses was developed.

8.4 Introduction to Modeling

The practicality of using computer simulation codes to predict the dynamic performance of rail vehicle/track systems has increased dramatically in recent years. This can be attributed to several factors, including:

- Sophisticated computer codes that in the past required large mainframe computers and workstations for implementation, now can be run quickly and economically on desktop computers.

- Extensive international research and development into rail vehicle/track mechanics since the 1960s has resulted in a set of validated analytical models based on proven theories. Computer simulation codes based on these models can be used with good confidence.

- Computer simulation codes provide the opportunity to quickly and economically evaluate variations in track component designs for a wide range of operating conditions involving different vehicle types. The cost to perform tests covering these conditions (if indeed all of the conditions of interest could be established) could be prohibitively large.

In this document, we describe the types of available analytical tools and computer simulation codes for evaluating the dynamic performance of direct fixation track components, as well as methodologies for implementing these as part of component and track system design processes.

8.5 Motivation for Using Dynamic Models for DF Track Evaluation

The primary value of dynamic models in the development of DF track structures lies in the ability to predict wheel/rail dynamic interaction. With this ability, dynamic models can be used to address the following key issues:

1) The safety-related dynamic performance of the vehicle/track system for different DF fastener characteristics,

2) The dynamic forces and moments in the DF fasteners, the other track components and the vehicles operating on the track,

3) Track degradation mechanisms such as rail wear and corrugation formation, and

4) "Optimal" DF track characteristics for maximizing safety-related dynamic performance, minimizing component forces (and thus maximizing component life), and mitigating track degradation due dynamic processes such as wear and corrugation formation.

A significant benefit of using dynamic models is that a wide range of DF fastener designs under traffic from a wide range of vehicles, operating and environmental conditions can be examined with dynamic models much more quickly and economically than with an experimental "build and test" approach.

A wide variety of analytical models, computer simulation programs, and solution techniques are available for evaluating vehicle/track systems. These provide a powerful arsenal for performing dynamic evaluations. However, they also provide the opportunity for misuse, which can lead to erroneous results. To mitigate this, it is important to understand the factors associated with selecting an appropriate model for DF fastener evaluation. Issues such as the modeling assumptions used, how the model was validated and the model's range of usefulness must be considered. Some selection guidelines are provided in the following sections.

8.6 Model Selection Criteria

8.6.1 General Considerations

It is generally desirable to use the simplest, credible model that will provide the required information. The following aspects of a model must be considered in order to achieve this objective:

- Degrees-of-freedom and bandwidth
- Linearity
- Validation
- Solution Technique

Each of these is discussed below in detail.

8.6.1.1 Degrees-of-Freedom and Bandwidth

For dynamic modeling, simplicity can be interpreted in at least two ways: 1) minimum degrees of freedom or 2) minimum bandwidth, with the proviso that the essential dynamic behavior of the vehicle/track system is preserved. As the number of degrees of freedom or bandwidth increases, the number of components, connections, and parameters needed to describe the model increases. However, this added detail does not necessarily mean added accuracy, because information from which parameter values can be assigned often is unavailable or inaccurate.

The model's bandwidth essentially is dictated by the range of natural frequencies associated with the vehicle/track system model. For models where the static response is calculated, the minimum frequency is zero. The maximum frequency generally is larger if more components are used to describe a given

component (e.g., a wheelset model with torsional and bending flexural degrees-of-freedom has a much higher bandwidth than a rigid wheelset model). The choice of bandwidth and degrees-of-freedom is based on the model objectives. For example, a relatively low-bandwidth model with few degrees-of-freedom describing the complete vehicle may be adequate to evaluate steady-state curving behavior and lateral stability. In contrast, a relatively high-bandwidth model with a high number of degrees-of-freedom describing the wheelsets, and no degrees-of-freedom describing the car body, may be adequate for evaluating wheel/rail impacts and corrugation formation. Steel wheel/ steel rail systems tend to have a wide bandwidth due to the stiffness of the wheel/rail interface and the large masses of the components. Ride quality studies that involve the secondary suspension are rich in low natural frequencies due to the soft secondary suspension and large mass of the car body. Wheel/rail force, curving, and corrugation studies have very high frequencies due to the low rail mass relative to the stiffness of the wheel/rail contact stiffness.

8.6.1.2 Linearity

One of the most common assumptions used in vehicle/track models is linear behavior of the components. This type of assumption may be made for computational efficiency, for simplicity, or for lack of more accurate information on the component characteristics. For DF fasteners, linearity assumptions may be made for the force versus deflection (stiffness) and force versus velocity (damping) characteristics. Although the general dynamic behavior of the vehicle/track system may be predicted reasonably well using these assumptions, significant errors in the predicted fastener deflections and forces may occur if the stiffness and damping characteristics are nonlinear. A rather obvious example is if one ignores the fastener's deflection limits or "stops," then under some conditions the predicted forces will be underestimated and deflections overestimated. The model's range of validity is determined largely by these assumptions of linearity. In general, it is desirable to include the nonlinear characteristics of the fastener in a vehicle/track model because the predictions will be more accurate.

8.6.1.3 Validation

Validation is the primary means for establishing a model's credibility. Credibility implies that the model's predictions are similar to the actual observed behavior of the physical system that it is representing. There are several ways in which a model may be validated. Three levels of validation may be considered. These are:

1. Qualitative Validation: The most basic level of validation is that the vehicle/track model has qualitatively similar behavior as that for the physical system. The usefulness of a model validated only at this level is to predict general trends in behavior over a range of conditions

2. Quantitative Validation of Dynamic Behavior: An intermediate level of validation would be demonstrating that the model accurately predicts the overall dynamic performance of the physical system (e.g., hunting speeds, speed limits on curves based on derailment criteria, natural frequencies of vehicle/track components). Models validated at this level may be useful for predicting the influence of salient component design characteristics on dynamic performance related to safety and comfort.

3. Quantitative Validation of Components Forces and Motions: The highest level of validation demonstrates that the model accurately predicts the time-varying motions and forces between components of the vehicle/track system. If validated at this level, a model may be used with confidence to provide detailed information on the component loading environment, from which estimates of component life may be made.

8.6.1.4 Solution Technique

There are three basic types of solution techniques for analytical models of vehicle/track dynamic interaction. These are

1) frequency-domain solutions for predicting stability, modal response and forced response to random and periodic excitation,

2) time-domain solutions for predicting time-varying forces and motions, and

3) steady-state solutions for predicting behavior in curves.

Frequency-domain models are computationally fast and very useful for ride quality and fatigue-related load evaluations. The weakness in this technique is the need for linearization, where system non-linearities must be handled by approximations, such as by describing functions. An implicit assumption is that dynamic motions are small (i.e., second- and higher-order motions may be neglected).

Frequency domain models are of necessity linear or "quasilinear" in structure. The equations of motion are set up in a matrix format, and solved using a Laplace transform method. The equations of motion may be developed using Lagrangian or Newtonian mechanics, and the complex variable elements are separated into the real and imaginary parts of the matrices. The complex matrix then is inverted using standard matrix inversion subroutines (a Gaussian substitution technique, for example), multiplying the result by the input column matrix. Track geometry inputs matrixes are handled at trailing axles by phase-shifting the input at the leading axle. Using these techniques, the natural frequencies, modal damping and mode shapes of the vehicle/track system can be predicted and linear critical (hunting) speed and limit cycle (hunting) conditions determined.

For a frequency domain model to provide useful results, realistic inputs must be used. Track geometry irregularities tend to exhibit a random variation in amplitude and wavelength. In addition to random geometry errors, track will display particular spectral peaks related to spatially repetitive events such as rail joints or welds. These may be added to the random geometry power spectrum through separate closed-form functions.

By assuming the track geometry to be a stationary random function over a broad frequency range with a Gaussian amplitude distribution, the response spectrum for each output variable may be calculated from the linear model. Solutions are obtained for the individual random geometries (surface, crosslevel, etc.) and an overall root-mean-square (rms) response calculated. These rms responses can represent vehicle body accelerations and forces, and can be used to estimate various ride quality indices such as the NASA, Wz, Peplar, and ISO criteria.

As stated previously, the weakness of the frequency domain approach is the need to linearize all elements in the simulation, including the fundamentally nonlinear wheel-rail contact elements. Describing function methods are commonly used to approximate nonlinearities such as hardening springs and Coulomb friction. Typically, the first term of an infinite series representation of the nonlinear function is used.

Time-domain solutions are perhaps the most commonly used for vehicle/track system modeling. Using numerical integration schemes, response time-histories of forces and motions can be determined directly for even highly nonlinear vehicle/track models. Although time-domain solutions can be computationally more involved than the other solution techniques, they can be programmed and executed conveniently on desktop computers, and provide all of the information necessary to characterize the dynamic response of the vehicle/track system.

Time-domain models handle the nonlinearities in a straight-forward manner and can simulate limit cycles, even chaotic behavior. These models can provide peak loads and accelerations on vehicle and guideway components, and can be configured to predict wheel climb and other safety-related limiting events.

Time domain solutions, while computationally less efficient than frequency domain solutions, have the advantage of representing nonlinearities explicitly.

The time domain simulation model takes a more direct approach to the solution of a set of nonlinear differential equations representing the vehicle and guideway. Again, these equations may be developed using Lagrangian or Newtonian mechanics. The vehicle and guideway may include rigid-body (lumped-parameter) representations, or flexible-body (distributed-parameter) modes. Body degrees of freedom may be set up as first-order state variables or as second-order equations. In either form, a time integration routine is used to predict body accelerations and motions based on inter-body forces and torques. These may range from the simple Euler approximation to more mathematically complex routines. The most commonly used method is the 4th-order Runge-Kutta algorithm. The use of an appropriate time step is a critical compromise between computational accuracy and solution time and cost. Some time domain programs include a variable time step feature to improve solution efficiency.

Inputs to a time domain model may include track geometry variations (rail surface, alignment, gauge, and crosslevel; track curvature and superelevation; and wheel-rail contact parameters), track modulus or guideway beam support stiffness variations, wheel tread geometry variations (wheel flats or runout), inter-car forces (buff and draft loads due to train action), traction or braking torques, or externally applied forces such as wind gust loads. These inputs may be transient, repetitive, or steady state.

Geometry variations represent rail position and rate-of-change of position (velocity) as a function of time (distance/velocity along the track). In the vertical direction, the surface geometry errors are “pulled through” the nonlinear Hertzian wheel-rail contact stiffness to generate time-variable vertical dynamic forces. Changes in relative wheel-rail lateral position and velocity due to line and gauge errors cause variations in creep forces. These are weakly coupled to the wheelset up to the point of flange contact, at which point the wheel and rail are strongly coupled dynamically.

Outputs from a time domain model can include time histories of body accelerations, absolute and relative velocities and displacements, forces (for example, at suspension elements and at the wheel-rail interface), wheel-rail lateral-to-vertical force (L/V) ratios, fastener forces and guideway bending moments. Maximum/minimum peak values, total energy dissipation, and wheel-rail wear indices may also be computed as part of the solution. Time history outputs may be post-processed by Fast Fourier Transform (FFT) algorithms to provide estimates of their frequency response. High-speed stability (hunting) can be investigated by inducing small perturbation inputs as train speed is incrementally increased and checking for divergent response.

Steady-state solutions represent limiting cases of frequency or time domain solutions where system inputs are uniform or unchanging. The primary modeling assumptions required to implement these solutions are that the vehicle is travelling at constant speed and that perturbations about the mean path of the vehicle in the curve may be neglected as small. Steady-state solutions are used commonly to predict the curving behavior of the vehicle/track system, particularly where the specific interest is car body accelerations and deflections in the context of ride quality and overturning safety, or average fastener and wheel-rail forces in the context of wheel and rail wear.

The linear curving model involves the steady-state solution of a set of algebraic equations. However, to handle the important non-linearities such as fastener nonlinear stiffness, wheel-rail flange contact, creep saturation, and suspension stops, an iterative solution of the set of equations is necessary. This involves assuming a wheel flanging condition, and iterating until l force and torque equilibrium is achieved. The process is repeated for all possible flanging conditions. Program outputs included individual wheel creep

and flanging forces, wheelset, truck frame, and car body displacements, and estimates of wheel-rail flange wear. Whereas the linear model is computationally fast, the nonlinear models (e.g., those that include saturation of wheel/rail tangential forces) are not, generally requiring a large number of iterations to obtain a valid solution.

Steady-state solutions are valuable for exploring the effects of DF fastener stiffness and spacing and vehicle characteristics on the mean response during curve negotiation. However, they are not suitable for evaluating behavior during curve entry and exit.

8.6.2 Modeling Requirements for DF Fastener Dynamic Performance Evaluation

Generally, one may consider four categories of DF fastener dynamic performance evaluation. These are:

- Safety-Related Dynamic Behavior
- DF Fastener Loads
- Wheel/Rail Impacts
- Vibration and Noise Transmission

These are discussed below in some detail.

8.6.2.1 Safety-Related Dynamic Behavior

The dynamic behavior of the vehicles and track may be strongly influenced by the inertial, energy storage (stiffness) and energy dissipation (damping, friction, etc.) properties of the vehicle and track components. Depending on these properties, significant dynamic interaction may occur that could result in unsafe behavior. A classic example is freight car "rock and roll", in which the 39-ft wavelength of bolted joint rail has been observed to excite roll resonances in some cars over a rather narrow speed range (typically 18-22 mph). Analytical models that include representations of a complete vehicle and overall track compliance and geometry characteristics are effective for predicting the following aspects of safety-related dynamic performance:

- Lateral (hunting) instability—self-excited, coupled lateral/yaw oscillations of the bogies above a threshold "critical" speed.
- Wheel climb—on curved track, the combination of a sufficiently high single wheel L/V ratio, wheel/rail coefficient of friction and wheelset angle of attack may result in single point wheel/rail contact on the wheel flange that forces the wheelset up and over the rail, leading to derailment.
- Rail rollover—a sufficiently high L/V ratio between bogie and one rail may result in rotation of the rail about its base and derailment of the vehicle.
- Gage widening—sufficiently large outward lateral displacements of the rail heads will cause a wheelset to drop off the gage sides of the rails, resulting in a vehicle derailment
- Car overturning—excessive vertical unloading of one rail can result in vehicle overturning and derailment. This can occur in curves due to overspeed and on any track where excessive car body roll or bounce motions are excited by track geometry inputs.

In general, these aspects of safety-related dynamic performance may be influenced by DF fastener properties such as

- the overall stiffness and damping properties in the vertical, lateral and roll axes,
- fastener spacing, and
- fastener alignment characteristics (e.g., variations in vertical and lateral positions between adjacent fasteners).

Analytical models of a complete vehicle on compliant, irregular track can be used effectively to determine desirable DF fastener properties to ensure safe performance from the standpoint of avoiding instabilities and derailments induced by excessive wheel/rail forces.

8.6.2.2 DF Fastener Loads

While the analytical models described above can be used to predict safety-related dynamic performance and overall track forces and displacements, they do not calculate the forces, moments and displacements acting on the components of the individual fasteners. This information is essential for establishing fastener design loads and estimating fastener fatigue life, and generally requires more detailed modeling of the geometry and mechanical properties of the individual fastener. A typical iterative approach to obtaining this information is to a) calculate wheel/rail forces based on assumed rail/fastener properties, b) use beam-on-elastic foundation (BOEF) solutions to calculate fastener loads for these wheel/rail forces, c) back-calculate the rail/fastener properties required to achieve these fastener loads, and d) adjust the assumed rail/fastener properties and repeat these steps until a generally nonlinear set of fastener characteristics is derived that achieve acceptable wheel/rail forces. A more rigorous approach is to expand a complete vehicle/compliant track model to represent explicitly an array of DF fasteners under each rail. A simple form of this is a series of discrete lateral and vertical spring/damper combinations. In this manner, the analytical model would calculate the time-varying lateral and vertical fastener forces at each fastener location. These forces in turn could be used in detailed finite element models of the fasteners to predict deflections, strains, and stresses throughout the fastener.

8.6.2.3 Wheel/Rail Impacts

Wheel/rail impact dynamics—particularly the formation of rail corrugations—are associated with relatively high-frequency dynamic response of the vehicle/track system involving components in close proximity to the areas of wheel/rail contact. Analytical models for evaluating the initiation and development of corrugations generally include degrees-of-freedom that are ignored in complete vehicle/track system models. Recent corrugation research has indicated that significant influences include the bending and torsional compliance of the wheelset and rails, and fastener compliance and damping. Because of the difficulty in measuring wheel/rail interaction forces directly, these analytical models have become essential to estimating tendencies for the formation of corrugations based on fastener properties. Because of the high-frequency nature of vehicle/track dynamics related to corrugation formation, lower-frequency responses associated with car body and truck frame motions typically can be ignored. For evaluations of DF fasteners, an effective analytical model would include a single, flexible wheelset that is suspended below a primary suspension system and lays on a compliant track system that has masses, inertias, stiffnesses and damping coefficients associated with the rails, fasteners and supporting structure (crossties, ballast, concrete invert, bridge superstructure, etc.).

8.6.2.4 Vibration & Noise Transmission

Mitigation of transmitted noise and vibration through the track structure to nearby areas is a critical environmental concern for many railroad and rail transit applications. Dynamic models can be used to

evaluate how well DF track structures mitigate vibration and noise caused by vehicle/track interaction. The modeling requirements are somewhat similar to those for evaluating wheel/rail impacts. It is particularly important that the dynamic characteristics (e.g., transfer functions) of the fasteners and supporting structures over the frequency range associated with the vibration and noise sources (e.g., at frequencies up to several kilohertz) are represented accurately, and the generation of the excitation sources are modeled (e.g., vibratory modes of the rails, wheel rim and wheel flange, wheel/rail impacts). Laboratory experiments can be used effectively to provide the necessary parameters to use in such models.

8.6.2.5 Desirable Model Characteristics

A salient characteristic of railroad systems is that there exists dynamic interaction between the rail vehicles and the track structure. Thus, analytical models to predict dynamic performance must include those parts of the vehicle and the track that participate and interact in the scenarios under evaluation. Table 8-1 provides some guidelines for selecting the most appropriate forms of an analytical model for these three levels of DF fastener evaluation.

Table 8-1. Example dynamic model characteristics for evaluation of DF fasteners

Component of Vehicle Track Model		Modeling Objective		
		Safety-Related Dynamic Performance *(Stability, Curving Forces, Derailment Potential, etc.)*	**DF Fastener Loads** *(Influence of Fastener Stiffness, Spacing, etc.)*	**Wheel/Rail Impacts, Corrugation Formation & Vibration/Noise Transmission** *(High-Frequency, Short-Duration Load Events)*
Track Structure	**Foundation** (Ballast/Subgrade, Invert, Aerial Structure, etc.)	Neglect inertial properties of track Use overall track vertical and lateral stiffness (e.g., based on Beam-on-Elastic Foundation Theory) Include rail geometry irregularities	Include stiffness, damping properties and effective masses	
	Fastener-to-Foundation Interface (Crosstie, Two-block system, Anchor bolts, etc.)		Include tie, block masses and inertias, rail pad stiffness and damping	
	DF Fastener		Represent DF fasteners as an array of discrete stiffness and damping elements,	Include explicit (nonlinear) stiffness and damping properties
	Rail-to-Fastener Interface (Spring clips, bolted connections, etc.)		Include bilinear stiffness characteristic to represent loss of rail base contact with DF fastener	Include relative stiffness between rail and fastener
	Rails		Include bending and torsional flexure of rails	Include flexural dynamics of rail and rail geometry irregularities

Table 8-1. Example dynamic model characteristics for evaluation of DF fasteners (continued)

Component of Vehicle/Track Model		Modeling Objective		
		Safety-Related Dynamic Performance *(Stability, Curving Forces, Derailment Potential, etc.)*	**DF Fastener Loads** *(Influence of Fastener Stiffness, Spacing, etc.)*	**Wheel/Rail Impacts, Corrugation Formation & Vibration/Noise Transmission** *(High-Frequency, Short-Duration Load Events)*
Rail Vehicle	**Wheelsets**	Assume rigid wheelset		Include wheelset flexural dynamics
	Primary Suspension	Include nonlinear stiffness and damping characteristics (clearances, stroke limits, friction, etc.)		
	Motors/Drive Train	Include mass and inertia properties and connection stiffness and damping characteristics		
	Truck Frame	Include truck frame mass and inertia properties Include any truck warping or racking motions Neglect truck frame flexural modes		Typically can neglect truck frame and bolster dynamics as having small effect on wheel/rail impact dynamics and rail corrugation Truck designs should be evaluated to determine if/how truck dynamics should be included in model
	Secondary Suspension	Include nonlinear stiffness and damping characteristics (clearances, stroke limits, friction, etc.)		
	Bolster	Include bolster mass and inertia Assume rigid bolster		
	Tertiary Suspension	Include nonlinear stiffness and damping characteristics (clearances, stroke limits, friction, etc.)		
	Car Body	Assume rigid car body with appropriate degrees-of-freedom		Assume car body is a rigid, moving ground plane
	Inter-Vehicle Connections	Neglect inter-vehicle connections, except for articulated trains		

8.7 General Strategies for Implementing Dynamic Models

The effective use of dynamic models in the DF track design process requires an understanding of the operating and environmental conditions, the vehicle types, traffic mix and service life requirements. A general procedure for using analytical models in the DF track design process is illustrated below in Figure 8-1.

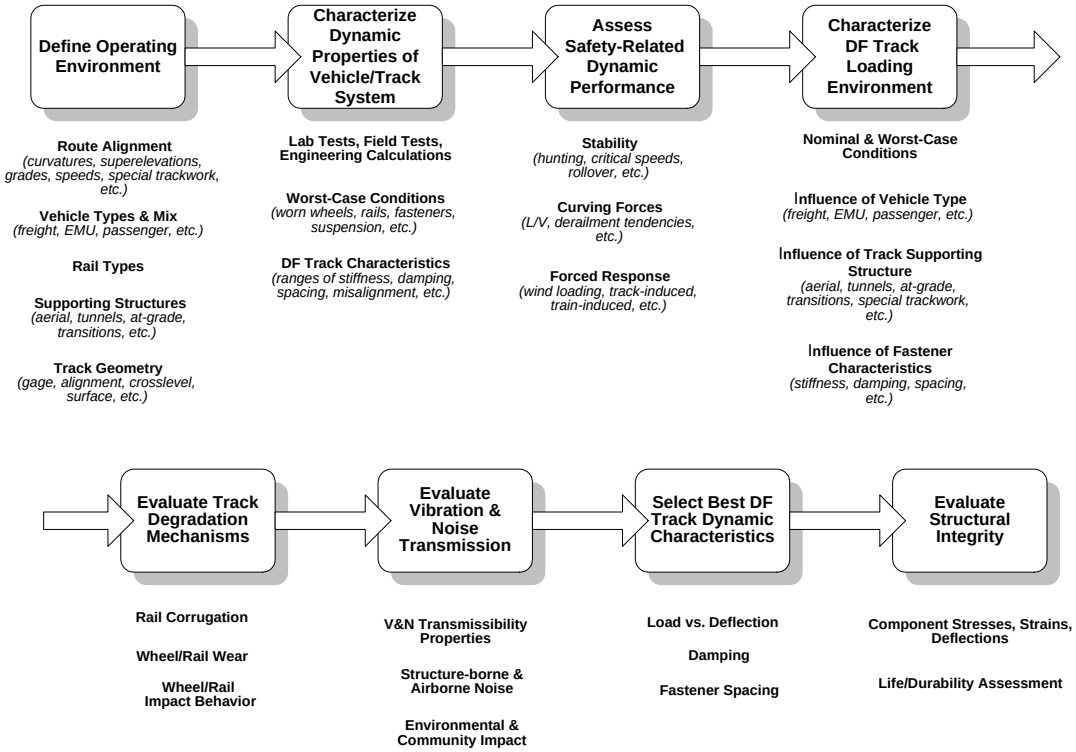


Figure 8-1 A general procedure for applying analytical models to support DF track design

As indicated by the first two steps shown in the figure's flowchart, an essential requirement for implementing analytical models is to accurately define the range of characteristics of the vehicle/track system for which DF track structures are being considered. This information establishes the basis for selecting appropriate models and the range of vehicle and track characteristics that should be evaluated. For systems having a wide variety of vehicles and track structures, effective analytical models are useful for indicating, for example, if it is feasible to use a single DF fastener type on the system.

The next five steps shown in the flowchart involve applying suitable analytical models to assess DF track performance. Because of the sometimes conflicting performance requirements associated with DF track structures (e.g., there are conflicting requirements for a relatively high fastener stiffness to prevent rail rollover and a relatively low stiffness to mitigate vibration transmission and impact forces), these steps generally should be carried out concurrently. In this manner, those characteristics that provide the best overall performance can be identified.

The final step in the process shown in Figure 8-1 involves using the results of the dynamic modeling studies—i.e., the predicted loads and deflections in the track components—in structural analyses and

laboratory tests to determine component stresses, strains and deflections. Predictions of component life then can be made using these data along with materials properties data and estimates of the types and mix of component loads expected over the service life of the component.

8.8 Examples of Candidate Vehicle/Track Dynamic Models for Evaluating DF Fasteners

A large number of rail vehicle dynamic models have been developed over the past 30 years to predict nearly every aspect of dynamic behavior. Descriptions of many of these models are provided in the report developed by Battelle for The Volpe Center under a program funded by the Federal Railroad Administration (Contract No. DTRS-57-D-00027, TTD No. VA-3204, report dated January 1995). The report indicates that most of these models assume a rigid track structure and therefore are not suitable for supporting DF track design studies. Among the commercial multi-body system dynamic codes that modeled the track stiffness and damping characteristics were the following. [NOTE: This list contains all those known to the authors at the time of this writing. Any omissions were inadvertent. No endorsements are implied.]

- MEDYNA—A package originally developed to support high speed rail and Maglev projects in Germany. It integrates all options for multi-body analysis into one package and can simulate fully nonlinear elements with bodies connected either open or closed loop. A large program, it is capable of handling large problems including vehicle-guideway interactions. It requires a powerful work station or mainframe computer.

- NUCARS—A code developed partly out of a need to investigate vehicle-track interactions on U.S. freight railroads. It is basically a time-integration type analyzer with a selection of track geometries, wheelset profiles, and nonlinear interconnections (suspension elements). It has the capability for simulating any type of vehicle, even though applications have been concentrated on freight cars. It has been used to investigate safe speeds through both American and European designs of turnouts. To date, the track structure characteristics are represented by spring-dashpot elements. The package is a tool for investigating time-varying response of nonlinear vehicle systems.

- VAMPIRE—The product of 20 years development at British Rail Research, it contains a varied array of tools for rail vehicle analysis. Applications include British Rail high speed rail evaluation, and freight derailment problems. It offers a combination of modeling and analysis features and will run on IBM-compatible PCs.

- ADAMS/Rail—The ADAMS (Automatic Dynamic Analysis of Mechanical Systems) software package dates back to the early 1970s. In the beginning, ADAMS concentrated mostly on linear analysis, with no real industry demand for nonlinear capabilities. In the early 1990s, with a joint effort between ADAMS and the Nederlanse Spoorwegen railway, ADAMS/Rail was developed to provide rail vehicle modeling capabilities. The ADAMS/Rail module provides various levels of dynamic analysis, ranging from Level I linearized with no rail wheelset Capabilities to Level III including wheelsets and full nonlinear creep contact theory. At the present time, two point contact analysis is not available. ADAMS/Rail is based on an open architecture format, and is customizable to each user's specific needs. The Rail

module is in its developmental stage, requiring the input of North American railways. ADAMS/Rail requires the basic ADAMS module to operate. It is supported in both the PC and mainframe environments.

- A'GEM—The A'GEM program, an acronym for Automatic Generation of Equations of Motion, was developed by the Mechanical Engineering Department of Queens University in Kingston, Ontario, Canada. The rail vehicle model is built using a graphical user interface of AUTOCad. The program exits to the DOS shell for execution of the processing modules. The post processing features include wheel unloading, vehicle stability, vehicle curving, and ride quality. The software includes nonlinear analysis, time and frequency domain based analysis, graphics, and animation capabilities.

- OMNISIM—A rail vehicle software simulation package under development for FRA projects by Foster Miller Inc., OMNISIM is currently in development and is not yet available for general release. The OMNISIM software has the capacity to model both the rail vehicle and track, including the rails and ties and ground through lumped mass, spring, and damper connections. The rail is represented as interconnected rigid bodies. The general model is nonlinear. The rail transverse roll degree of freedom is not yet included, however, the Kalker rolling contact model and true wheel and rail profiles are available. It is described more fully in a report available from the FRA

In addition to commercial codes, consultants around the country have developed specialized dynamic codes to predict vehicle track dynamic interaction. Examples of codes that are known to Battelle staff and suitable for evaluating vehicle/track interaction on DF track structures are:

- SSCURV—A model to predict steady-state curving of a rail vehicle with radial freight trucks. Lateral rail flexibility is included in this model. (maintained by Dr. Mark L. Naguraka , currently at Marquette University)

- VEHDYN—Nonlinear time-domain models of a rail vehicle on tangent track, spirals and curves. Vertical and lateral track compliance and damping are included in this model. (maintained by Battelle)

- RAILCORR—A nonlinear time-domain model of a rail vehicle during curving. This model has a detail representation of track component masses, inertias and impedances, and was developed to investigate rail corrugation phenomena. (maintained by Battelle)

- IMPWHLQ—A nonlinear time-domain wheel/rail impact model with detailed track dynamic characteristics. This code was developed to investigate wheel/rail impacts caused by wheel flats and rail surface defects. (maintained by Battelle)

These codes represent the types of analysis functionality needed to perform a vehicle/track interaction study. A number of consulting firms or individuals have a combination of the commercial and specialized codes available for hire. These models tend to be complex, and expertise in the area is needed to perform detailed analysis. The development of input data can be an especially taxing endeavor. Specific details of the specialized models from each consultancy are proprietary, and no comprehensive list of these models is available. We have attempted to list the major models known to us through professional interaction.

8.9 Summary

It is important from the standpoints of both performance and safety that careful consideration be given to the dynamic interaction between rail vehicles and DF track structures. Computer codes based on analytical models of the vehicle/track system are powerful and cost-effective tools for evaluating the influence of DF track design characteristics on the performance of the vehicle/track system.

A wide range of analytical models are available to support the DF track design process. A description of these models and a roadmap for their application has been presented in this report. It is essential for the successful use of analytical models for this purpose that a) the models are selected carefully based on their demonstrated range of validity, solution techniques and underlying modeling assumptions; b) values for critical model parameters values are accurate and based on reliable information; and c) the range of operating conditions associated with the vehicle/track system is known with good confidence.

8.10 Example Implementations of Computer Simulation Tools

Example # 1: Design of New DF Track: Requirements for Direct Fixation Fastener Systems for Mixed Traffic and Heavy Haul Operations

The Problem

An Asian railroad company was designing a new rail system. They required operation of passenger (EMU and locomotive-hauled) and freight (double-stack articulated) vehicles at very close headways over a track system that included tunnels, elevated structures and at-grade track. Axle loads were projected to range from 12 to 36 tonne (27 to 81 kip). To meet the requirements for low maintenance, excellent safety, good ride quality and low community noise, the company commissioned a study of non-ballasted track systems. A focus of the study was to determine direct fixation fastener characteristics that would provide acceptable vehicle/track dynamic interaction for the range of rail vehicles that would operate on the new system.

The Approach

Since no experience existed for such a wide range of axle loads, it was decided that computer simulation would be the most effective tool for investigating vehicle/track interaction issues. Thus, a nonlinear time-domain simulation program was used to predict the safety-related dynamic performance of representative passenger and freight vehicles operating on DF track. A model was selected that predicted curving dynamics of a complete vehicle on compliant track. The following operating scenarios were selected for the simulation studies:

- Operation at constant speeds into and through three curves, including the sharpest curve on the proposed route: the probability of high-rail flanging should be high for operation at the maximum unbalance speed in the sharpest curve; excitation of significant vehicle/track dynamics would be likely for operation at the maximum unbalance speed on a gentler curve; and high low-rail loads would be expected for operation at a significant underbalance speed.

- Maximum allowable track alignment and crosslevel geometry errors applied near the entry spiral/curve transition point: This was considered to provide a worst-case severe excitation of the vehicle during normal operations.

- Tare and fully-loaded rail cars: Vehicle and track forces and overall vehicle/track dynamic behavior are influenced significantly by axle load.

- A wide range of fastener stiffnesses, damping factors and spacings: These represented the primary independent variables which would be varied to address the critical issue of what fastener characteristics were required for the type of operation envisioned on the new rail system. The range of characteristics selected was based partly in laboratory tests conducted on candidate DF fastener concepts. Lateral and vertical components of stiffness and damping were varied separately and in combination.

The results of the parameter studies were evaluated in the context of the following safety-related dynamic performance measures. These are described in Table 8-2.

Table 8-2. Safety-related performance measures

Performance Measure	Safety Issue	Criteria
Single Wheel L/V	Wheel Climb	< 0.8 - 1.2
Truckside L/V	Rail Rollover	< 0.6 max
Gage Widening	Wheel Drop	<~75mm
Vertical Load Ratio	Car Overturning	
	--in Curves	> 0.4*Static Wheel Load
	--in Spirals	> 0.1*Static Wheel Load
Lateral W/R Load	DFF failure	DFF Design-specific

These performance measures are described below in greater detail.

- Single Wheel L/V: The maximum value of the ratio of lateral to vertical wheel/rail load on the vehicle's wheels was determined. For cases of vehicle running at overbalance speeds, the lead outer wheel on the leading bogie generally experienced the highest values of Single Wheel L/V.

- Truckside L/V: This was defined as the sum of the lateral loads on both wheels on one side of a bogie, to the sum of the vertical loads under the same wheels. For overbalance running, the maximum Truckside L/V values occurred on the high-rail side.

- Gage Widening: This was defined as the maximum increase in instantaneous track gage that occurred during the simulation. In the context of the simulation studies, gage widening refers to a dynamic change in gage, rather than a permanent change due to fastener failure.

- Vertical Load Ratio (VLR): This was defined as the minimum fraction of static vertical wheel load that occurred under any wheel while the vehicle was either in the spiral or in the curve. Minimum VLR occurred on the inner wheels during curve entry and curving at overbalance speeds, and occurred on the outer wheels during curving at underbalance speeds.

- Lateral W/R Load: This was defined as the maximum lateral wheel/rail load that occurred under any wheel during the simulation.

The Results

The results of the simulation studies comprised a set of simulation results that characterized the influence of DF fastener properties on safety-related dynamic performance of freight and passenger trains. Some of the results are described in Figures 8-2 to 8-7 and are summarized below.

1. Safe running of both the EMU and freight vehicles was indicated over the range of fastener characteristics that were examined and for the operating scenarios that were simulated.

2. The influence of fastener stiffness on safety-related dynamic performance was small for the operating scenarios that were simulated.

3. The influence of fastener damping on safety-related dynamic performance was negligible for the operating scenarios that were simulated.

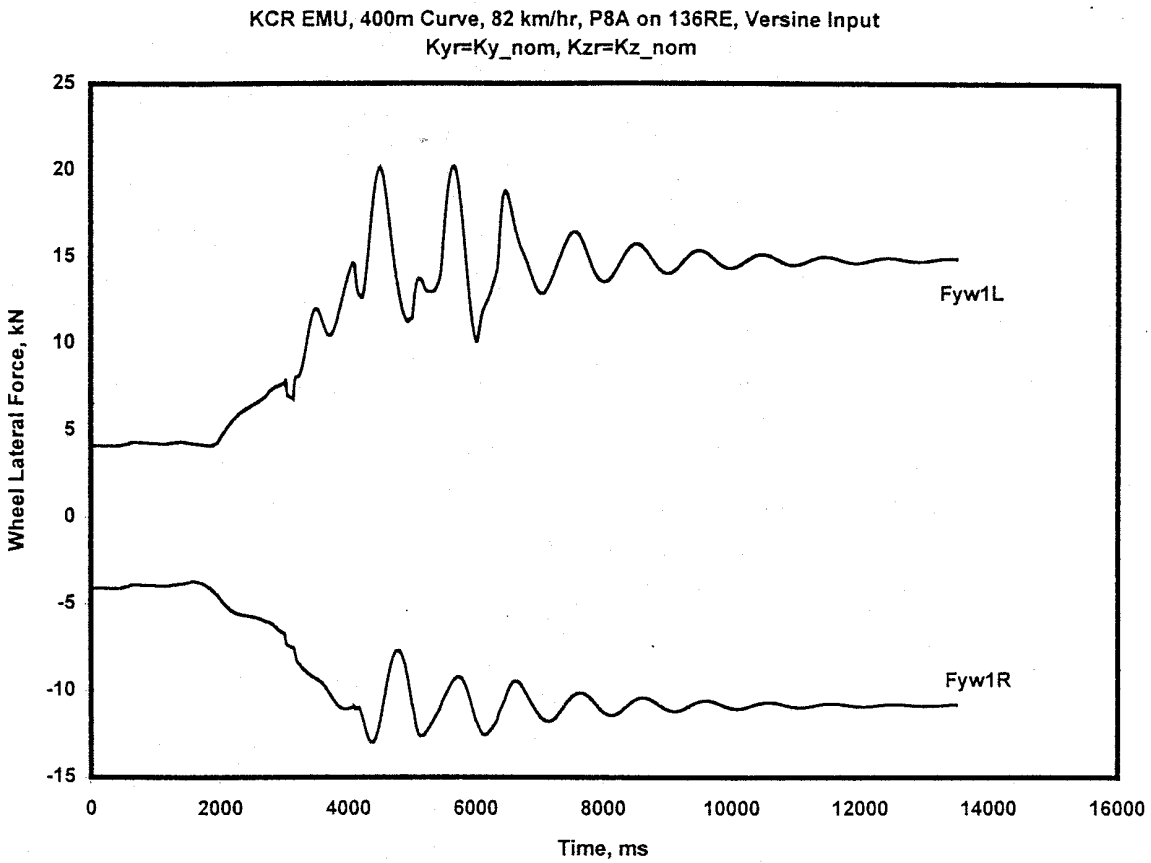


Figure 8-2. Example time-histories of lateral wheel/rail forces on leading wheelset: Loaded EMU in 400 m curve

Time-histories of wheel/rail forces generated while entering and negotiating curves provide valuable information on loads applied to the DF track structure and vehicle/track dynamic behavior. The time-histories shown above indicate significant dynamic components of lateral wheel/rail force in response to rail geometry errors located at the end of the spiral to a 400m curve. These loads attenuate as the vehicle moves away from the geometry errors, indicating that the vehicle is running stably at this particular speed.

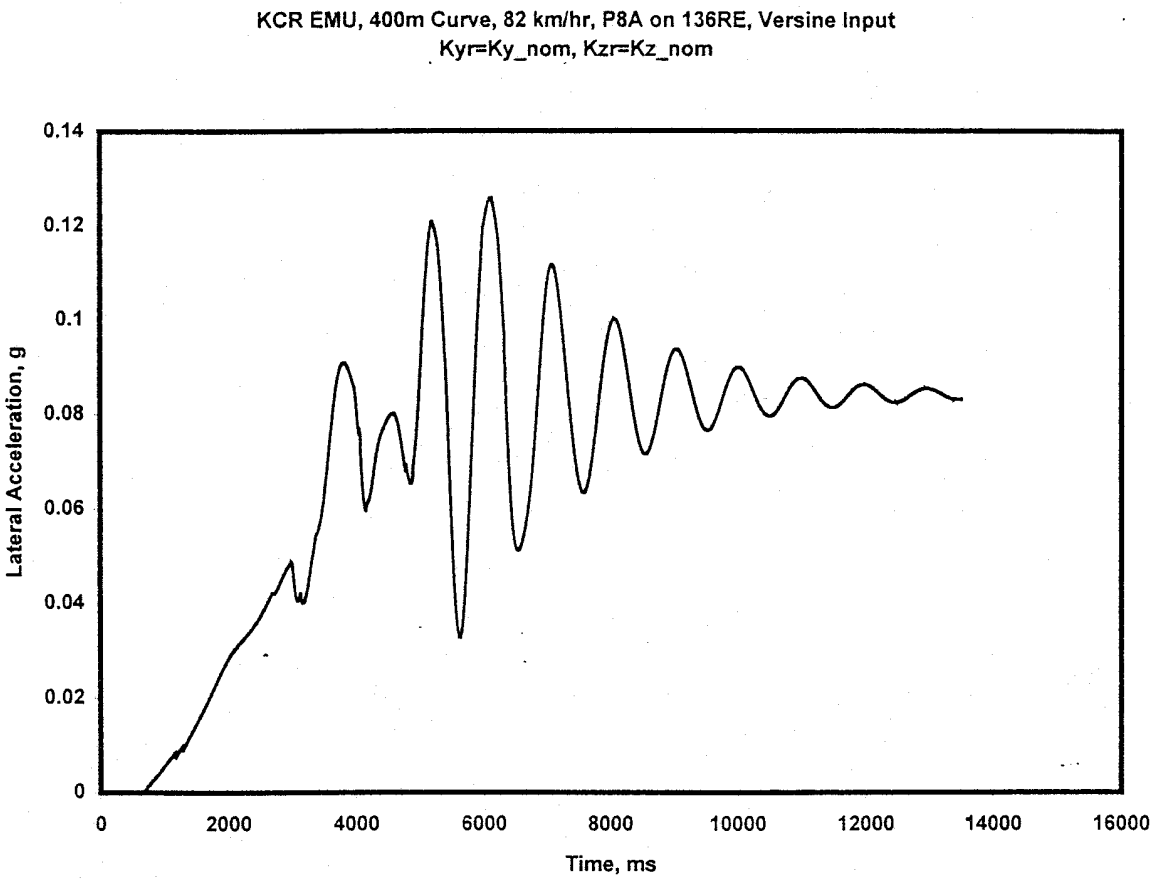


Figure 8-3. Example time history of lateral acceleration of car body center of gravity: Loaded EMU in 400 m curve

Time-histories of lateral acceleration of the car body provide an indicated of passenger ride quality on the track structure. As shown above, peak car body lateral accelerations of about 0.13 g were encountered on DF track as the vehicle entered a 400m curve at maximum allowable unbalance speed (82 km/h). The simulation studies showed that for the vehicle and track characteristics examined, DF fastener stiffness had a negligibly small effect on car body lateral accelerations. Based on these and other results, it was concluded that ride quality on the DF track structures being considered would be comparable to that for the existing rail systems.

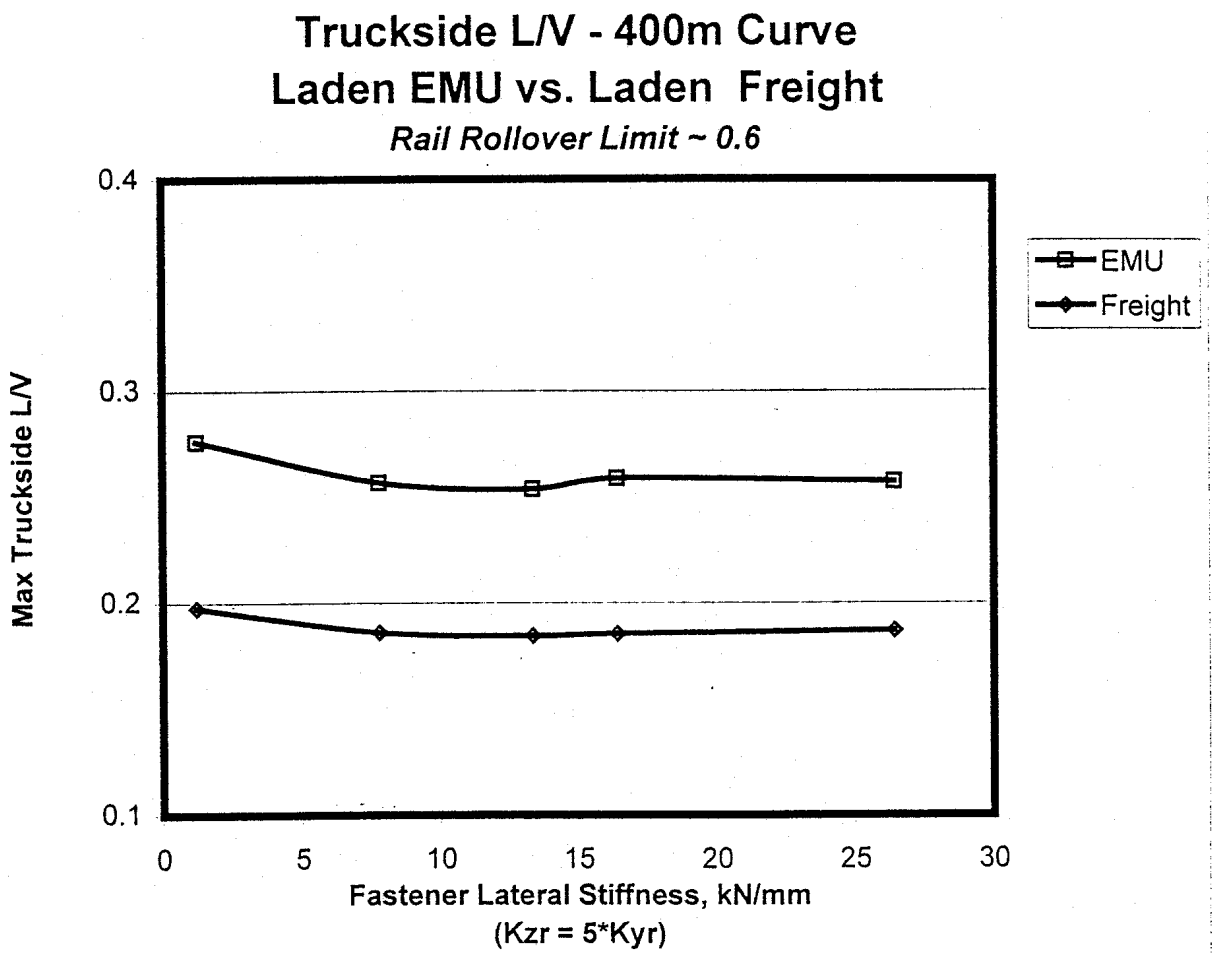


Figure 8-4. Influence of fastener stiffness on truckside L/V ratio: Loaded EMU vs. loaded freight vehicle in 400 m curve

Trend plots like these provide a quick-look summary of the influence of DF fastener characteristics on safety-related performance. This figure shows that, over the range of fastener stiffness characteristics being considered for the client's rail system, rail rollover tendency was influenced only slightly on the 400 m curve. Further, the maximum truckside L/V ratio—the indicator used for rail rollover tendency—was well below what was consider an unsafe condition (a value of 0.6). Finally, the rail rollover tendency was shown to be consistently higher for EMU operation than for freight operation. Based on these and other results, it was concluded that rail rollover was not likely on this system.

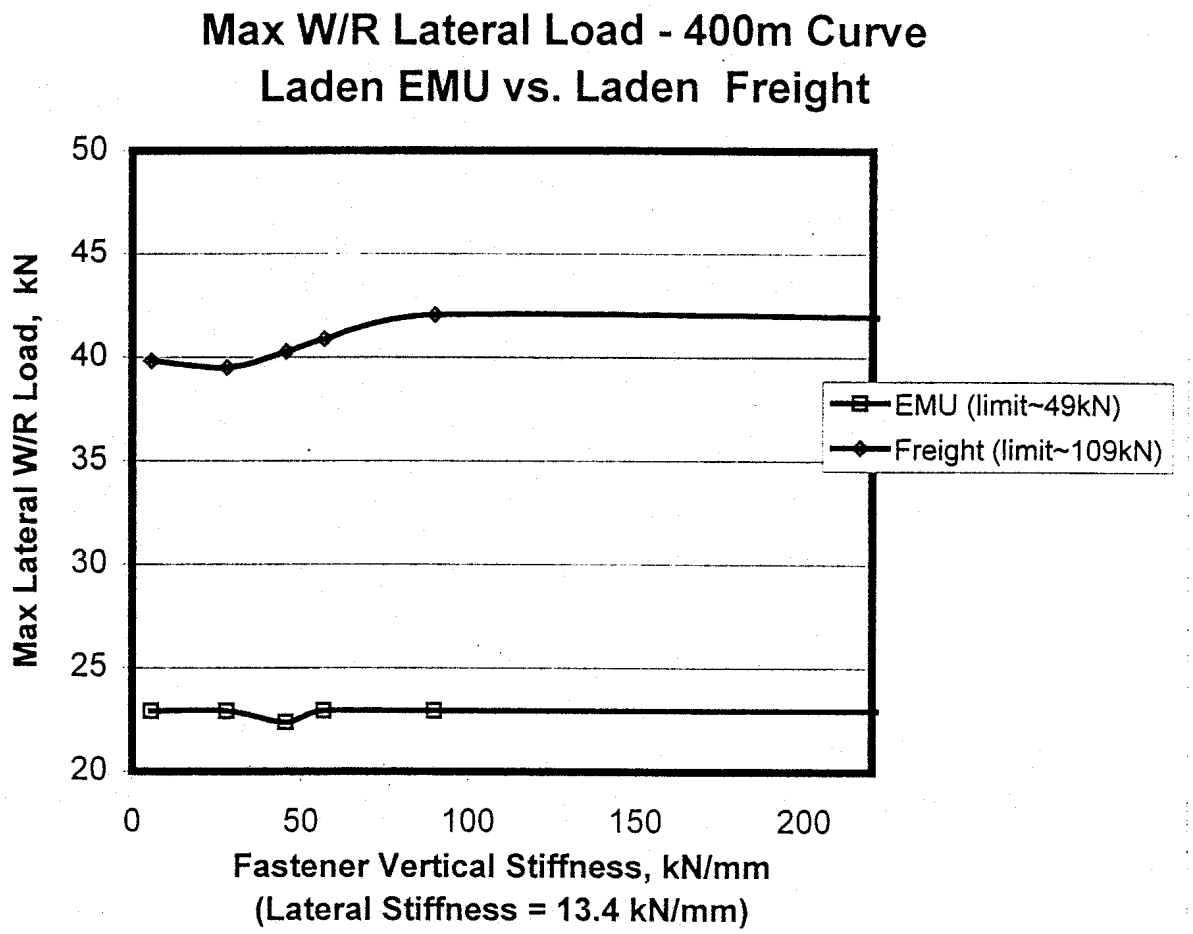


Figure 8-5. Influence of fastener vertical stiffness on single wheel L/V ratio: Loaded EMU vs. loaded freight vehicle in 400 m curve

This trend plot shows that fastener vertical stiffness had a modest influence on the maximum wheel/rail lateral force during operation in the 400 m curve. Further, much higher loads were generated by freight operation than by EMU operation. Finally, these load levels were well below those considered limits based on track lateral shift on conventional wood-tie track. Based on these and other results, it was concluded that track lateral shift was not a concern on this rail system.

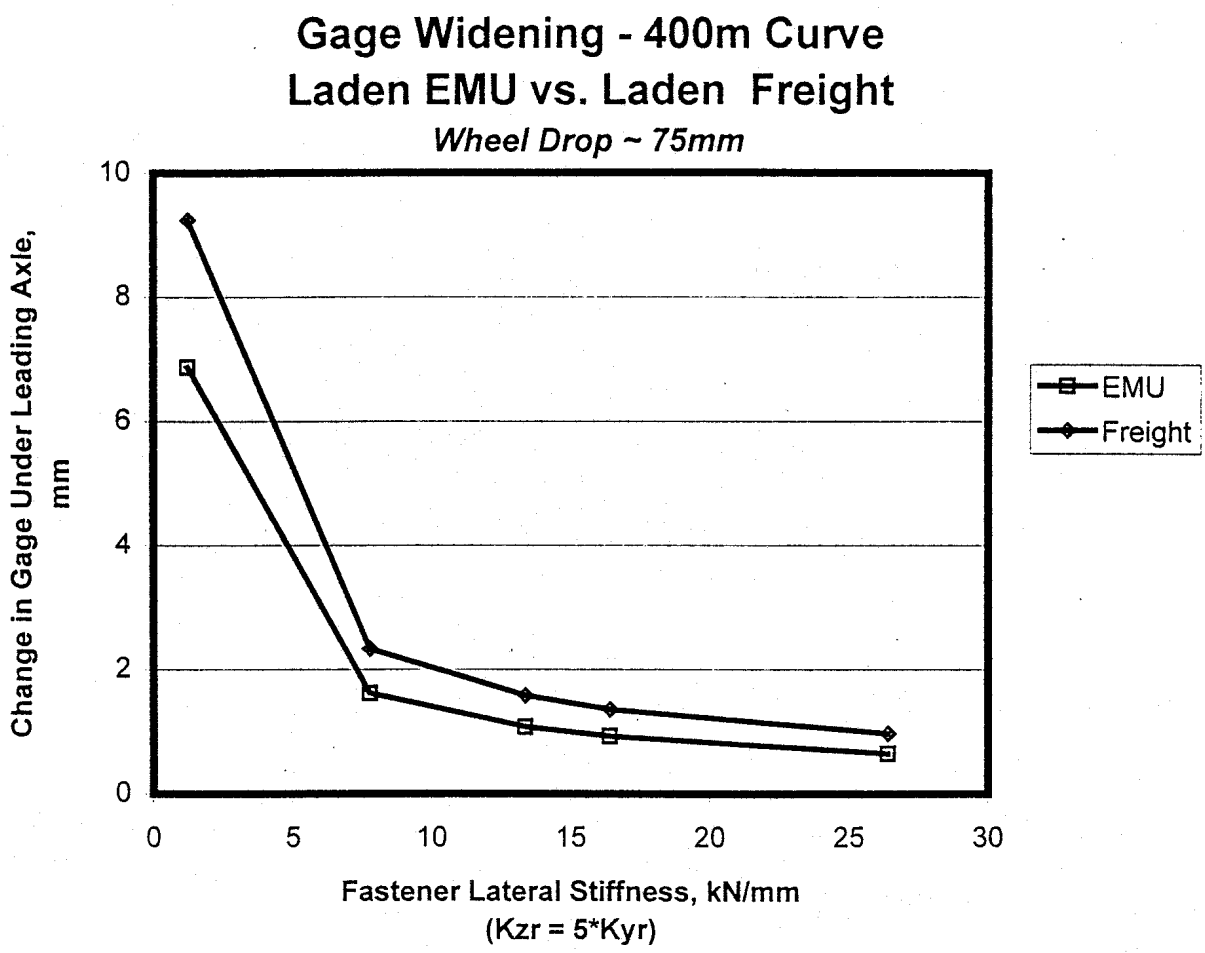


Figure 8-6. Influence of fastener stiffness on maximum gage widening displacement under leading wheelset: Loaded EMU vs. loaded freight vehicle in 400 m curve

Excessive gage widening was evaluated to see if the track dynamic response could include momentary increases in gage could lead to wheel drop between the rails. For the equipment used in the subject rail system, it was determined that wheel drop would occur if the increase in gage was at least 75 mm. As shown in the figure, the lateral stiffness characteristics of the DF fastener had a strong effect on the maximum change in gage during operation in the 400 m curve. Further, similar gage-widening behavior existed for EMU and freight operation. Finally, the magnitudes of gage widening (less than 10 mm) were well below the threshold for wheel drop. Based on these and other results, it was concluded that gage widening was not likely for the rail system.

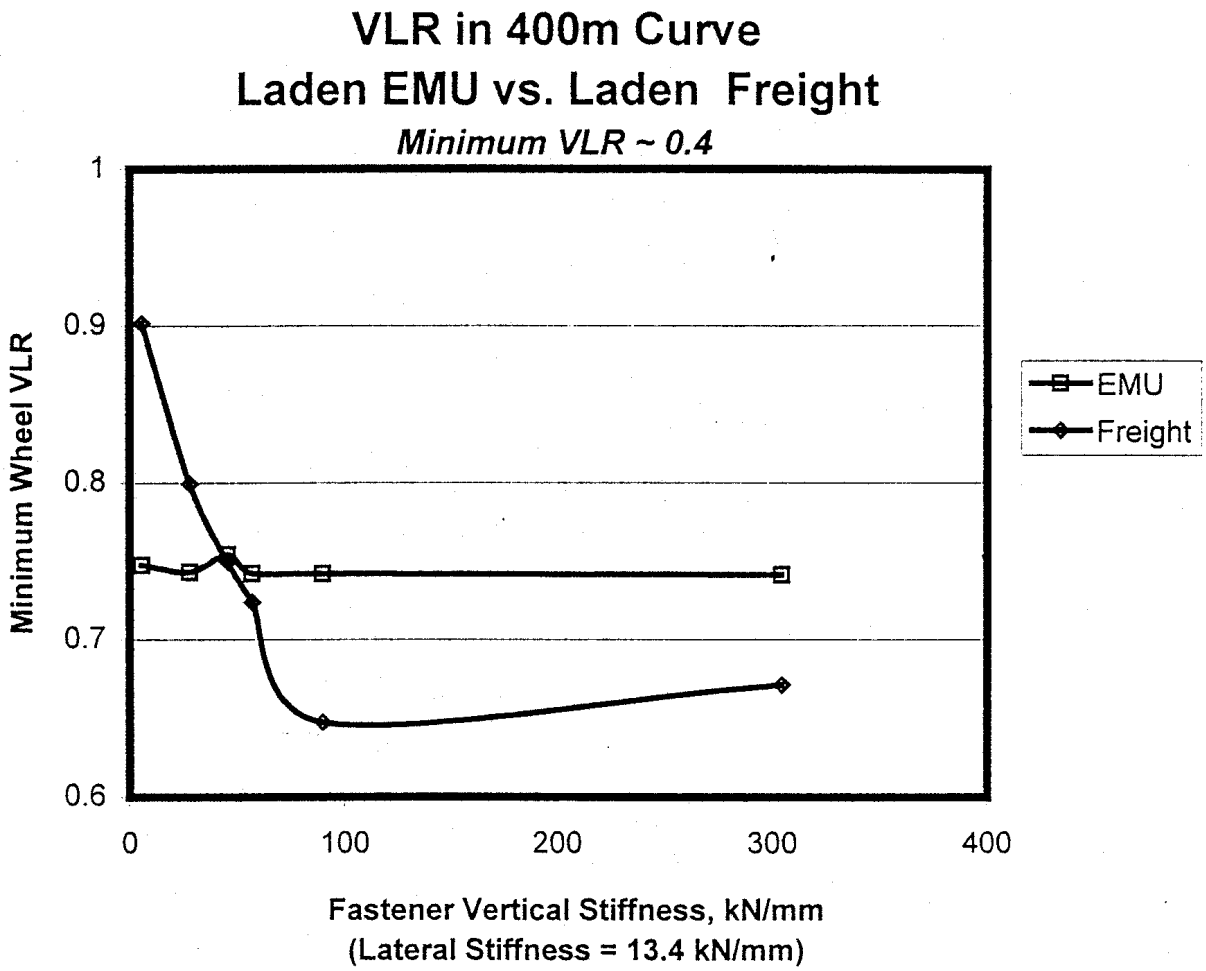


Figure 8-7. Influence of fastener vertical stiffness on minimum vertical load ratio (VLR) in curve: Loaded EMU vs. loaded freight vehicle in 400 m curve

The differences in vehicle design characteristics between the EMU and the freight vehicle are reflected in how differently DF vertical stiffness affected the shift in vertical wheel/rail loads from the inside to the outside wheels during curving. This load shift is indicated by the vertical load ratio or VLR, for which a minimum acceptable value of 0.4 was assumed to prevent car overturning. As shown here, the overturning tendency of the EMU was low and relatively unaffected by DF fastener vertical stiffness. In contrast, there was a somewhat greater load shift tendency with the freight vehicle, and this tendency varied dramatically with fastener vertical stiffness. Thus, although the minimum values of VLR were in all cases above the threshold value for car overturning, a relatively low value of DF fastener stiffness was desirable to mitigate this tendency in freight vehicles.

A significant result of this work was the establishment of an effective tool for predicting vehicle/track dynamic interaction. In addition to the scenarios that were evaluated in the study, the following additional issues were identified as requiring evaluation using the models:

1. The influence of track transition zone characteristics (e.g., vertical stiffness gradients and track geometry errors along the transitions between ballasted and non-ballasted track) on vehicle bounce/pitch dynamics, ride comfort and track forces.

2. The influence of other wheel/rail profiles (e.g., various worn wheel and rail profiles) on safety-related dynamic performance.

3. The influence of fastener stiffness and damping on high-frequency vehicle response (related to corrugation formation and impact-induced track and vehicle damage) and ride quality.

Example #2: Evaluation of Existing DF Track: Performance Assessments

The Problem

A U.S. transit authority experienced several problems with a direct fixation fastener system. These problems included accelerated component wear, loosened fastenings, broken spring clips, and rail corrugation. A study was commissioned to evaluate the contributing factors to these problems.

The Approach

The study included on-site inspections, laboratory tests on DF fasteners, analyses of rail corrugation wavelengths and rail stresses, and modeling and simulation of vehicle-track dynamic interaction. The focus of the modeling and simulation work was to identify combinations of fastener and vehicle characteristics that could result in dynamic behavior that contributed to the observed problems.

A nonlinear time-domain dynamic model of a rail transit vehicle operating on tangent track was used to evaluate the influence of DF fastener characteristics on vehicle-track interaction dynamics. The vehicle and track characteristics were representative of those on the existing property.

Simulation Study Design

The following configurations were evaluated in the simulation study:

Vehicle Type: existing coach; new (as-designed) and worn conditions

Primary Suspension Properties: three values each of lateral and vertical components of primary suspension stiffness and damping – nominal, 50% of nominal and 200% of nominal; lateral and vertical components varied proportionally. (The objective of varying the primary suspension characteristics was to identify suspension conditions resulting in strong vehicle/track dynamic interaction and high DFF loads.)

Operating Speeds: 30 to 60 mph (typical operating range); for model verification purposes, additional runs were made at speeds up to onset of lateral (hunting) instability.

Track Alignment: tangent only (chosen for conciseness; it was assumed that tangent track simulations would be sufficient to identify vehicle/track dynamic interaction effects for this particular problem).

Track Geometry: combined cross level and geometry errors (continuous staggered dipped joints); vertical DFF misalignment (these were considered to be the significant sources of dynamic excitation)

DFF Properties: three values each of lateral and vertical components of fastener stiffness and damping – nominal, 50% of nominal and 200% of nominal; lateral and vertical components varied independently; DFF spacing implied by stiffness and damping characteristics.

Key Output Variables: The output variables of primary interest were the maximum values of wheel/rail lateral force (related to fastener loads and derailment safety), suspension lateral force (related to component loads and safety) and car body lateral acceleration (related to passenger ride quality).

The Results

Typical results from the study are shown in Figures 8-8 to 8-11, where the influence of vehicle speed on dynamic response is plotted for several combinations of fastener lateral and vertical stiffness (in the legends, "L" = low stiffness, "N"= nominal design stiffness and "H"= high stiffness). The results indicated that the influence of fastener stiffness on dynamic response was stronger at higher speeds, and that the trend in dynamic response with increasing speed was not monotonic. In particular, local maxima in dynamic response were predicted at a speed near 40 mph; this was interpreted as coupled lateral/yaw oscillations of the vehicle bogies. The results of the study suggested that—at least for this property—it was desirable from the standpoint of derailment safety and component wear to implement DF fastener with lower than nominal lateral stiffness and high than nominal vertical stiffness characteristics. Other results of the study indicated that a modest amount of vertical misalignment between adjacent fasteners could cause significant increases in suspension forces. Further, it was found that bogies with primary suspensions of relatively high lateral stiffness and relatively low vertical stiffness were desirable to reduce wheel/rail and suspension forces. In contrast, a low lateral/high vertical stiffness combination provided improved ride comfort.

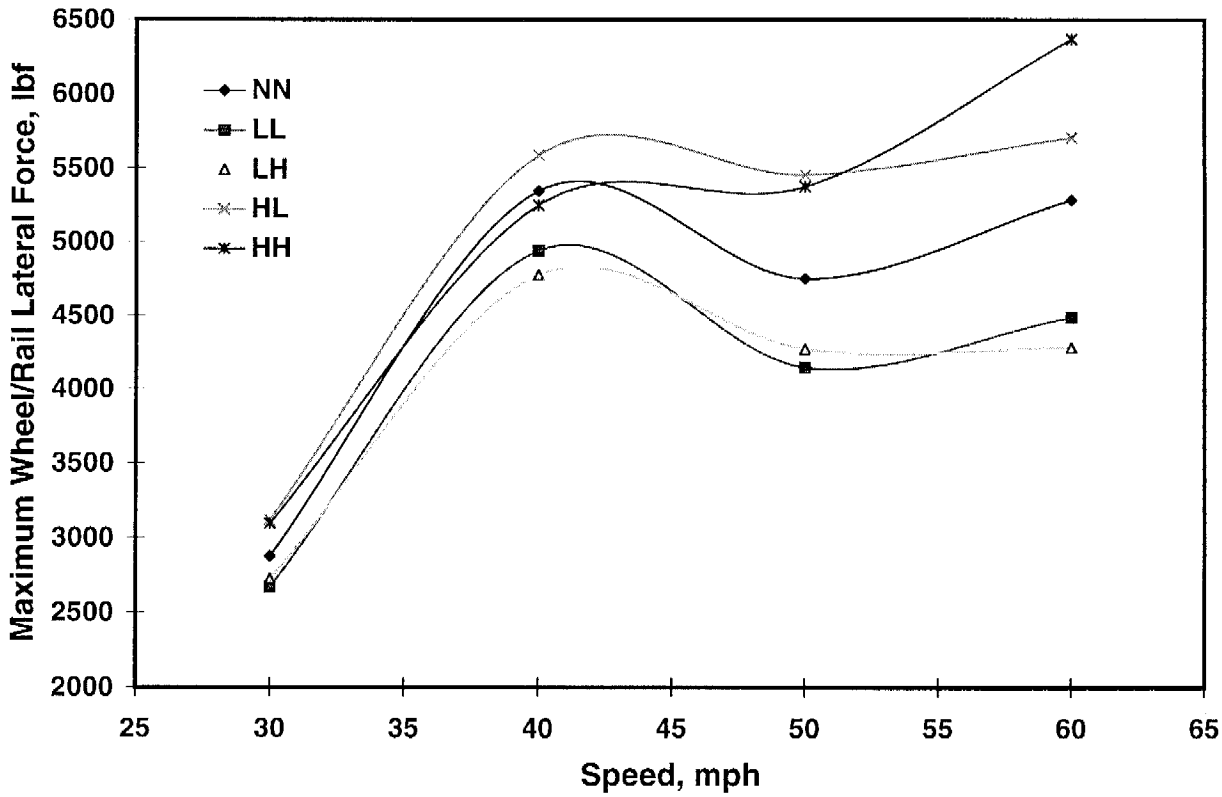


Figure 8-8. Fastener stiffness variation

Trend plots such as this were used to evaluate how different combinations of DF fastener lateral and vertical stiffness influence vehicle/track dynamic interaction on a particular rail system. By using speed as the independent variable in these plots, behavior associated with resonant response of the system can be identified. As shown above, the maximum wheel/rail lateral forces during tangent track operation over continuous staggered joints did not increase monotonically with speed: at speeds near 40 mph, there is a local peak in the curves, which was attributed to couple lateral/yaw oscillations of the wheelsets. Above this speed, the forces start to decrease, but then tend to increase again at speeds above about 50 mph. Further, the results indicate that, on average, DF fasteners with lower than nominal lateral stiffness characteristics and higher than nominal vertical stiffness characteristics (i.e., the "LH" curve) may be most desirable from the standpoint of low wheel/rail lateral forces.

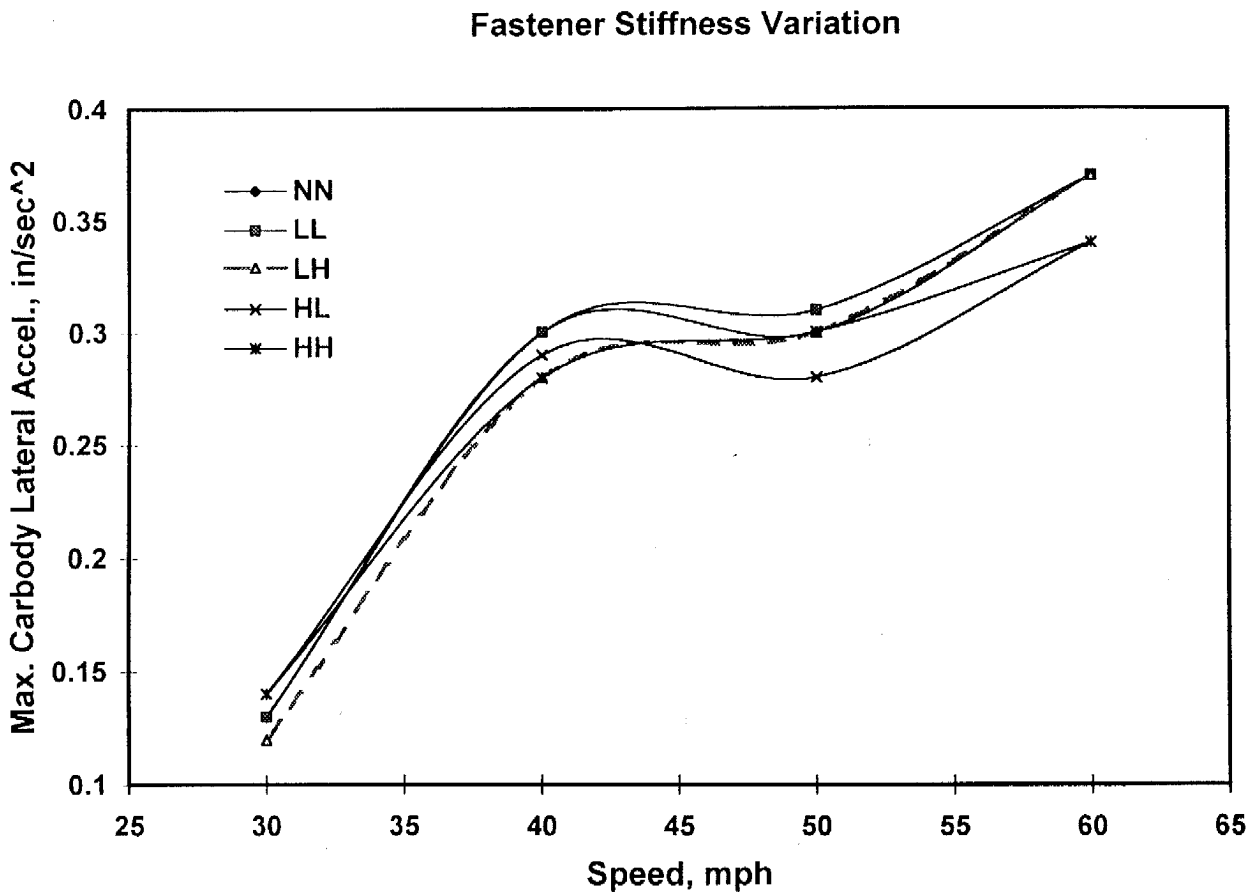


Figure 8-9. Influence of speed on peak car body lateral acceleration for several combinations of DFF lateral and vertical stiffness (response to continuous staggered joints)

To generate the results shown above, simulation cases were run for a vehicle operating over continuous staggered joint track at speeds from 30 to 60 mph and with different combinations of DF fastener characteristics. These results indicate that from the standpoint of lateral ride quality (car body lateral accelerations), DF fasteners with relative low lateral stiffness and relatively high vertical stiffness characteristics (i.e., the "LH" curve) are desirable for operation over the lower range of speeds, while the opposite combination (the "HL" curve) is more desirable at higher speeds. As in the previous figure, the trends with speed are generally not monotonic, indicating conditions where significant vehicle/track dynamic interaction exists.

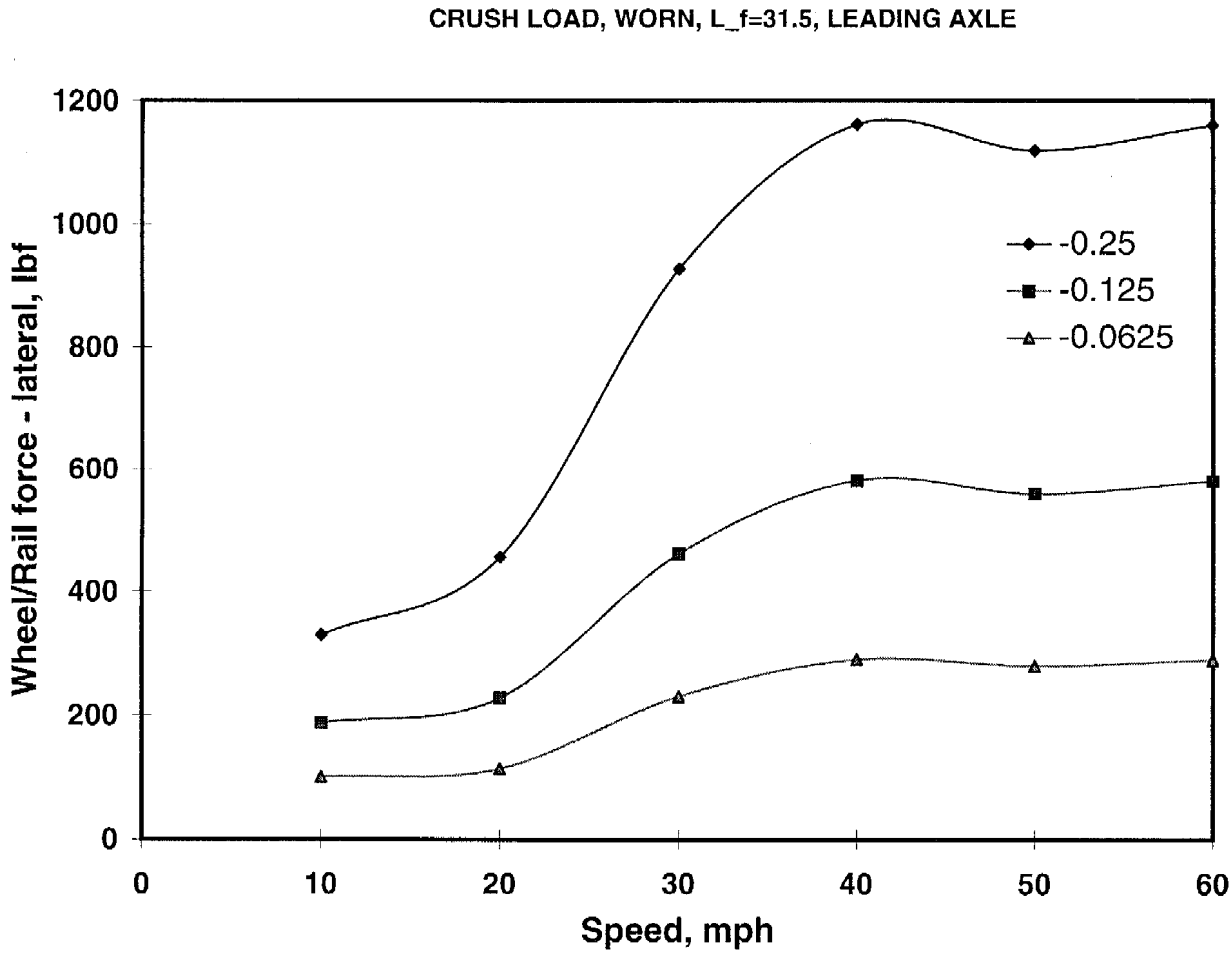


Figure 8-10. Influence of speed on peak wheel/rail lateral force for three values of DFF vertical misalignment (in inches)

A potential source of dynamic loading to the vehicle/track system was vertical misalignment between adjacent DF fasteners. To examine this, the case of a DF fastener installed lower in the track than the adjacent fasteners was modeled in the computer simulation. The influence of operating speed on wheel/rail lateral force (on the leading wheelset) is shown above for three values of DF fastener vertical misalignment. The need to maintain good fastener alignment is readily apparent, particularly for safe operation at higher speeds.

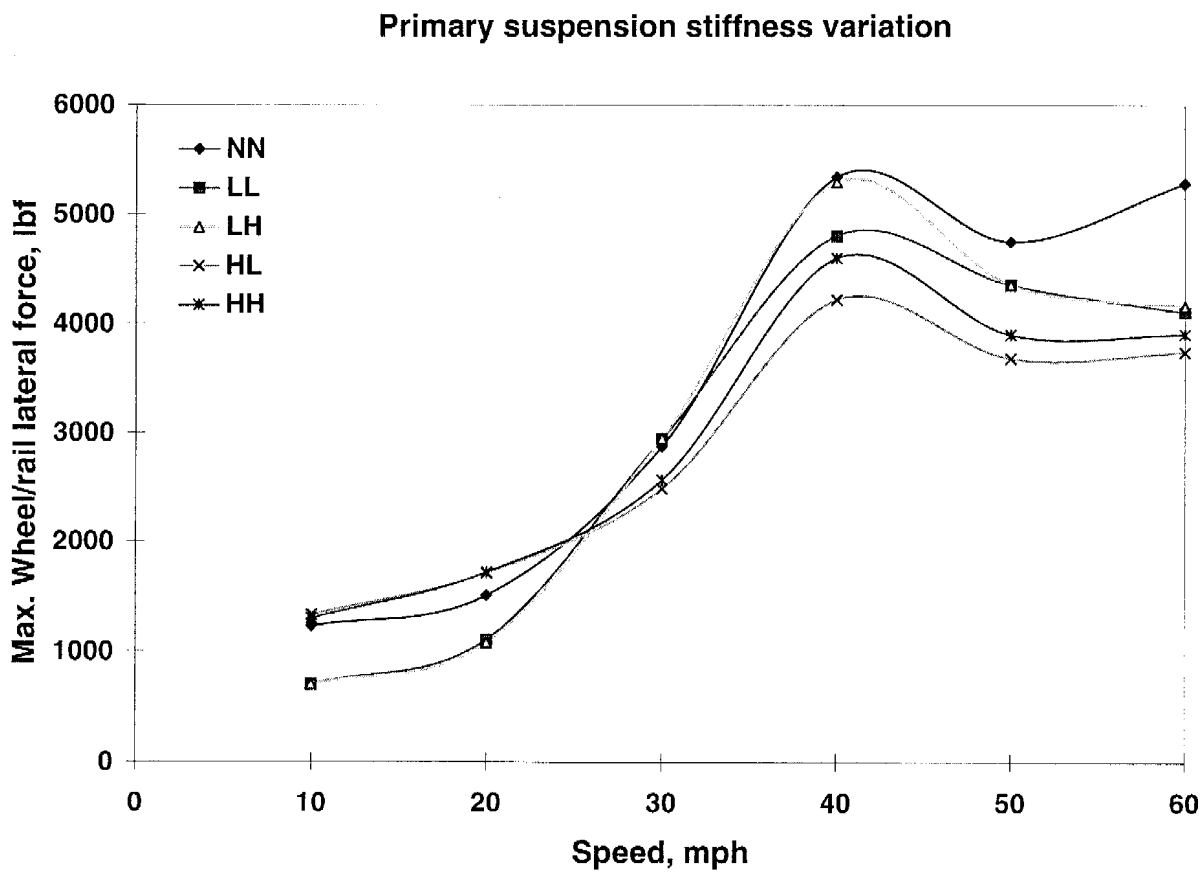


Figure 8-11. Influence of speed on peak lateral wheel/rail force for several combinations of vehicle primary suspension stiffness (response to continuous staggered joints)

Suspension characteristics can vary widely from vehicle to vehicle for the same design, primarily because of differences in component wear and degradation. Small changes in suspension characteristics can sometimes "tune" a vehicle with its track, resulting in significant increases in dynamic response. Thus, it can be somewhat misleading to conduct simulation studies using only the "as designed" properties of the vehicle. The results shown above are from cases where the lateral and vertical stiffness properties of the vehicle primary suspension system were varied. The most desirable combination of primary suspension characteristics (in this case, as determined by minimum wheel/rail lateral force) varies depending on the operating speed.

9. Maintenance and Installation Issues

During the construction and use of the test beds for the fatigue and combined loads testing, a number of different observations were documented. The following text and photographs (Figures 9-1 to 9-25) illustrate some of the maintenance and installation considerations identified during the program.

Detailed installation instructions were provided with the embedded block system. It is imperative that the installation procedures be followed closely. In fact, the supplier sent an on-site engineer to witness the concrete pours to ensure that they were done correctly. Such detailed instructions were not received with any of the other systems.

- Figure 9-15 shows a view of the testbed for the frame fastener 1 tests. Unlike the casting process for the embedded block system, there is no hydrostatic pressure head on the concrete to help keep it in good contact with the shim under the fastener. This makes "top-down" construction very difficult for a baseplate system. The cast-in-place retrofit recently used by several contractors has a lot of merit as a method to possibly correct this problem with top-down construction and baseplate implementation. It may be possible to remove one complete step of disassembly and secondary concrete finish from the track construction process if such a pre-cast support block is used.

- Figure 9-20 shows a spring clip that has backed partially out of the shoulder due to the rail shifting in the longitudinal direction. If the insertion direction of the restraint clip is the same as the restraining direction, then it is definitely necessary to have positive restraint on the fastener if any rail running is likely to occur. More recent clip designs do not have this problem, since the insertion direction is perpendicular to rail movement.

A view of the broken frame of a Frame fastener 1 test article is shown in Figure 9-21. It is recommended that the serrations in any hold-down plate be rather large. Once during testing, the fastener shifted laterally one notch due to lateral load and coil springs that were not quite tight. The possibility would be more likely with small serrations that would require small vertical displacements to ratchet over as opposed to large serrations. As shown in Figure 9-22, when this fastener is not under load it is virtually impossible to tell that it is broken. Any covering of steel structural members should be of a brittle nature so failures are inspectable.

Figure 9-23 shows the underside of the frame type fastener and the top of the concrete surface after testing. Notice the abrasion of the supporting rubber against the concrete surface. This raises the concern about the need to coat the seating surface to prevent long term plinth abrasion and/or rubber abrasion.

- Figure 9-24 shows a view of the Embedded block rail clip and insulator. The bolts associated with the clip were difficult to install even after brief exposure to the elements. For this reason, the selection of a boltless rail fastener is supported. Previous experience with bolted rail hold-downs has shown it to be very difficult to work with a threaded fastener in the rail environment.

Figure 9-1. Completed test beds for a frame fastener 3 and a embedded block trackforms. A Frame fastener 1 is included in the photo for a size reference. The test beds consisted of welded steel frames that were pretapped and ready for attachment to the 600 kip test machine loading bed.

Figure 9-2. Embedded block test bed ready for concrete pour. Notice the reinforcing, the strapping tape holding the boot in place, and the tape sealing the top of the boot from concrete entry during the pour. The fasteners are held in place by the rail in a top down method of construction. The rail is situated at 1:40 and tack welded to the steel frame to ensure proper positioning.

Figure 9-3. Embedded block system concrete pour showing proper method of loading concrete from one end and vibrating it under the tie blocks. The flowing motion of the concrete serves to remove air from under the block.

Figure 9-4. Close-up of vibrating concrete with Embedded block system

Figure 9-5. Almost full test bed and vibration for Embedded block system

Figure 9- 6. Finished Embedded block pour after the tape is removed from the boot. Notice the clean surroundings and good finish around the Embedded block.

Figure 9- 7. View of bottom of Embedded block boot and cavity in concrete pour. Notice the small cavities and their rather even distribution under the boot. The supplier states that up to 20% of the boot bottom may be unsupported. The impressions of the boot positioning tape are evident.

Figure 9- 8. The instructions did not explicitly state the need to cover a small (2 mm) hole in the boot with tape during the pour. As a result it was missed and a patch of concrete seeped into the cavity. This seepage can be seen on the right side of the photograph. This seepage quickly broke up into pieces that embedded themselves in the microcellular pad during testing. Notice also that some moisture was in the boot as a result of the washdown process.

Figure 9- 9. Embedded block that had been removed and replaced. Notice the turndown of the upper lip on the left end of the boot. Also notice the notch in the side of the white plastic insulator. This notch is used to monitor the compression of the spring clips, a somewhat delicate operation for a track crew. The space under the flat plate must be monitored with a feeler gage while the holddown bolt is tightened. Common wisdom would indicate that this operation might present dificulties in the field.

Figure 9- 10. Cracked end of Embedded block test bed. It is preferred not to have a free surface laterally for at least 8 - 10 inches past the end of the block. The system works best with a second pour that is flush to the structure wall. Even with this degree of concrete fractures no boot failure occurred.

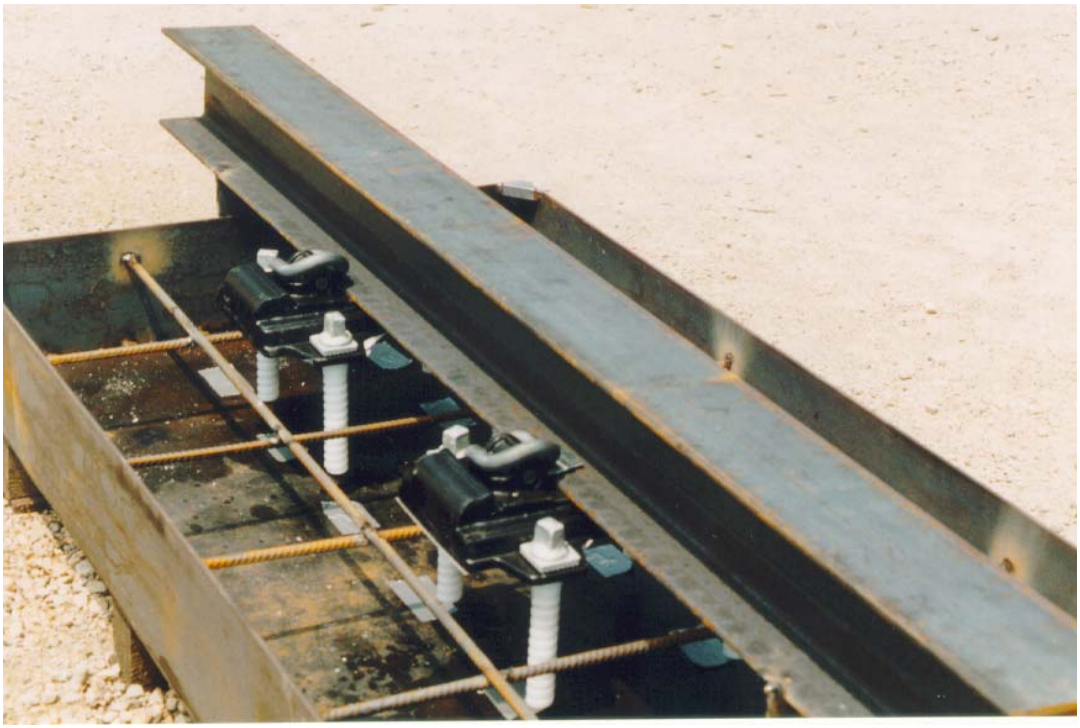


Figure 9- 11. Frame fastener 3 test bed ready for concrete pour. Again a top-down method was used. Since the fasteners are referenced off the bottom of the rail it was acceptable to use a substitute section of an I beam for the rail.

Figure 9- 12. Frame fastener 3 test bed and vibrating concrete into place

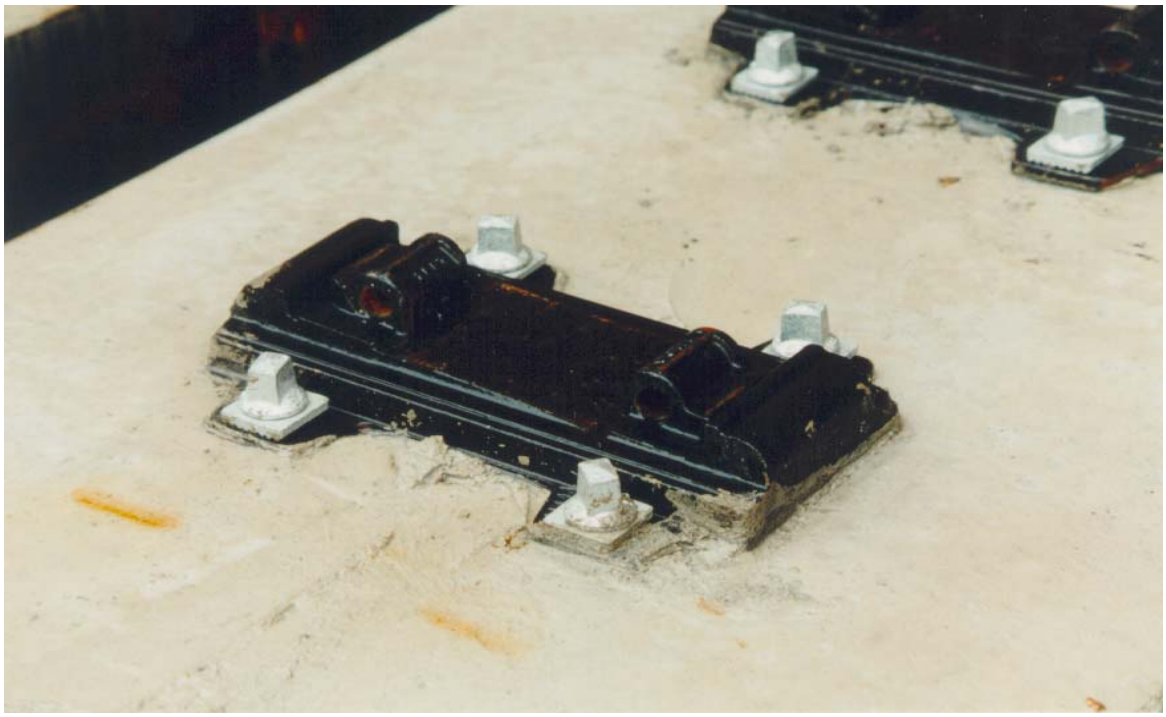


Figure 9-13. Finished test bed for Frame fastener 3. Notice the rough uneven edge surrounding the fastener and concrete pour.

Figure 9-14. Finished concrete pour for Frame fastener 1. Notice the wood shim under the fastener to prevent entry of concrete into the underside of the fastener. Also notice the difficulty in achieving a good finish around the fastener.

Figure 9-15. Frame Fastener 1test bed after removal of the rail. Notice the rough surface of the concrete.

Figure 9-16. Top of concrete of the frame fastener 1 test bed after removal of the fasteners. Notice the flow of the concrete around the edges of the fastener.

Figure 9-17. Top of concrete of the frame fastener 1 test bed after removal of the fasteners and removal of all loose and soft concrete. Notice the plastic inserts in the concrete.

Figure 9-18. Top of concrete of the frame fastener 1 test bed after second filler and finishing coat of high strength concrete.

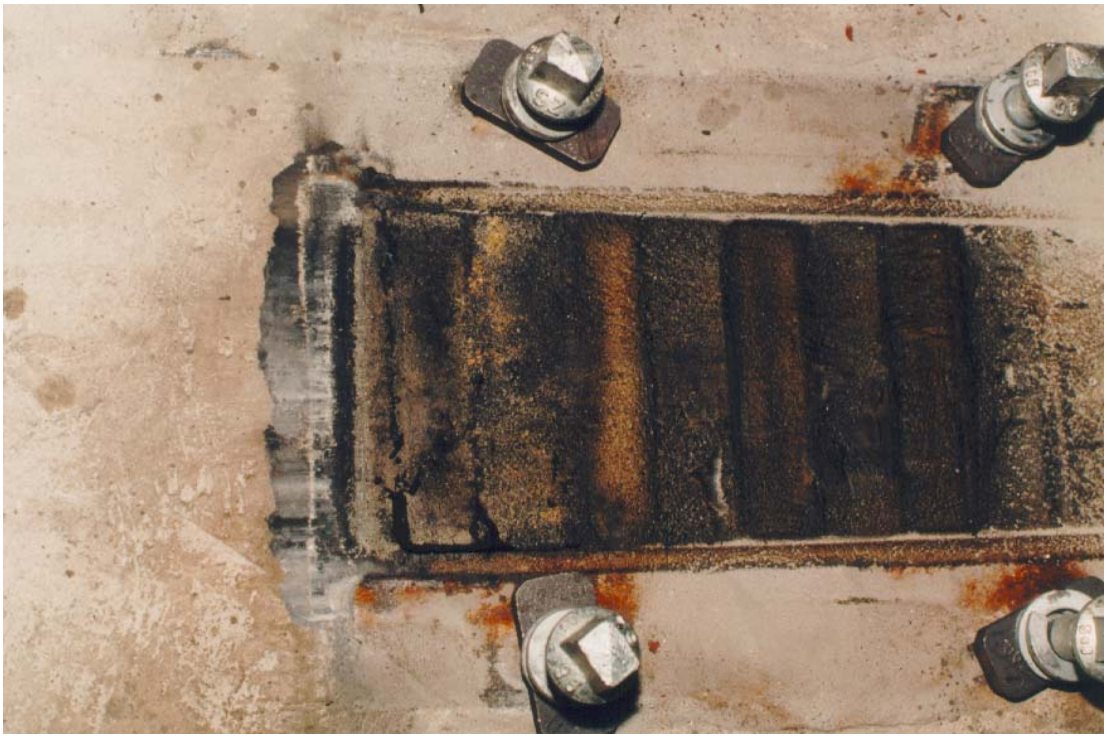


Figure 9-19. View of Frame fastener 1 underside and top of concrete surface after testing. Notice the abrasion of the supporting rubber against the concrete surface.

Figure 9-20. View of Frame fastener 1 underside and pad abrasion after testing. This fastener has through-cracks in the corner of the test frame. The rubber bonds held and this fastener was difficult to spot as broken except under load. The failure was rather benign in that nothing catastrophic occurred, although deflections of the rail got rather large due to the lack of lateral rail restraint.

Figure 9-21. View of Embedded block rail clip and insulator

Appendix A
Glossary of Terms

This Glossary lists terminology relevant to Direct Fixation Fasteners. **Boldfaced** terms within a definition are further defined in the Glossary.

This Glossary is annotated to include common usage(s) and fundamental engineering relations for Direct Fixation Fasteners. Context-sensitive variations of a term's meaning are explained where appropriate. The annotations explain confusion from intuitively similar terms (such as **elastic fastener**, **fastener body**, **bonded fastener**, **resilient fastener system**, **elastomeric plate**) that are sometimes erroneously used interchangeably.

The Glossary lists and cross-references terms that refer to the same thing (**rail pads, tie pads** for example).

The Glossary includes general terms (such as **Anchor Bolt**) that have specific meaning in Direct Fixation Fastener applications.

The Glossary attempts to reflect variations in colloquial terminology.

A-Weighted Sound Level (dBA)	The sound pressure level in decibels as measured on a sound level meter using the internationally standardized A-weighting filter or as computed from sound spectral data to which A-weighting adjustments have been made. A-weighting de-emphasizes the low and very high frequency components of the sound in a manner similar to the response of the average ear. A-weighted sound correlate well with subjective reactions of people to noise and are universally used for community noise evaluations.
Accelerated Aging Tests	Commonly used during the development and testing of fasteners, a family of tests is employed to simulate the long-term degradation effects of the environment on a fastener, fastener body, elastomeric coatings, or insulators to determine failure point and wear mechanisms as a function of aging in the field. Batteries of tests are used to most closely replicate the combination of weather (freeze-thaw cycles) and contaminants in a hostile track environment (salt and corrosive baths, application of lubricants, oil and acids). To accelerate the effects of natural aging in the laboratory, these materials are applied on a 24-hour basis through many cycles over an intensive period of time with pressurized applicators and hot baths. The type and number of tests specified should be formulated on a site-specific basis with consideration given to the actual combination of materials planned for installation. A good test replicates the field environment as closely as possible while it is understood that no set of **accelerated aging tests** can duplicate the effects of years of actual service in the field.
Acceleration Level	Also referred to as "vibration acceleration level." Vibration acceleration is the rate of change of speed and direction of a vibration. See **accelerometer.** The acceleration level is 20 times the logarithm to the base 10 of the ratio of the RMS value of the acceleration to a reference acceleration. The generally accepted reference vibration acceleration is 10^{-6}g (10^{-5}m/sec).
Accelerators:	Accelerators are catalysts that reduce the curing time of elastomers by a factor of 10.
Accelerometer	A vibration sensitive transducer that responds to the vibration acceleration of a surface to which it is attached. The electronic signal generated by an accelerometer is directly proportional to the surface acceleration.

Alignment (Track)	Design alignment of the track. Vertical track design alignment is the **Track Profile.** Lateral track design alignment is the **Horizontal Alignment**. Depending on the context, the term may refer to either the horizontal alignment, the track profile, or the deviation of track from design alignment.
Ambient Noise	The prevailing general noise existing at a location or in a space, which usually consists of a composite of sounds from many sources near and far.
Anchor Bolt:	A bolt or threaded rod (most typically) that holds a direct fixation fastener to supporting concrete. An anchor bolt is fastened into a **female insert** in the supporting concrete. A threaded rod may be cast or grouted into the supporting concrete without an insert.
Angle of Attack	The angle on a curve between the wheel and rail contact patches relative to a curve tangent. This angle is one of the factors correlated with truck skewing, wheel-rail wear, derailment probability and consequent ride quality. **Creep forces, L/V ratio** and **angle of attack** interact closely together with the applied loading to determine the forces for which the DF fasteners, both singly and in combination, are subjected to on a given curve.
Angular Velocity	Frequency
Anode	The electrode in a battery that gives off positive ions; the positive pole of a battery or other source of current.
Anti-degradants (antioxidants):	Substances added to make elastomers resistant to oxygen and ozone. The two main classes of antioxidants are amine derivatives (such as ketones) and phenol derivatives.
Anti-oxidants:	see **Anti-degradants**.
As-built Drawings	When DF trackwork is constructed, the actual alignment, cross-section or materials used may differ from that which was originally specified due to unforeseen obstacles which may arise during construction. Substitutions of DF components or materials may be allowed if the performance of the alternative component meets or exceeds the original contract specification requirements. This determination is usually made by the on-site construction/engineering manager or the resident engineer. When a system is completed, all plans, tests, and compliance certification results should be labeled "as-built" to avoid sources of future confusion.
Background Noise	The general composite non-recognizable noise from all distant sources, not including nearby sources or the source of interest. Generally background noise consists of a large number of distant noise sources and can be characterized by L_{90} or L_{99}.
Balance Speed	The theoretical speed at which a passing train negotiates a curve at a given superelevation on a given curve. The objective is to overcome the effects of centrifical force by applying exactly the same train weight between the low and high side of the rail. The following formula is used to calculate balanced speed and balanced superelevation given a specified radius by substituting terms: To find **speed** (V) in miles per hour: V= 0.5 Sqrt(E*R) To find **superelevation** (E), in inches: $E = \frac{4V^2}{R}$ To find **radius** (R), in feet: $R = \frac{4V^2}{E}$

Ballast Resistance (or guideway resistance)	Electrical resistance between running rail on the same track. A better term for DFF Systems is **guideway resistance** because DFF track is ballastless. The principle is the same for ballasted and ballastless track.
Bolted Fastener System	Any fastener system containing a bolt (exclusive of **Anchor Bolts**) to hold the elastic rail clip in position. See also **threadless fastener system**.
Bonded Fastener:	A **resilient fastener** where the elastomeric material is bonded to a steel top plate and a steel bottom plate. A common manufacturing practice is to apply an adhesive to the steel plates, place the plates in the mold with the compounded but uncured elastomer, then conduct the elastomer **curing**. Bonding and **curing** occur in the same process.
Cant	Angle of a **rail seat**, stated as a ratio of rise to run (e.g. 1:20, 1:40)
Cant Deficiency	A railroad term used to describe the nominal superelevation in track profile which the track would have to be raised to achieve balanced speed operation between low and high rail side of curve. Term is similar to **unbalanced superelevation**.
Carbon Black	Carbon, obtained by burning oil in a controlled atmosphere, used as a filler compound in elastomers to improve elasticity and tensile strength.
Cast-in-Place Inserts	Threaded inserts for anchor bolts (studs) used with concrete slab structures.
Cathode	The electrode that emits electrons; the negative pole of a battery or other source of electric current.
Characteristic Equation (Dynamics)	An algebraic equation describing the frequency response characteristics of a dynamic system, using which the stability of the system can be determined.
Clip	See **elastic rail clip**, **rigid rail clip**
Clip Insulator	Dielectric insulator between rail clip and rail base.
Cologne, Toronto & American Egg	An oval-shaped elastomerically encased fastener consisting of two metal plates fully encased in a 50 **durometer** Shore A elastomer to dampen forces and provide electrical isolation. The top plate fits within the walls of the outer plate to provide lateral restraint due to curving/ shear forces. Two anchor bolts fit through the bottom plate of the "egg" which protrudes beyond the elliptical shape limits as an integral part of the frame. A one-piece bottom plate casting absorbs and isolates forces induced to the concrete invert vertically. The design enables shear forces to be fixed between the inner and outer wall of the egg in the elastomeric buffering region. The "egg" has been in domestic and Canadian transit service since the early 1980's and has been used as an intermediate ground-borne noise/ vibration mitigation device where necessary especially on elevated structure and bridges. Toronto Transit Commission and the MBTA pioneered application of the "egg" in North America.
Coloumb Friction	Dry Friction, Static Friction
Community Noise Equivalent Level (CNEL)	The L_{eq} of the A-weighted noise level over a 24-hour period with a 5 dB penalty applied to noise levels between 7 p.m. and 10 p.m. and a 10 dB penalty applied to noise levels between 10 p.m. and 7 a.m.

Compression Modulus (Elastomeric materials):	$E_c = E_o (1 + 2KS^2)$ E_c = Compression Modulus E_o = Young's Modulus (94 to 9.2 kg/cm^2 for elastomers) K = Correction Factor (0.42 to 0.093 for elastomers with durometers between 30 and 75) S = Shape Factor $S = \frac{Load\_Area}{Bulge\_Area}$ Load Area = fastener top surface = Length * Width = L*W Bulge Area = 2(L+W)t t = fastener thickness
Construction Tolerance	The specified limit of accuracy required by contract during the first and second-pour (as applicable) during new construction. Concrete tolerances in the ± one-eighth to one-quarter inch range are common. Zero tolerance can be specified in contracts where both in-house and contract forces are sufficiently experienced and equipped to implement the tightest tolerances.
Corrosion	The process of wearing away the surface of a solid, especially of metals, by converting the compact, cohesive substance into a friable one as a result of chemical action or the surface action of moisture. See **Galvanic Corrosion**, **Electrolytic Corrosion**, **Stray Current**, **Electrochemical Reactions**.
Corrosion Test	A fastener qualification test that exposes the fastener system to salt or an acid liquid, either as a spray or in a bath test. The test is an accelerated test of corrosion resistance.
Coupling Dynamic Coupling (Dynamics)	The interaction between elements of a physical system (e.g., a rail vehicle and the track on which it operates comprise a coupled dynamic system, because the dynamic behavior of the vehicle influences that of the track and vice versa.
Critical Damping	The amount of damping of a vibratory mode in a physical system for which an excited system returns to its equilibrium state in minimum time and without oscillation. The damping ratio for a critically damped system is 1.0.
Critical Frequency	Resonant frequency.
Crosslevel	The vertical distance between horizontal lines from the top of each running rail. Generally, this term refers to variations in track from the design **superelevation** and non-elevated track.
Curing (Elastomers):	Chemical processing of elastomer materials. For rail fastener materials (largely made of natural or synthetic rubber), **curing** uses vulcanization processes or processes similar to vulcanization (see **Vulcanization, Sulfur Curing, Peroxide Curing**)
Damped Natural Frequency	The resonant frequency of a damped mechanical system, which generally is lower than the undamped natural frequency.
Damping	The process by which oscillations of a mechanical system steadily diminish in amplitude over time due to the dissipation of energy, usually through friction.
Damping Ratio	The fraction of actual damping to the value of critical damping for a mechanical system.
Day-Night Sound Level (L_{dn})	The L_{eq} of the A-weighted noise level over a 24-hour period with a 10 dB penalty applied to noise levels between 10 p.m. and 7 a.m.

Decibel (dB)	The decibel is a measure on a logarithmic scale of the magnitude of a particular quantity (such as sound pressure, sound power, sound intensity) with respect to a standardized reference quantity.
Degrees of Freedom	The number of independent motions in which a mechanical system can respond to an excitation.
Direct Fixation Fastener:	A sub-category of **elastic fastener** where the fastener attaches immediately to a rigid support (concrete invert, concrete deck, floating slab, open deck structure). Direct fixation systems are systems that do not use ballast. **Resilient Fasteners** and embedded concrete blocks with elastomeric boots (embedded in invert concrete notches) are within the general definition of direct fixation fasteners.
Driving Potential	Voltage.
Dynamic to Static Test	A fastener qualification test that measures the ratio between the stiffness obtained from dynamic vertical loads and the vertical stiffness obtained from the **Vertical Load Test** (a static load test). This test intends to limit elastomer idiosyncrasies which are: **non-linear** under static loading, stiffness sensitivity to dynamic loading and stiffness sensitivity to the amount of strain introduced by deflection. The goal is obtain a dynamic stiffness as close to the static stiffness as possible. Most specifications allow the dynamic stiffness to be 1.5 times the static stiffness. The governing criteria for the Dynamic to Static Stiffness ratio is ground-borne vibration considerations. The engineer that is responsible for ground-borne vibrations typically calculates a fastener stiffness for quasi-static loading. The engineer sets a Dynamic to Static Stiffness value to control the possibility the calculations may be invalidated if the in-service stiffness is much different than the specified value based on static tests. For the same reason, this test is conducted after one of the other “aging” tests to replicate a fastener condition that is less than optimal.
Eigenvalue, Eigenvector, Eigen functions	The natural frequencies and mode shapes, respectively, of a vibrating mechanical system.
Elastic Fastener System:	Any rail fastening system that includes an **elastic rail clip**. This term encompasses a broad class of track fastener systems (many of which are not direct fixation systems) and is often a source of confusion (and mis-communication) where the intent is to refer to more specific components or types of components. Improper equivocation frequently occurs between this term and **resilient fastener**, **direct fixation fastener**, **bonded fastener**, and **elastic rail clip**.
Elastic Foundation	A uniform support for a mechanical system that behaves in an elastic manner. This is an assumption used typically for the ballast/subgrade in modeling and analysis of vehicle/track interactions.
Elastic Rail Clip:	A mechanical spring designed to hold a rail to its support (tie plate, elastomer plate, tie, etc.), providing continuous contact with the rail and the support during restraint of rail rotation and longitudinal rail movement. Equivalent terminology: Rail Clip, Elastic Clip.
Elasticity	The degree to which a deformed body returns to its undeformed shape after a load is removed.
Elastomer:	Any member of a class of synthetic polymeric substances which, in the vulcanized state, can be stretched repeatedly to at least twice its original length and, upon release of the external load, will immediately return to approximately its original length.
Elastomeric Plate	See **bonded fastener**.

Electrical Resistance and Impedance Test	A fastener qualification test that measures the fastener insulation properties. The test is generally conducted in dry and, separately, wet test conditions. The purpose of the test is to determine whether the fastener meets specified insulation requirements. The insulation requirements are governed by **stray current** considerations.
Electrical Resistivity (soils)	ohm-cm
Electrochemical Reactions	Chemical changes that are associated with the passage of electrons across interfaces between metal and solution. A process whereby electrical energy is converted directly in to chemical energy is one of electrolysis; i.e. an electrolytic process. The process may take may forms. For transit applications, the process of greatest concern is chemistry changes from positive ion migration at a pipeline or structural steel to a current leakage point on the negatively charged rail. This process is accelerated in the presence of highly conductive ground conditions (such as with high water tables) and acidic ground conditions. In practical terms for transit, as **stray current** leaves one metallic conductor (the rail) to pass into moisture-containing earth en route to another conductor, it removes a portion of the conducting metallic surface.
Electrolytic Corrosion	Corrosion where a solid substance is dissolved in a suitable solvent becoming an ionic conductor. A bi-directional process of electron transfer between a system with (1) applied DC current, (2) a negatively charged electrode (cathode), (3) a positively charged electrode (anode), and (4) an intervening electrolyte. The cathode can be a rail; an anode can be a pipeline or steel in a structure. The bi-directional electron transfer occurs as positive ions migrate to the negative electrode, while negative ions migrate to the positive electrode. The overall effect of the two processes is the transfer of electrons from the negative ions to the positive ions, a chemical reaction. See **Electrochemical Reactions**.
Embedded wood block systems (in concrete inverts):	This type of system may be a direct fixation system because it "fits" the definition. However, this system does not necessarily require an elastic rail clip (and usually does not). This is a compromise system that defies narrow definition. However, its successful longevity (well over 50 years in Chicago tunnels without maintenance) requires its inclusion in our thinking.
Emergency Protection Rails	Rails installed either between two running rails or on a bridge deck to prevent trains from falling off the structure. Also used at tunnel portal entrances or other hazardous locations where derailment can cause excessive damage to equipment and structures.
Endurance limit:	The maximum stress for infinite fatigue life.
Energy Equivalent Level (L_{eq})	The level of a steady noise which would have the same energy as the fluctuating noise level integrated over the time period of interest. L_{eq} is based on the logarithmic or energy summation and it places more emphasis on high noise level periods than does L_{50} or a straight arithmetic average of noise level over time. This energy average is not the same as the average of sound pressure levels over the period of interest, but must be computed by a procedure involving summation or mathematical integration.
Fastener Body	An **elastomeric plate**. A **bonded fastener.** The rail support component of a **resilient fastener system**. The term "fastener body" refers to a single component of bonded steel and elastomer. The fastener body provides the rail support in a **resilient fastener system**. The terminology is inherently confusing because the rail support component of many Direct Fixation Fastener systems can be bonded or unbonded (elastomer sheet sandwiched between steel plates). The use of other terms to refer to the fastener body is frequent, such as **elastic fastener** and **resilient fastener**. While the local terminology refers to specific designs that are reasonably understood by constituents within a specific agency, caution in these terms is useful in limiting interpretation permutations when dealing in contracts, outside engineers and others external to the agency.

Fastener Qualification Tests	A battery of tests on prototype fasteners that evaluate the design of the fastener material, geometry and performance characteristics (spring rates, damping, fatigue resistance). Fastener qualification tests verify only the design of the fastener. Fastener qualification tests are not production quality control procedures (although some aspects of the qualification tests are incorporated in checking production run fasteners).
Fastener Resistance	The electrical resistance of a single fastener between the rail and the fastener's support. Fastener Resistance unit of measure is ohms.
Fastener Spacing	The distance between adjacent fasteners on the same rail
Fastener Vertical Spring Rate	$K = (A * E_c)/t$ K = Compression Spring Rate E_c = Compression modulus of elastomer A = Projected load areas of elastomer t = elastomer thickness
Female Insert:	An internally threaded component that is designed to anchor a threaded fastener such as an anchor bolt to a concrete support.
Fillers (for elastomer materials):	Substances compounded in elastomers to improve elasticity and tensile strength. The main filler for rubber-based products is carbon black which may make up 50% of the volume of the finished component. Silica is an excellent filler for extending the temperature range of elastomers, but is expensive.
Floating Slab Track	A system of track support integrating the DF fastener and isolators on the slab which is pre-cast, cured, and laid in-place on a fully prepared high-strength concrete invert supporting structure. The slab is allowed to deflect vertically under train load. Forces are absorbed by a set of rubber encased "donuts" positioned between the slab and structural invert; hence the name "floating slab". The slab serves as a mechanical filter for vibration energy, typically isolating higher frequencies and converting them into low frequency vibrations. WMATA was among the first to use this type of construction in the U.S. (both first and second generation) followed by a number of other properties including MBTA, TTC, NFTA, MARTA, LACMTC, BART and elsewhere. The first generation slabs have "sunk" over time at several properties (WMATA and MBTA Red Line) due to a combination of donut failure and geothermal instability. The first floating slab designs had no quick and easy way of replacing donuts by jacking the slab and accessing the void. The second generation re-design enables relatively efficient maintenance for replacement of donuts and other purposes.
Forced Vibrations	The dynamic response of a mechanical system to an applied steady force, such as that generated by random track surface geometry errors or dipped rail joints.
Forcing Function	The mechanical description of a time-dependent applied force.
Forward Transfer Impedance	The ratio of the sinusoidal force magnitude transmitted by a blocked base plate to the input top plate sinusoidal velocity magnitude, measured at the rail web. This a method developed by Wilson Ihrig Inc. for measuring the **vertical dynamic stiffness** of elastomeric fasteners. Note that the term impedance is an electrical engineering term and an acoustical engineering term that is not found in formal mechanical engineering texts for dynamic analysis (that is, don't bother looking for "impedance" in a dynamics text). The "impedance" terminology is analogous in mechanical engineering to **transfer function** that, with acknowledgment of the developers license to coin their own phraseology, allows useful understanding of the term.
Free Vibrations	The dynamic response of a mechanical system to a suddenly applied and removed load (e.g., a single impact load).

Frequency (Hz)	The number of oscillations per second of a periodic vibration (mechanical) or noise (acoustical) expressed in Hertz (abbreviated Hz). Frequency in Hertz is the same as cycles per second.
Frequency Ratio	Generally used to describe the ratio of the excitation frequency to the natural frequency of a mechanical system.
Frequency Response	The response of a mechanical system over the range of frequencies important to the system's function. See **natural frequency**, **resonance**.
Friction Damping	Attenuation of vibration of a mechanical system caused by sliding friction.
Galvanic Corrosion	Corrosion where direct-current electricity produces chemical changes. See **Electrochemical Reactions**.
Grout Pad	A raised rectangular platform which supporting the DF shoulder with threaded male stud or **female insert** assembly. Grout pad is usually "formed-out" after first concrete pour which created invert supporting structure. A concrete bonding agent is usually used between grout and concrete to insure against delamination of two dissimilar materials. Rail rests on top of anchoring hardware flush with concrete grout pad with or without an elastomeric pad.
Half Space	A semi-infinite body, typically assumed for the ballast/subgrade when evaluating track response.
Harmonics	Frequencies that are integer multiples of a primary vibrating frequency.
Heat Aging	A fastener qualification test that exposes fastener components (primarily elastomers) to elevated heat soaking for extended time periods. The test procedure generally precedes a subsequent test (for a specimen in an aged condition) and has minimal pass-fail requirements (usually only annotation of visible condition).
Helical Spring Lock Washer	A washer design with one or more coils within the general class of springs that accommodate compression loading (as compared to springs designed for tension loading or torsional loading). Lock washers incorporate a bolt or nut engagement protrusion (a sharp edge or serrations) intended to supplement bolt/nut back out friction resistance.
High Restraint Fastener	**Elastic Fastener Systems** with maximum longitudinal rail restraint allowed by the particular fastener design. Generally, the term is invoked in projects that use both a low restraint system and a normal, maximum restraint, fastener. The term distinguishes between the normal fastener and the **low restraint fastener** deployed on that project.
Hold Down	A colloquialism for the set of hardware components which typically include **anchor bolt** and **female Insert** providing a rigid mechanical support between either the bottom of the **shoulder** or **bonded/ unbonded plate** to the supporting structure (e.g. concrete invert or timber block).
Horizontal Alignment (track)	The design curvatures and connecting tangents that comprise the railroad route. Depending on the context, the term may refer to deviations of the track from the design alignment.
Inelasticity	The properties of a material that do not behave in an elastic manner.
Insert Coating	A qualification test (and usually a production test also) of **female insert** coating. Typically, corrosion control specifications require an epoxy based coating on the exterior of female inserts for elimination of **stray currents** as well as corrosion protection of the insert itself.

Insulator	An insulating component between the elastic clip and the top of the rail base, overlapping the rail base edge and interlocking with the fastener's body or shoulder. Same as **rail insulator**. See **shoe**.
Insulated Joint	Signal block isolation where the running rail provides negative ground return necessitates the need for a rail joint which is electrically isolated. Most of today's **insulated joints (IJs)** make use of epoxy on fiberglass reinforced materials which are factory bonded with a rubber encased steel joint bar to add girder strength/stability. The bar is not eliminated and hence the need for a **"J" clip** where **spring clips** are specified and installed.
Invert	Generalized term for poured concrete base structure.
"J" Clip	Special **spring clip** designed to accommodate a rail joint bar protruding below the rail fillet region at the base. Similar to the **"E" clip** except for the shape of the fastener "neck".
L/V Ratio	The ratio of lateral to vertical dynamic forces applied by wheel contact at the gage face of the rail head on a curve. When this ratio exceeds a critical value, derailment can occur. A threshold value typically used is 0.4 to insure safe wheel/rail contact.
L_1, L_{10} L_{50}, L_{90}, L_{99}	The noise or vibration levels that are exceeded for 1%, 10%, 50%, 90% and 99% of a specified time period. Environmental noise is often described in these terms.
Lateral Load Test	Fastener qualification test that measures the combined rail lateral translation of stiffness and rail rotational stiffness as a single value under static loading.
Lateral Restraint Test	Fastener qualification test that measures the lateral translation stiffness (the stiffness without rail rotation) under static loads.
Lateral Stiffness (elastomeric fasteners):	The stiffness of an elastomeric fastener perpendicular to the rail vertical and longitudinal planes, generally from loads applied at the rail base. If the fastener incorporates a canted rail seat, the stiffness is generally measured in a plane parallel to the bottom of the elastomeric fastener (rather than perpendicular to the rail vertical centerline).
Lateral Fastener Stiffness	K = (A * G)/t K = Shear spring rate (lb/in) G = Shear modulus of elastomer = Shear Stress/Shear Strain (within proportional limit) (Shear Stress = applied load/sample X-sect. area) (Shear strain is expressed as: $\varepsilon = \frac{\delta}{t} * 100$ ε = shear strain (%) δ = Shear deflection t = elastomer thickness) A = Projected load areas of elastomer t = thickness of elastomer
Leakage Resistance	The electrical resistance of the track between the rail and ground over a standard track length. Leakage resistance units of measure are ohms per standard length. The standard length is usually 1000 track feet. The required resistance is governed by **stray current** considerations

Linear, Linearity:	A descriptive term for a mathematical relation that produces a straight line. For elastomeric fasteners, the term usage generally refers to the straightness of stiffness (load-deflection) characteristic curves. The importance of linear relationships is higher confidence in engineering predictions of response and performance. Elastomers can be highly non-linear and the linearity can vary with load rates (as in highly dynamic railroad environments) and temperature to the point of loss of confidence in even sophisticated engineering predictions.
Longitudinal Profile (Track)	Track geometry variations in the vertical plane from the **track profile**. See **vertical track profile**. The term refers to very long deviations in the track that are measured as offset from a chord that is 31 feet or longer. See **longitudinal rail profile** (short variations in rail surface).
Longitudinal Rail Direction	Parallel to the principal rail axis in the direction of train traffic.
Longitudinal Rail Force:	The state of force in the rail longitudinal direction from train loads or from thermal expansion. The definition of longitudinal force in fully constrained rail from thermal expansion only is $P = EA\alpha * \Delta T$ $\boldsymbol{P}$ = Force in fully constrained rail (lb) $\boldsymbol{E}$ = Young's Modulus, Modulus of Elasticity, of steel (30 x 10^6 psi) $\boldsymbol{A}$ = Rail cross sectional area (in^2) α = Steel coefficient of expansion (6.33 x 10^{-6} in/in/^{o}F to 6.7 x 10^{-6} in/in/^{o}F) $\Delta \boldsymbol{T}$ = Rail Temperature difference between the neutral temperature and the actual temperature of the rail (^{o}F).
Longitudinal Rail Profile	The variation of the rail running surface from a uniform line. A measurement of rail surface roughness and rail corrugations. This measurement characterizes short rail surface features between 1" to 72" in length with variations as little as 0.001" from a uniform line. This measurement is distinct from **Longitudinal Profile (track)** which measures overall vertical geometry of track relative to a baseline of 15 to 70 feet.
Longitudinal Rail Restraint:	Restraint provided by a rail fastener against movement in the longitudinal rail direction. For elastic fasteners, longitudinal restraint is defined as $R = \mu * 2T$ $\boldsymbol{R}$ = Longitudinal Rail Resistance (lb) per rail seat. $\boldsymbol{\mu}$ = Coefficient of Friction (the effective coefficient of friction is the larger of that between the rail and the rail clip/insulator, or between the rail and the supporting tie pad or tie plate). $\boldsymbol{T}$ = Toe Load (lb) of one rail clip.
Longitudinal Restraint Test	A fastener qualification test that measures the **longitudinal rail restraint** and the longitudinal fastener stiffness of the fastener system under static loading. Vibrations that normally occur in track can significantly reduce the longitudinal restraint of systems with elastic rail clips. In 1994, the American Railway Engineering Association adopted an additional longitudinal restraint test that imposes vibrating load while the longitudinal restraint is measured. This requirement is appearing in some transit specifications (Portland Westside Extension) as well.

Low Restraint Fastener	**Elastic Fastener Systems** designed with less **longitudinal rail restraint** than potentially available from the fastener design. Low restraint fasteners are applicable on tall aerial structures to reduce longitudinal load transfer to piers, thereby reducing structure construction costs. See also **Zero Longitudinal Restraint Systems**.
Low Vibration Track	A complete system of track using a rigid-bolted DF fastener with the **hold-down** bolt applying rail compression force through a top plate assembly where the **anchorage** is held by a **female inset** set in an independently floating concrete block. Alternatively, a **spring clip** version is specified by most North American transit properties. Rubber boots encase the blocks which move vertically within their deflection range and rest on micro-cellular pads. Structural support is provided by two pours of concrete forming the invert on the second pour. LVT systems and their prior permutations are in use at SEPTA, MARTA, DART, Tri-Met and elsewhere where vibration attenuation and low maintenance is the objective in stations, tunnels and at-grade.
Matrix (Dynamics)	Mass, stiffness, damping matrices
Methylmethacrylate Resin	A bonding agent used to insure lamination of dissimilar materials such as concrete to concrete poured at different times, injection grout with concrete and steel to concrete. Primarily used for bonding two concrete surfaces. WMATA reports excellent results using this high-tensile strength resin where other methods and materials have failed. The two primary applications in use are, a) to promote bond between **female insert** and **grout pad**; and, b) to prevent delamination between **grout pad** and **concrete invert**. Material is highly toxic until cured and should be applied with proper protective clothing and breathing apparatus.
Modulus of Elasticity:	The response of a material to a force of known cross section to a specified elongation. In steels, the elongation is 0.2% of the specimen's unloaded length. In elastomers, the elongation is 100% to 600% of the unloaded specimen length.
Natural Frequency	In mechanical systems, the primary or "fundamental" frequency of response to force. In track systems, the fundamental or natural frequency is associated with the overall track stiffness and mass.
Neutral Temperature:	The rail temperature at which there is no longitudinal force in a fully constrained rail (i.e. as in continuously welded rail track).
Noise Reduction Coefficient (NRC)	A measure of the acoustical absorption performance of a material, calculated by averaging its sound absorption coefficients at 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz.
Octave Band -- 1/3 Octave Band	One octave is an interval between two sound frequencies that have ratio of two. For example, the frequency range of 200 Hz to 400 Hz is one octave, as is the frequency range of 2000 Hz to 4000 Hz. An octave band is a frequency range that is one octave wide. A standard series of octaves is used in acoustics, and they are specified by their center frequencies. In acoustics, to increase resolution, the frequency content of a sound or vibration is often analyzed in terms of 1/3 octave bands, where each octave is divided into three 1/3 octave bands.
Oil Test	A fastener qualification test that exposes elastomers to oil. Natural rubber softens when exposed to oil. While petroleum products are added to rubber formulations to produce desirable hardness characteristics, the formulation also contains substances that reduce future absorption of oil that will change the designed characteristic.
Overturning Moment	The moment of inertia required to force a rail section to overstress the **spring clip** or **bolted fastener** to the yield point where it can rotate on its axis (the rail base) and cause the rail head to rotate toward the field side of the rail.
Ozone Test	A fastener qualification test that exposes fastener components to elevated ozone levels. Natural rubber, the most frequently used base material for Direct Fixation Fasteners, is susceptible to deterioration in naturally occurring levels of ozone. The chemical formulation includes **antioxidants** and **anti-ozone** ingredients to inhibit natural rubber absorption of ozone.

Period	1/frequency
Peroxide Curing:	Curing process for some synthetic rubbers (elastomers) that is similar to vulcanization but uses peroxide as the curing agent rather than sulfur.
pH	A measure of the acidity or alkalinity of a solution. 7 = neutral, increasing with increasing alkalinity and decreasing with increasing acidity. Range is 0 to 14.
Phase Angle	The delay between two oscillatory signals at the same frequencies.
Plastic, Plasticity	Unrecoverable deformation of a body.
Plasticizers:	Compounding substances used to soften elastomers. Mineral oil, bitumen, Vaseline, fatty acids and wood resins are among substances used for plasticizing rubber.
Push-Pull Longitudinal Test	A fastener qualification test that is similar to the **longitudinal restraint test** but is repetitive, the loads are above the slip load (see **longitudinal restraint capacity)** and fully reverse. The test "saws" the rail back and forth across the fastener under full slip to determine whether detrimental wear or other deterioration occurs in the fastener components. This test is necessary for systems with elastic rail clips because they inherently have insufficient longitudinal restraint to fully constrain the rail from movement for many transit operations. The test therefore is a check on possible related occurrences. This is a static test.
Quarter-Wave Resonance Frequency	Referring to Elastomeric Direct Fixation Fasteners: The frequency where the elastomer thickness is 1/4 of the vibration wave length. This frequency is defined by: $$f = \frac{\sqrt{E_o}}{4t\sqrt{\rho}}$$ Where: f = quarter-wave frequency (Hz) E_o = Dynamic Compression Modulus of Elastomer (psi) t = Elastomer thickness (inch) ρ = Density of the Elastomer (lb/in^3) The lower the 1/4 wave frequency, the more noise reduction is achieved.
Rail Anchor	1. Direct Fixation Fastener applications: A special track device that rigidly constrains the rail from longitudinal rail movement. The rail anchor is typically used in conjunction with **low restraint** or **zero restraint fastener** systems on elevated guideways. The rail anchor serves as a control point for longitudinal rail movement and is placed strategically to transfer the least load to the support structure. The rail anchor bolts to the rail and to the concrete or steel support in a manner that allows no relative motion of the rail to the support structure at the rail anchor. 2. General railroad applications: A drive-on, single piece clip that develops high longitudinal rail restraint by cam-locking mechanism between the clip, the rail and the rail support (usually a cross tie).
Rail Clamp	Generally, this term means **rigid rail clip**. Colloquial use varies
Rail Clip	See **elastic rail clip**, **rigid rail clip**
Rail Fastening System:	A system of components designed to resist lateral and longitudinal rail movement and restrain rail rotation, while providing vertical support.

Rail Insulator	An insulating component between the rail clip and other rail fastener components. Typically used to describe the component that is placed between the toe of the rail clip and the rail base top; the rail insulator usually overlaps the rail edge and insulates the rail laterally between the rail and fastener shoulders or other lateral restraint protuberances.
Rail Roll-Over	A dangerous rail failure mode which seldom occurs in transit. This condition is correlated with a combination of interaction forces associated with the wheel-rail dynamic in sharp curve territory, where high point loads are generated, with rigid trucks and poor curve negotiation leading to low side **creep forces** and **angle of attack** problems on the high side, and loss of DF restraint at the *systems/cluster level*. One or more combinations of forcing factors - including thermally induced stress - can result in a roll-over mode to relieve the stress and strain especially when the DF fastener has high longitudinal restraint and the rail is CWR. This phenomenon is usually associated with heavy haul railroad axle loadings which can accelerate the elastic fastener **overturning moment** and yield forces with loss of one of more clips. A variety of techniques are currently under study to prevent rail-roll over in the future.
Rail Resistance	Rail electrical resistance. Rail resistance unit of measure is ohms per rail length
Rail Seat	The portion of the supporting fastener (**fastener body**, **tie pad**, **tie plate**) that is in direct contact with the bottom of the rail base. The context of this term's usage can refer to the area below the fastener that is within the foot-print of the rail base, such as "the fastener bearing surface on the concrete slab within the rail seat area ...".
Rail Seat Pad	Resilient pad between rail base and DF fastener body to provide mechanical and electrical isolation (usually elastomeric material).
Rail Wear Limits	The amount of rail wear for condemnation of a rail. Head wear usually refers to vertical wear on the top of the rail; side wear (gage wear, flange face wear, face wear) is the wear at the gaging point on the rail head (see **track gauge**).
Repeated Load Test	A fastener qualification test for fatigue. Typically, the test involves compound vertical and lateral load on a full fastener assembly for 3 million cycles. See also **Uplift Fatigue Test**.
Resilient Fastener:	Direct Fixation Fasteners that use an elastomeric element between the rail and the support.
Resonance	In mechanical engineering, the condition(s) where a mechanical system of components produces an amplified response ("output") greater than the forcing function ("input"). In simple systems, resonance occurs at the mechanical system's **natural frequency**. In more complex systems such as railroad track coupled with rail vehicle systems, the system can have amplified responses at several frequencies where the natural frequency of the overall track stiffness will be among the largest responses, accompanied by **secondary frequencies.** Secondary frequencies can be multiples of the system's natural frequency (a harmonic) where the first natural frequency becomes the "fundamental frequency". The natural frequencies of individual components in the system can produce secondary resonant frequencies in the system's response that are important to some track mechanics such as rail corrugations.
Resonance Frequency	Natural frequency.
Restrained Insert Test	A construction quality control test for the pullout resistance of the **anchor bolt** from base concrete, or female insert in the base concrete. The load is between a reaction plate on the concrete base (invert or guideway surface) and the anchor bolt head (or a nut if a threaded stud). The plate has a centered hole slightly larger than the anchor bolt diameter. See **Unrestrained Insert Pull-out**.

Restraining Rail	This term is often used interchangeably with **Guard Rail**. At least one property (NYCTA) uses the guard term interchangeably with the restraining rail. However, most properties consider the **restraining rail** to be an **emergency protection rail.** **Restraining rail** is used on the low side of sharp curves to reduce the wheel-rail lateral ("back-to-back") forces generated between wheel and rail. The DF fastener must accommodate a **separator block** between the **guard rail** and low side running rail while maintaining proper flangeway gap. For example, NYCTA designates its **resilient plates** as "B" and "D" depending upon whether **embedded track** fastener/plate configuration is used on a curve. The "D" plate is an assembly of guard rail brace and plates together with a **spring clip** on both field and gage side of the assembly.
Rigid Clamp	Same as **rigid rail clip**
Rigid Rail Clamp	Same as **rigid rail clip**
Rigid Rail Clip	A rail clip design that does not deflect under load. An inelastic rail clip. Rigid rail clips are typically cast steel or ductile iron blocks held by a bolt to a support base or plate. The block bottom face has locking serrations that engage mirror serrations in the surface of the support base or plate.
RMS	Root Mean Square
Rotational Stiffness (elastomeric fasteners):	The stiffness of an elastomeric fastener rail rotation about the edge of the rail base from combination loading (lateral & vertical) at the rail head. Rotational deflections should be reported as angular deflections, but are not in some specifications. Caution: rotational stiffness values between specifications can vary substantially with the placement of the combination of loads used in testing.
Secondary frequencies	In mechanical systems, system responses to forces at a frequencies other than the **natural frequency** of the system. See **Resonance**.
Separator Block	On sharp curves, cast steel blocks which insure close flangeway tolerances between low side running rail and guard rail. Curvature dependant range for standard 115RE section is 1 3/4" to 2 1/4" measured at the gage point 5/8" below rail head. Blocks conform to the fillet region of both rail sections and are typically bolted in-place through the web. Alternatively, fully "Pandolized" assemblies rely on clamping force.
Shape Factor (elastomeric materials):	The ratio of constrained surface area to surface area that is free to move of an elastomeric component. For example, a flat, rectangular elastomeric material is sandwiched between two flat plates with the area of the top and bottom elastomer sides. The side perimeter of the elastomer is free to bulge. The shape factor is the ratio of the top and bottom (constrained or loaded) surface areas to the side perimeter areas that are free to move.
Shims or Filler Plates	Steel or plastic plates used to raise the track to desired **profile**, metal or plastic rectangular plates supplied in one-eighth increments up to an inch. Premium shims are galvanized or chrome-plated steel. Premium materials resist corrosion and are therefore preferred. Shims are usually allowable during new construction between the invert or **grout pad** and **plate**, but are discouraged. Rather, a "zero" tolerance specification for both **alignment** and **surface/profile** can avoid the use of shims. In practice, this is difficult to achieve. One way of encouraging contractors to meet tight construction tolerances is to specify the use of premium shim materials without allowing line-item payment over and above the contract price.
Shoe	A cast steel or elastomer (or combination of steel and elastomer) component between the top of the rail base and an **elastic rail clip**. The shoe shape conforms to the rail base top and side, with interlocking shapes (dogs) to the fastener body, shoulder or plate design.
Signal Circuit	The physical circuits that make up the wiring for the **Signal System** including **Track Circuits**.

Signal System	The wiring, relays, logic boards, aspect displays and controls that govern train movements.
Sound Pressure Level (SPL)	The sound pressure level of a sound in **decibels** is 20 times the logarithm to the base 10 of the ratio of the RMS value of the sound pressure to the RMS value of a reference sound pressure. The standard reference sound pressure is 20 micro-pascals (ANSI S1.8-1969, "Preferred Reference Quantities for Acoustical Levels".
Spring Clamp	See **Elastic Rail Clip**
Spring Rate:	equivalent to **stiffness**.
Standard Track Length	A track length used in stray current and track circuit calculations to determine the overall track resistance for a fastener electrical resistance. The most common standard track length is 1000 track feet.
Stiffness:	The mechanical ratio of load to deflection of a mechanical (usually spring or elastic) component. In the context of elastomeric rail fasteners, the stiffness (see **Vertical Stiffness**, **Lateral Stiffness**, **Rotational Stiffness**) refers to the fastener's properties but are measured deflections of a rail for loads applied to the rail while mounted on the fastener.
Stray Current	Electrical leak in the transit system. The term's widest usage applies in electrified systems where the running rail is the negative return conductor. Transit engineering considerations are • propulsion power levels at all locations under the worst power surges created by the transit operation. • Nearby corrosion-sensitive facilities (gas pipe lines, water pipe lines, structures, etc.) • Track insulation.
Sulfur Curing:	Curing process using sulfur as the curing agent in a time, temperature and pressure controlled environment.
Superelevation	The vertical distance between horizontal lines from the top of the inner and outer rail in curves.
Threaded Fastener System	See **Bolted Fastener System**
Threadless Fastener System	Any elastic fastener system that does not use a bolt (or other threaded component) to hold the **elastic rail clip** in position.
Toe Load:	The clamping load generated by an elastic rail clip on a rail base.
Track Circuit	Portion of the **signal system** that is part of the track structure including, primarily, the running rail.
Track Gauge, Track Gage	The distance between running rail measured at the rail head side facing the track centerline at the specified gage point. The gage point is 5/8" below the plane made by the top of running rail for heavy rail transit, most light rail transit and freight railroads. The gage point is 3/8" below the plane made by the top of running rail for trolley systems.
Track Modulus	An approximate bulk property describing the slope of the elastic stress versus strain curve for the ballast/subgrade.
Track Profile	Vertical design geometry of railroad track depicting gradients, elevations and vertical curves. See **vertical track profile**.
Track Stiffness	The effective spring rate associated with a track structure.
Train Control System	See **Signal System**

Transfer Function	The engineering relationship between the forces "input" to a mechanical system and the response, or "output", of the system. The mechanical system is described mathematically by inter-related matrices of masses, stiffnesses, and damping characteristics associated with the system's components. The output response can be characterized in terms of either deflection, velocity or acceleration. The primary purpose of transfer functions is analysis of system **resonance** or **frequency response**, although the analysis method allows insight into related issues such as fatigue.
Ultimate tensile stress:	The failure stress in tensile loading
Unbalance Speed	See **Balance Speed** The allowable speed prescribed by the Chief Engineer which enables trains to exceed balance speed by an amount which does not compromise safety where U is the desired unbalance superelevation in a curve, R is the curve radius, and E is the superelevation: To find **unbalanced speed**, or velocity, (V) in MPH: V= 0.5 Sqrt((E + U) $\times$ R)
Unrestrained Insert Pull-Out Test	A construction quality control test for the pullout resistance of the **female insert** for anchor bolts. An anchor bolt is loaded in tension between a reaction plate on the concrete support and the anchor bolt head (or nut if a stud). The reaction plate spans a distance that is twice the depth of the female insert's embedment in the support plus the insert's largest diameter. The test determines whether the insert bonding to the concrete support meets specification. See also **Restrained Insert Test**.
Uplift Fatigue Test	A fastener qualification test similar to the **Uplift Test**, but conducted repetitively to determine whether the fastener (primarily rail clips) loose restraint properties under cyclic loading.
Uplift Test	A fastener qualification test that measures the vertical stiffness of the fastener assembly under static uplift load. In **elastic fastener systems**, the uplift stiffness is primarily the **elastic rail clip** spring rate (for two clips) above the installation load. See also **Uplift Fatigue Test.** The test confirms the fastener system design includes restraint for upward forces on the fastener components that occur during rail rotation and during the passage of the precession wave adjacent to a wheel load.
Velocity Level	Also referred to as the "vibration velocity level." Vibration velocity is the rate of change of displacement of a vibration. The velocity level is 20 times the logarithm to the base 10 of the ration of the RMS value of the velocity to the reference velocity. A reference velocity may be 10^{6}in/sec. Above approximately 10 Hz, human response to vibration is more closely correlated to the velocity level than the acceleration level. Therefore, ground-borne vibrations (those more "felt" than heard) are reported in terms of velocity levels, while air-borne noise (that heard rather than "felt") are reported in terms of **acceleration levels**.
Vertical Load Test	Direct Fixation Fastener qualification measurement of fastener vertical stiffness (or spring rate).
Vertical Stiffness (elastomeric fasteners):	The stiffness of an elastomeric fastener from loads and deflections measured in the rail's vertical axis. If not stated explicitly otherwise, this stiffness value is measured with no rail cant.
Vertical Track Alignment	See **Track Profile**.
Vertical Track Profile	Track geometry in the vertical plane. Depending on the context, the term either means the **track profile** (designed track geometry) or variations of the track from the designed geometry.

Viscous Damping	Damping for which the force is linearly proportional to the rate of displacement or deformation.
Voltage Withstand Test	Fastener qualification test that measures current flow through the fastener under very high voltages (10,000 Vdc, typically). The purported reason for this test is verification the fastener will provide adequate insulation if a power line falls across the rail. Another reason suggests the test provides an indication of long term insulation performance of the fastener. Both reasons may be argumentative because more direct tests of fastener insulation are available (see **electrical resistance and impedance test**).
Vossloh Fastener	A proprietary elastic rail fastening system with a "W" shaped elastic rail clip that is retained by a bolt.
Vulcanization:	A chemical process by which the physical properties of natural or synthetic rubber are improved. In its simplest form, vulcanization is brought about by heating rubber in sulfur (see **Sulfur Curing)**. In the process discovered in 1839 by Charles Goodyear, sulfur chemically combines with rubber mostly in the form of cross-links, or bridges, between the long-chain molecules of the raw elastomer material. Modern processes add substances to accelerate (**accelerators)** curing, carbon black or zinc oxide to improve or change rubber qualities, **anti-oxidants** to retard deterioration caused by oxygen and ozone.
Water Absorption	A fastener qualification test that measures fastener swelling in a submerged bath for an extended period. Properly formulated fastener materials will swell about 1½% after 100 hours in 70° C bath.
Weighted Velocity Level	The vibration velocity level to which a weighting factor is added. The weighting de-emphasizes the low frequencies in a manner similar to human response to vibration. There is no internationally recognized velocity weighting filter.
Young's Modulus	Also known as the modulus of elasticity, the slope of the stress versus elastic strain curve for a material.
Zero Longitudinal Restraint Systems:	A special category of Direct Fixation Fastener that is designed to have zero longitudinal restraint. Zero Longitudinal Restraint Systems are virtually all resilient fasteners, but may be of other designs under this definition.

Appendix B
Request for Information on
Direct Fixation Fasteners

On April 21, 1995, Agencies were sent a request for the following information:

1. Design Criteria
    - 1.1 Formal
        - 1.1.1 Civil
        - 1.2.2 Structural
        - 1.2.3 Vehicle
    - 1.2 Not in Published Criteria

      Rail Neutral Temperature (DF Track Construction Specification), Broken Rail Gap Criteria, Noise, Ground-borne Vibrations Technical Reports and Recommendations

2. Direct Fixation Fastener Procurement Specification

    - 2.1 Qualification Specification
    - 2.2. Supplier/Contractor Submittals on Direct Fixation Fasteners (Drawings, Qualification Test Reports - particularly load-deflection test results)

3. Track Charts with DF Fastener Track Annotations

4. Installation Requirements (Direct Fixation Fastener Track Construction Specification)

5. Maintenance Requirements, Practices: Maintenance of Way Rule Book, Track Inspection Methods/Techniques/Practices, etc.

6. Observed Direct Fixation Performance
    - 6.1 Description of Direct Fixation Problems
        - 6.1.1 Problems with DF Fasteners
        - 6.1.2 Track Problems Attributed to DF Fasteners
    - 6.2 Characterization of Failures of DF Fastener Components
        - Failure rates DF Fasteners by components (rail clips, plates, anchor bolts)
        - Failure Environment (Surrounding Track, Operating Conditions Affecting Failures).
    - 6.3 Lessons Learned
        - 6.3.1. Remedies to DF Problems that Work
        - 6.3.2 Remedies to DF Problems that did not work or caused other problems
        - 6.3.3 Agency's List of Do's and Don'ts -- Recommendations to the Industry

7. Vehicle Types (if not included in the APTA Transit Vehicle Documentation, 1980)*

    Wheel Types (Profiles, Diameter)
    - 7.2 Suspension (Primary, secondary, yaw stiffness)
    - 7.3 Weights
    - 7.4 Dimensions

Appendix C
Site Visits and Interviews

Agency	Reporting Date
Baltimore (MTA)	5/3/95
Chicago (CTA)	5/22/95
Atlanta (MARTA)	4/20/95
Boston (MBTA)	5/17/95
Brooklyn (NYCTA)	6/19/95
Philadelphia (PATCO)	4/25/95
Philadelphia (SEPTA)	4/25/95
Washington DC (WMATA)	5/2/95
San Francisco (BART)	4/19/95
Los Angeles (LACMTA Red Line)	5/2/95

Appendix D
Fastener Characterization Plots

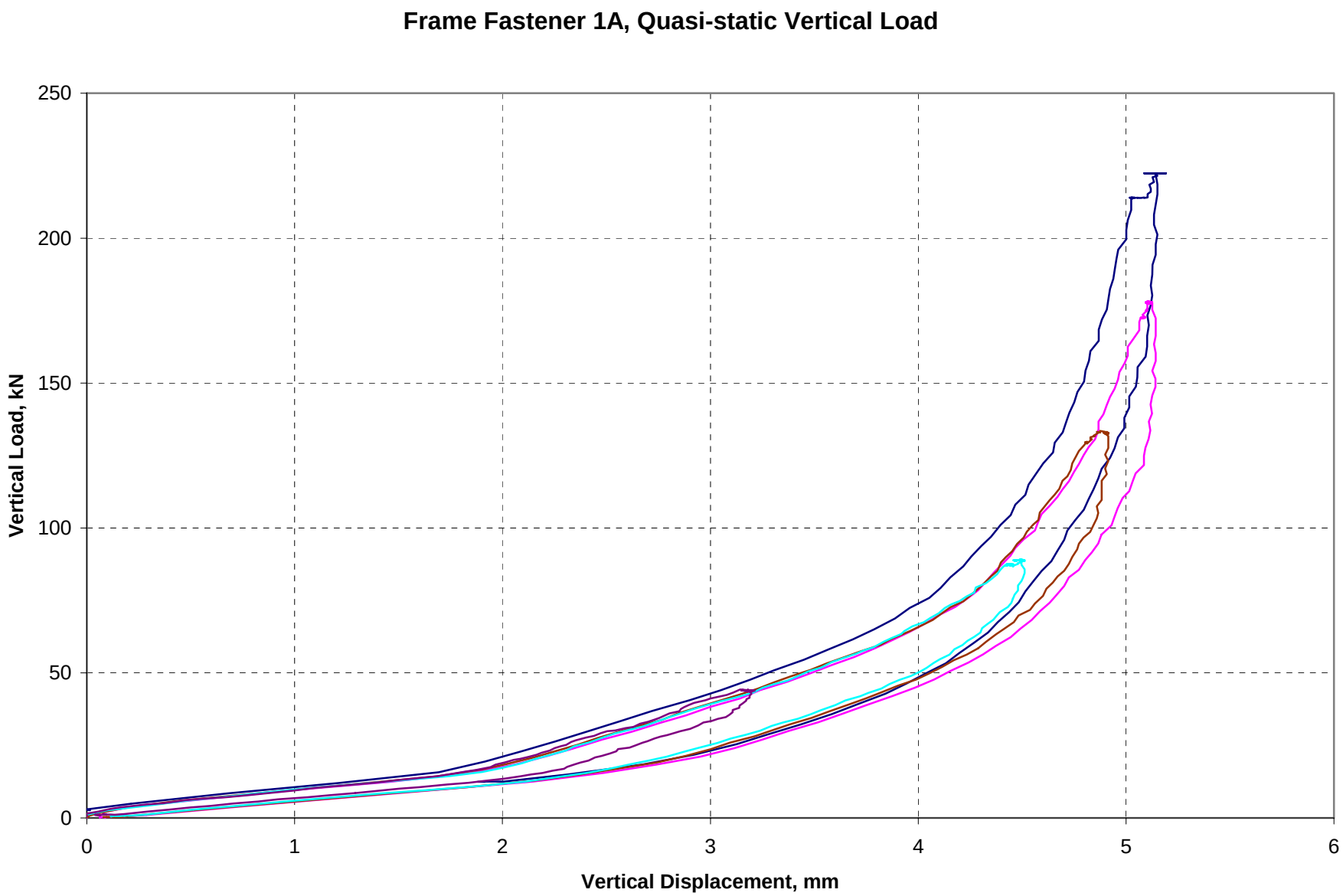
The starting point for the specification of a fastener is the stiffness as defined through the testing procedures described in Section 3.0. The stiffness determines rail deflection under combinations of vertical and lateral load. The testing equipment used to conduct these tests is described in Section 3.0 of the research report. The fasteners were selected for test based upon their availability and the needs of another research program that supported the majority of the testing. Several additional available fasteners were tested under this program to provide a wider range of representative fastener types and parametric values. This list is not comprehensive of all manufacturers, or all products, but these samples do provide a range of representative values and types of fasteners as a starting point for fastener use and design. The rail fasteners were tested under quasi-static vertical loading, quasi-static vertical and lateral loading, and dynamic vertical loading. In order not to identify a specific manufacturer or fastener they are presented by the type of fastener. The type of each fastener and the number of fasteners tested are shown in Table D-1. These data represent the characterization testing carried out during the research. These values are to be used as a starting point for a range of fastener parameter values and behaviors.

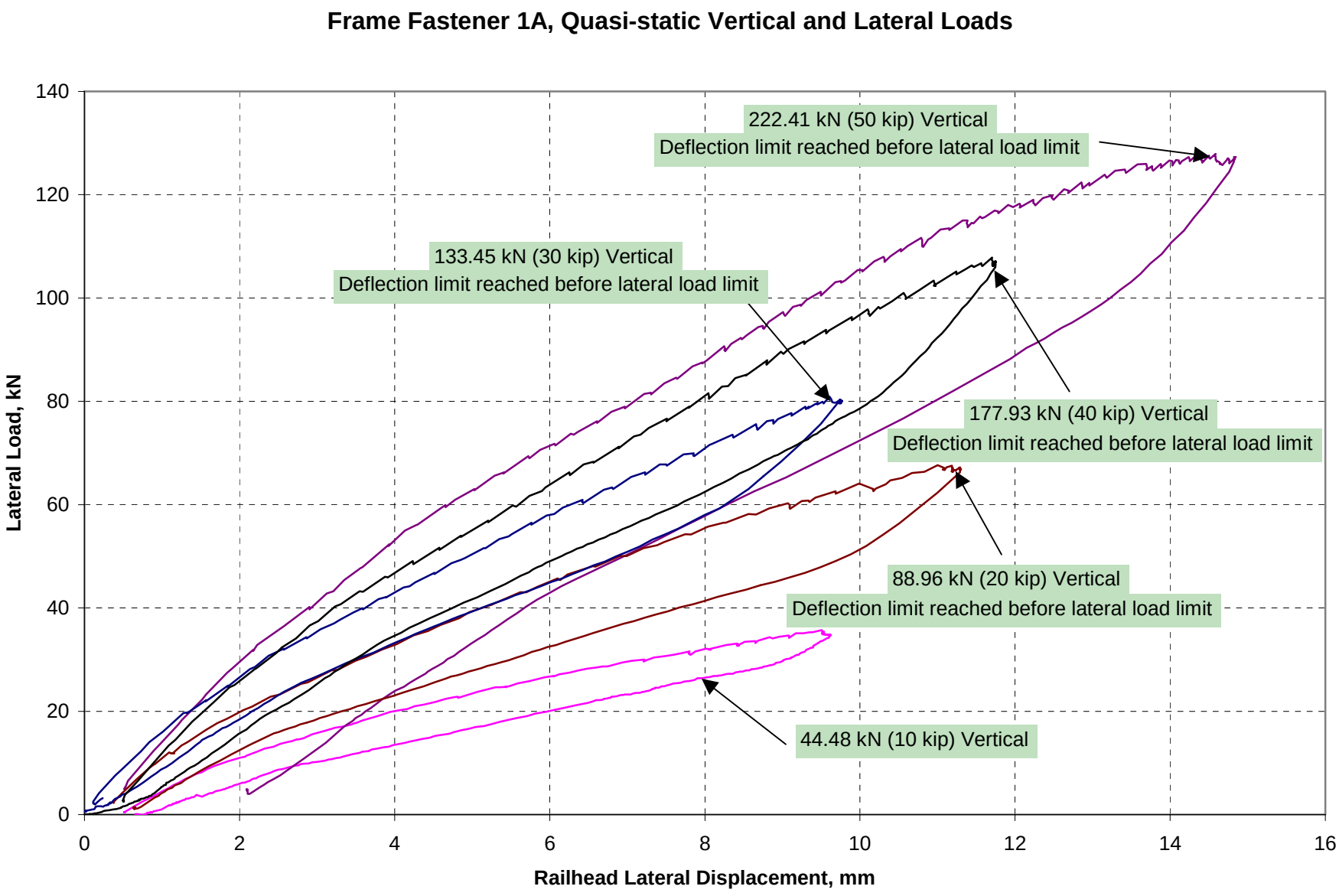
Table D-1. Single fastener characterization test matrix

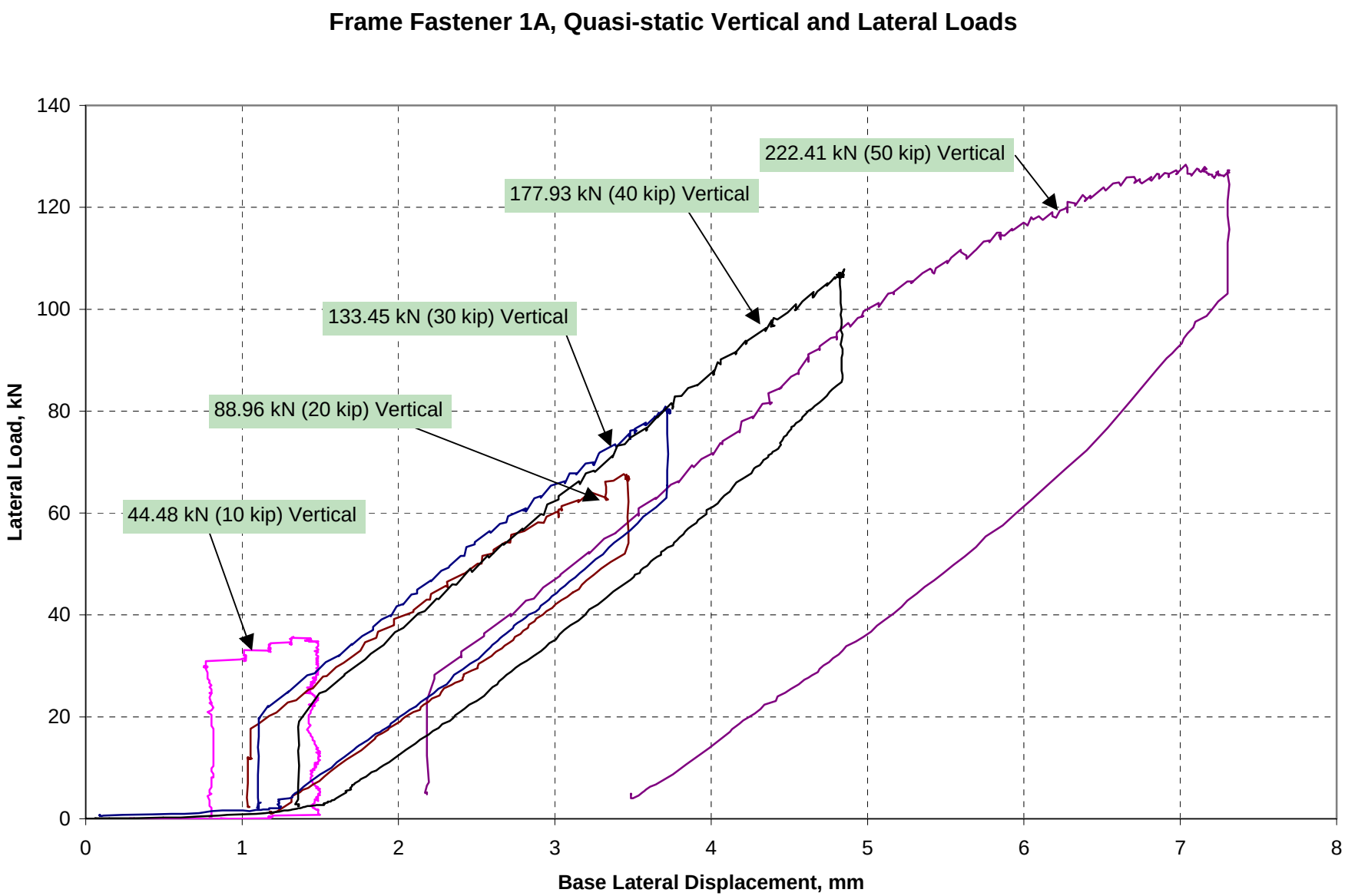
Fastener Name	Number Tested–Designation
Frame Fastener 1	5–A, B, C, D, E
Frame Fastener 2	3–F, G, H
Frame Fastener 3	3–I, J, K
Bonded Plate 3	1–L
Bonded Plate 2	1–M
Bonded Plate 1	1–N
Unbonded Plate–2 pad	1–O
Unbonded Plate–3 pad	1–P
Bonded Plate 4	2–Past test data

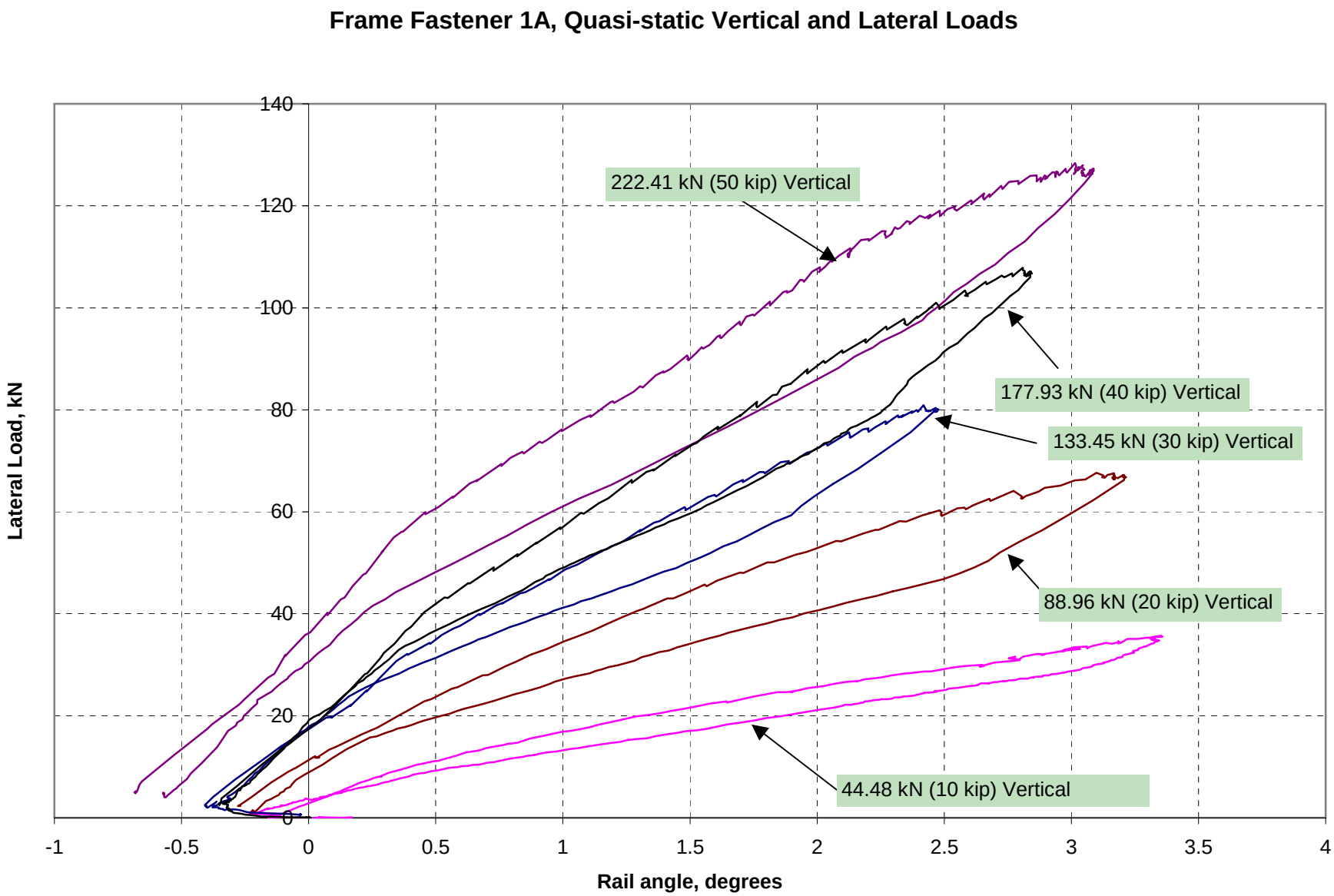
Plots of the test results for selected fasteners are shown on the following pages of this Appendix. The complete data are available electronically upon request.

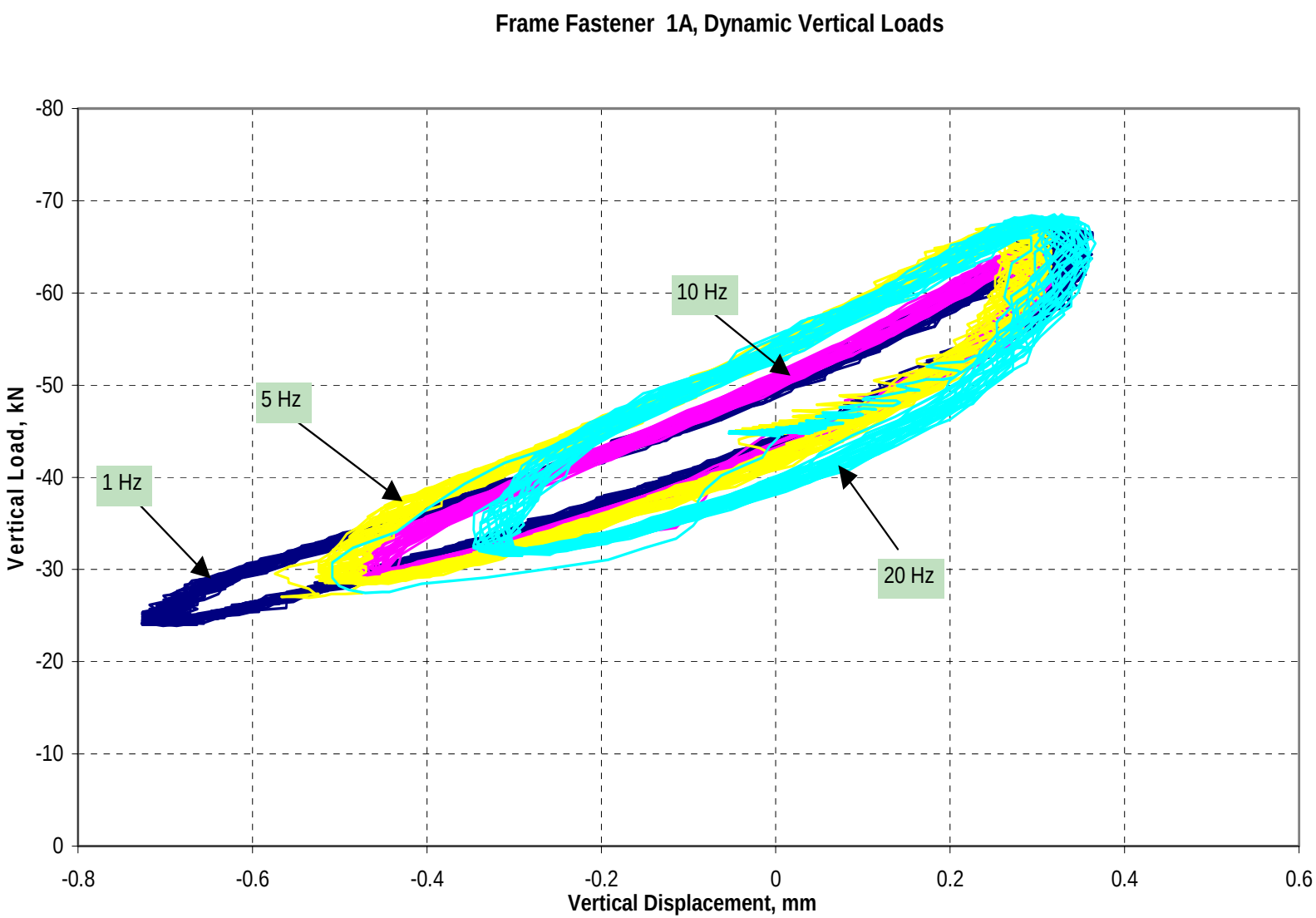
The force versus deflection plots may be used to calculate fastener stiffness and linearity in both the vertical and lateral directions. The lateral stiffness is dependent upon the applied vertical load, so a number of different curves are presented at different vertical loads. Curves for railhead and railbase displacements are given along with rail roll angles. Displacement at a particular load may be determined from the plots, as well as fastener stiffness using a secant or tangent methods. Finally, plots of displacement versus dynamic vertical load at frequencies of 1, 5, 10, and 20 Hz are presented to allow calculation of a dynamic stiffness ratio for each fastener. Using a different elastomer formulation in the same configuration allows the development of alternate stiffnesses for each design. In this manner fasteners may be tailored for specific needs and wheelloads.

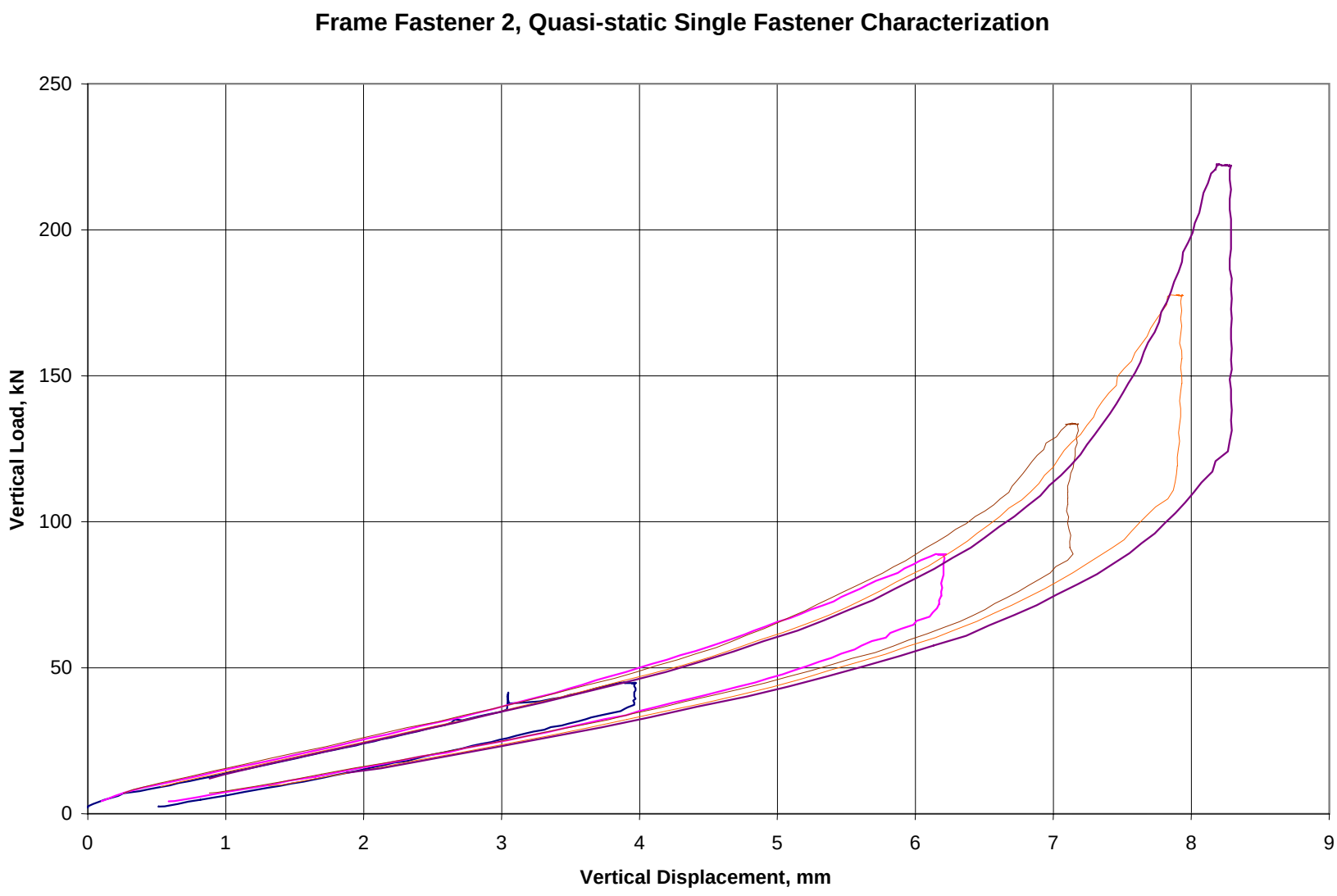

Frame Fastener 1A, Quasi-static Vertical Load
Vertical Load, kN
250
200
150
100
50
0
0
1
2
3
4
5
6
Vertical Displacement, mm

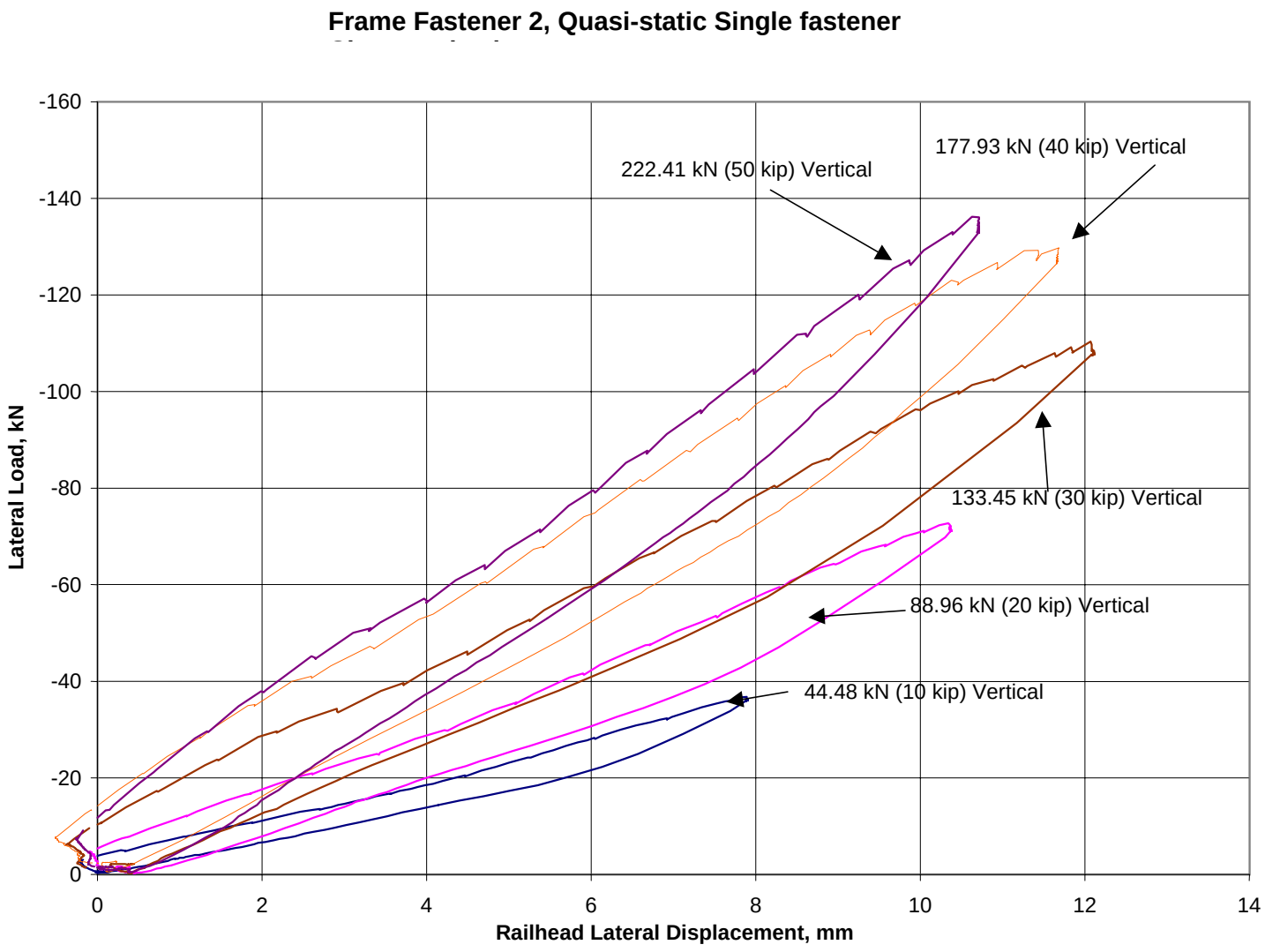

Frame Fastener 1A, Quasi-static Vertical and Lateral Loads
222.41 kN (50 kip) Vertical
Deflection limit reached before lateral load limit
133.45 kN (30 kip) Vertical
Deflection limit reached before lateral load limit
177.93 kN (40 kip) Vertical
Deflection limit reached before lateral load limit
88.96 kN (20 kip) Vertical
Deflection limit reached before lateral load limit
44.48 kN (10 kip) Vertical
Lateral Load, kN
Railhead Lateral Displacement, mm
0
20
40
60
80
100
120
140
0
2
4
6
8
10
12
14
16

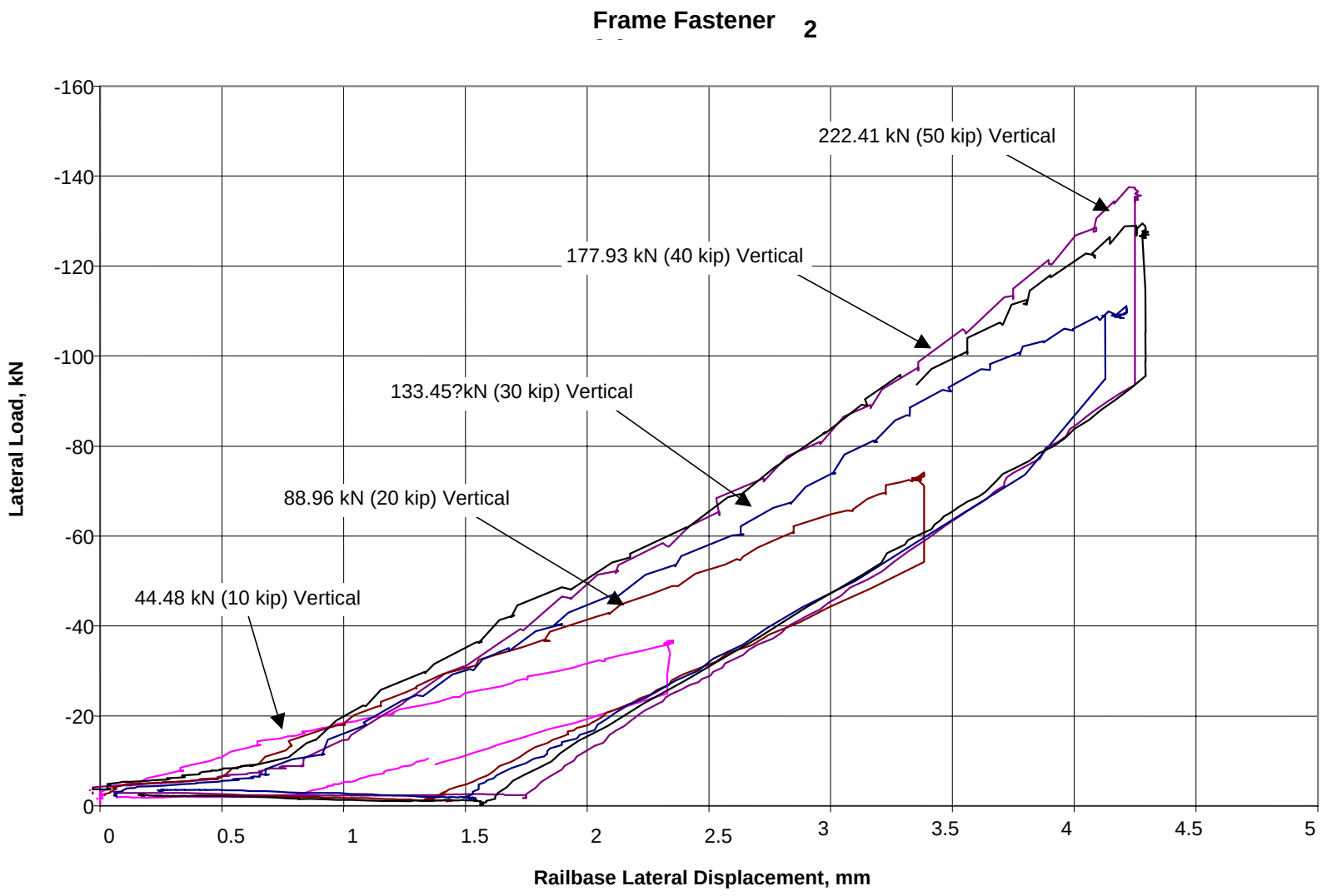

Frame Fastener 1A, Quasi-static Vertical and Lateral Loads
222.41 kN (50 kip) Vertical
177.93 kN (40 kip) Vertical
133.45 kN (30 kip) Vertical
88.96 kN (20 kip) Vertical
44.48 kN (10 kip) Vertical
Lateral Load, kN
Base Lateral Displacement, mm
0
20
40
60
80
100
120
140
0
1
2
3
4
5
6
7
8

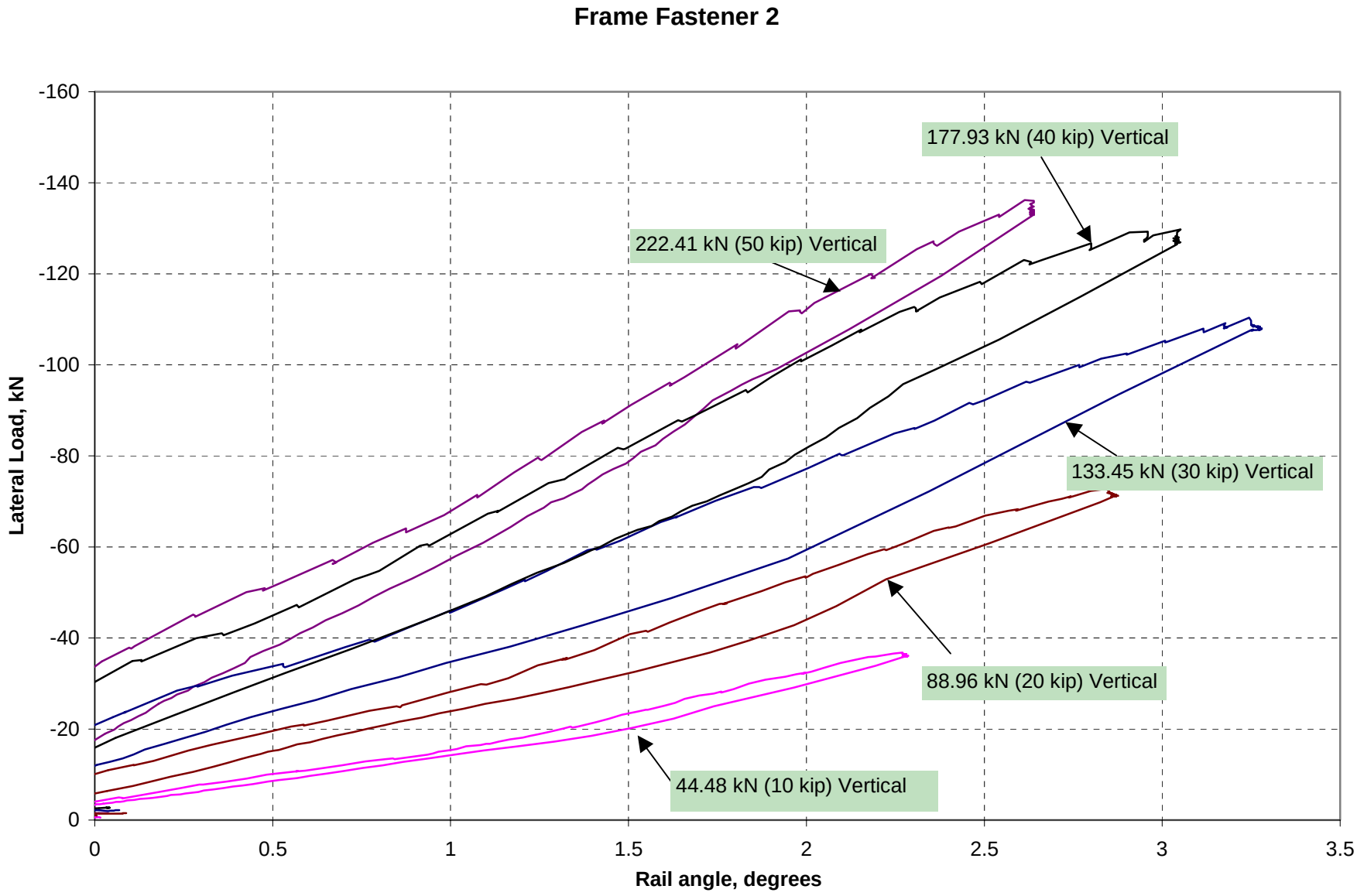

Frame Fastener 1A, Quasi-static Vertical and Lateral Loads
Lateral Load, kN
Rail angle, degrees
140
120
100
80
60
40
20
0
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
222.41 kN (50 kip) Vertical
177.93 kN (40 kip) Vertical
133.45 kN (30 kip) Vertical
88.96 kN (20 kip) Vertical
44.48 kN (10 kip) Vertical

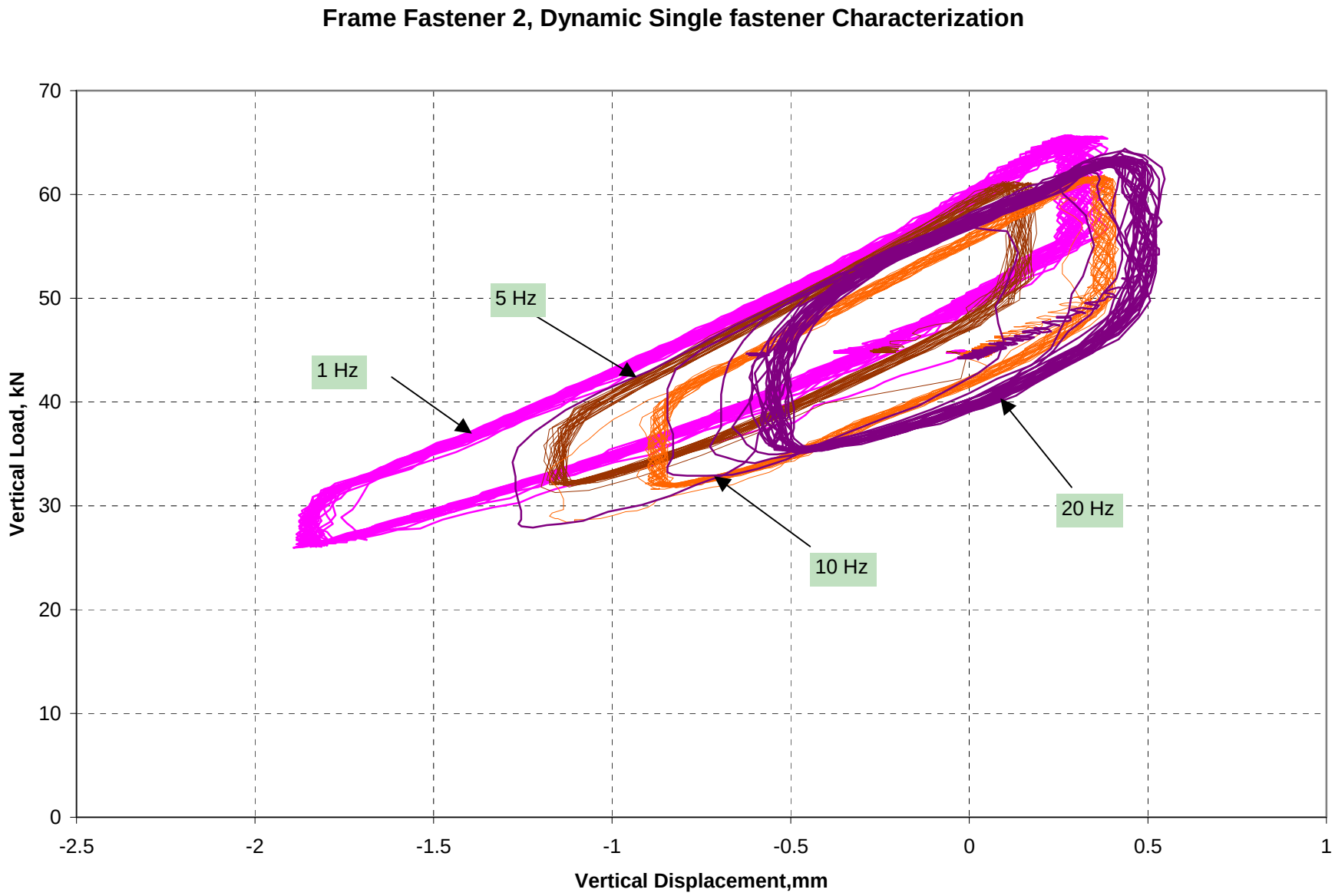

Frame Fastener 1A, Dynamic Vertical Loads
Vertical Load, kN
Vertical Displacement, mm
-80
-70
-60
-50
-40
-30
-20
-10
0
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
1 Hz
5 Hz
10 Hz
20 Hz

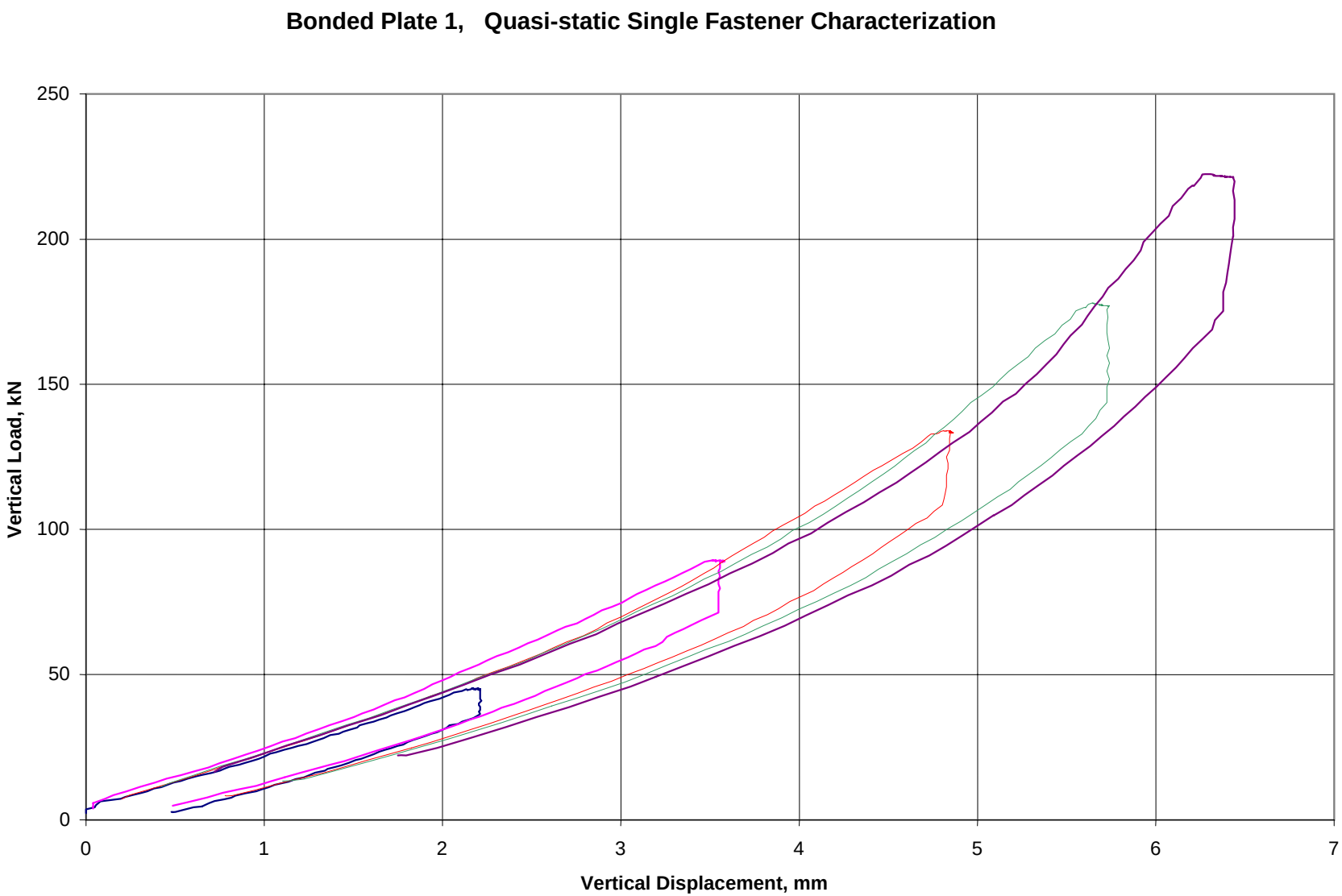

Frame Fastener 2, Quasi-static Single Fastener Characterization
Vertical Load, kN
Vertical Displacement, mm
0
50
100
150
200
250
0
1
2
3
4
5
6
7
8
9

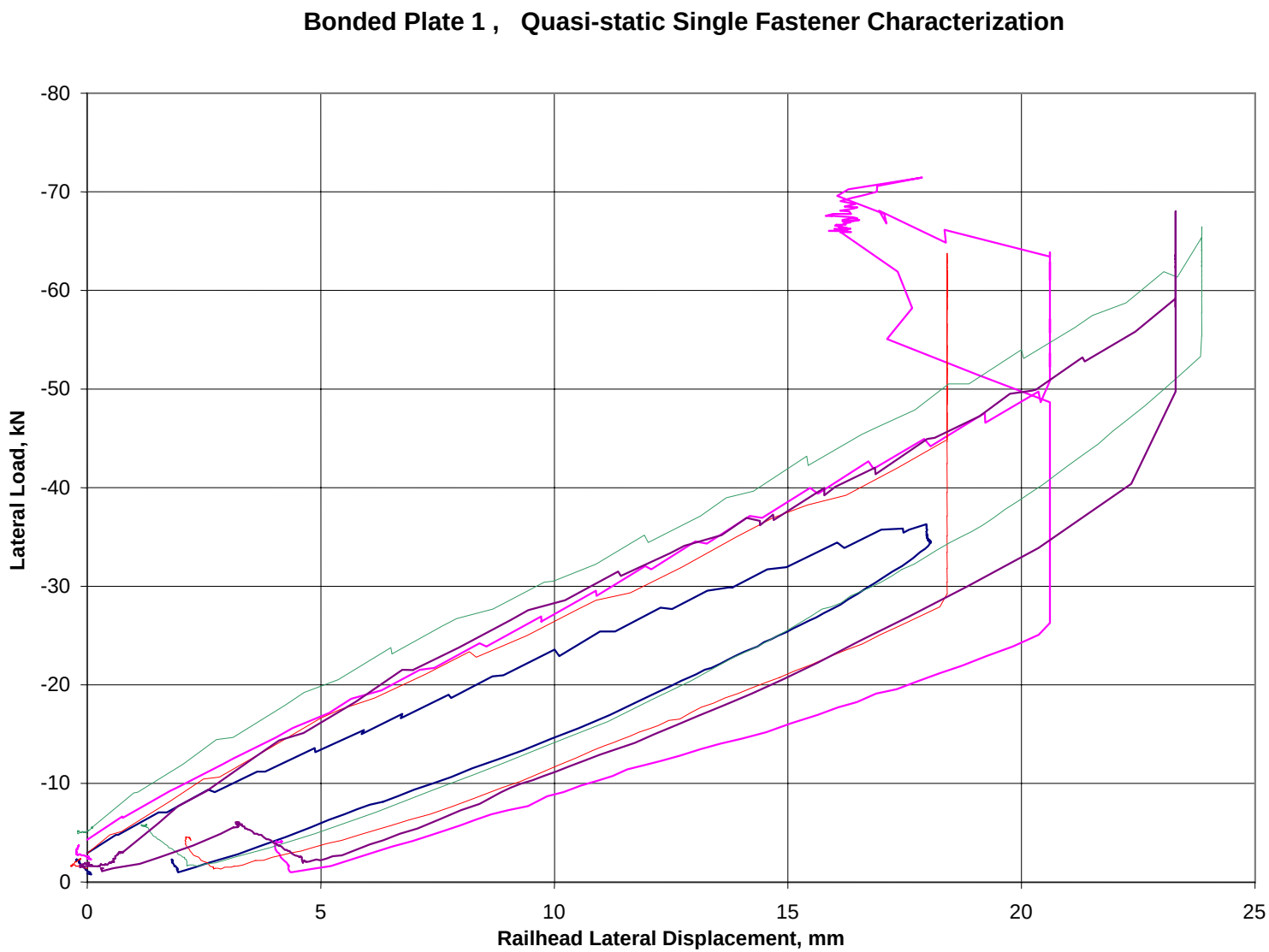

Frame Fastener 2, Quasi-static Single fastener
-160
-140
-120
-100
-80
-60
-40
-20
0
Lateral Load, kN
0
2
4
6
8
10
12
14
Railhead Lateral Displacement, mm
222.41 kN (50 kip) Vertical
177.93 kN (40 kip) Vertical
133.45 kN (30 kip) Vertical
88.96 kN (20 kip) Vertical
44.48 kN (10 kip) Vertical

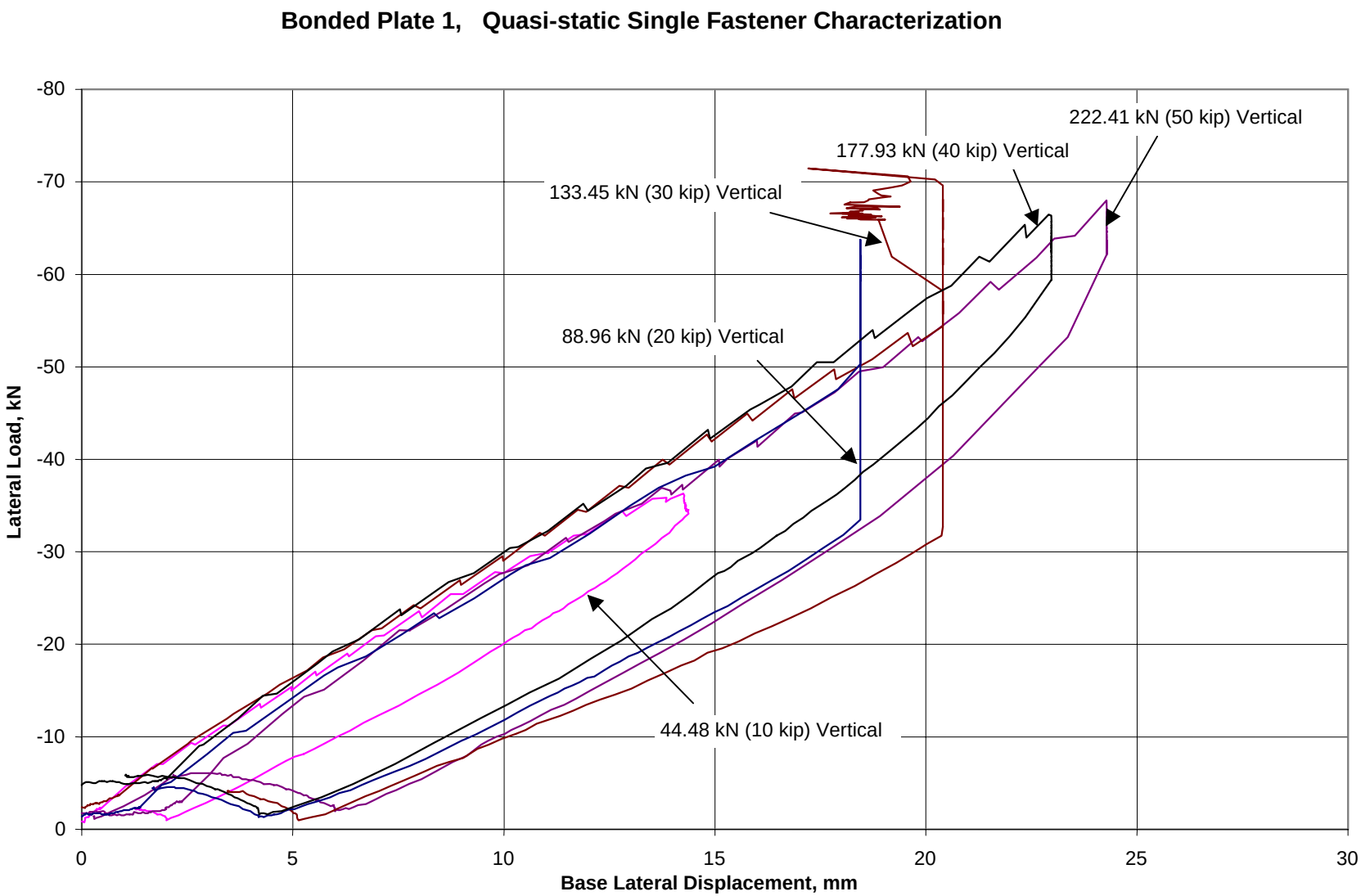

Frame Fastener 2
222.41 kN (50 kip) Vertical
177.93 kN (40 kip) Vertical
133.45?kN (30 kip) Vertical
88.96 kN (20 kip) Vertical
44.48 kN (10 kip) Vertical
Lateral Load, kN
-160
-140
-120
-100
-80
-60
-40
-20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Railbase Lateral Displacement, mm


Frame Fastener 2
Lateral Load, kN
Rail angle, degrees
-160
-140
-120
-100
-80
-60
-40
-20
0
0
0.5
1
1.5
2
2.5
3
3.5
177.93 kN (40 kip) Vertical
222.41 kN (50 kip) Vertical
133.45 kN (30 kip) Vertical
88.96 kN (20 kip) Vertical
44.48 kN (10 kip) Vertical

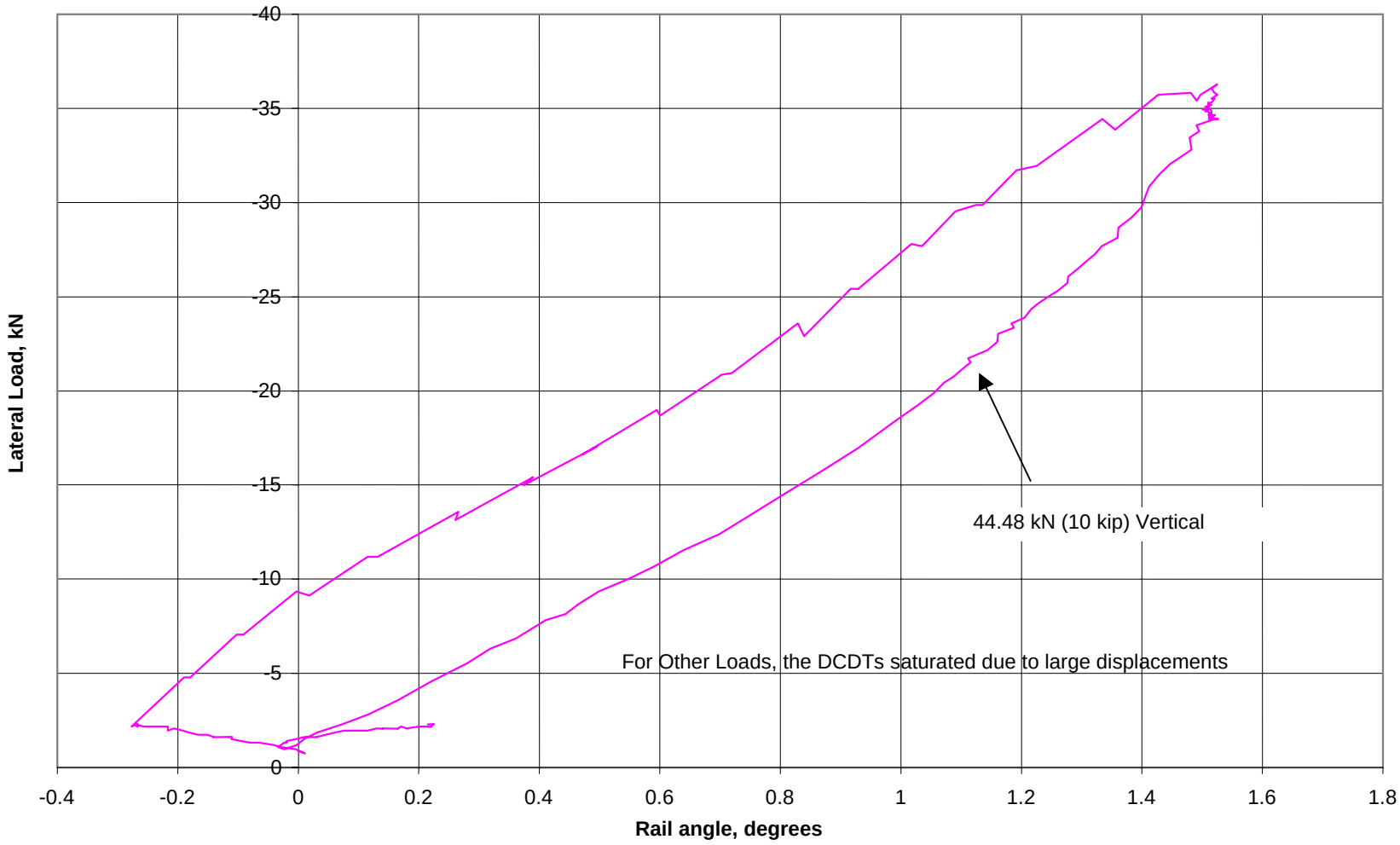

Frame Fastener 2, Dynamic Single fastener Characterization
Vertical Load, kN
Vertical Displacement,mm
70
60
50
40
30
20
10
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1 Hz
5 Hz
10 Hz
20 Hz

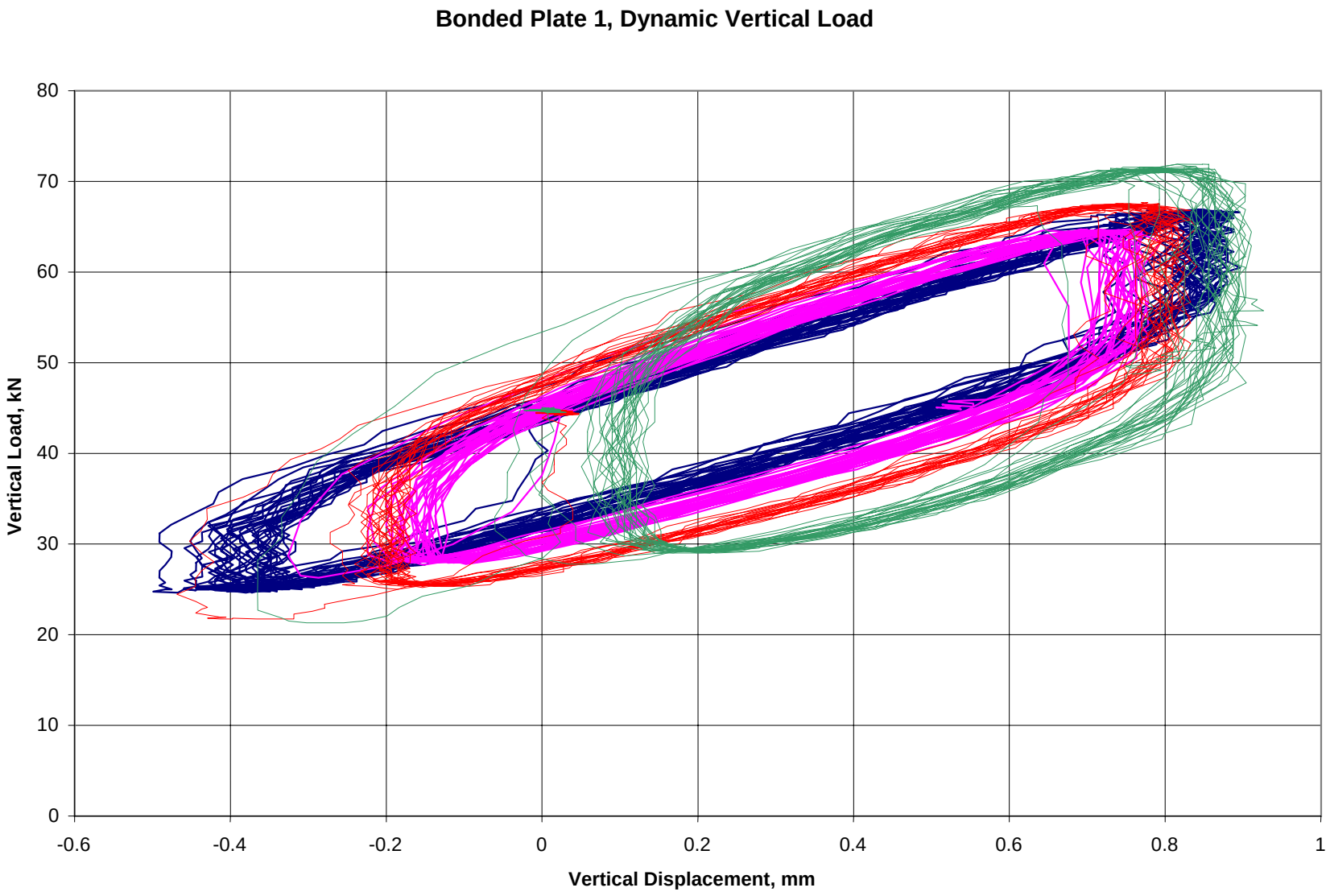

Bonded Plate 1, Quasi-static Single Fastener Characterization
Vertical Load, kN
Vertical Displacement, mm
0
50
100
150
200
250
0
1
2
3
4
5
6
7


Bonded Plate 1 , Quasi-static Single Fastener Characterization
Lateral Load, kN
-80
-70
-60
-50
-40
-30
-20
-10
0
0
5
10
15
20
25
Railhead Lateral Displacement, mm

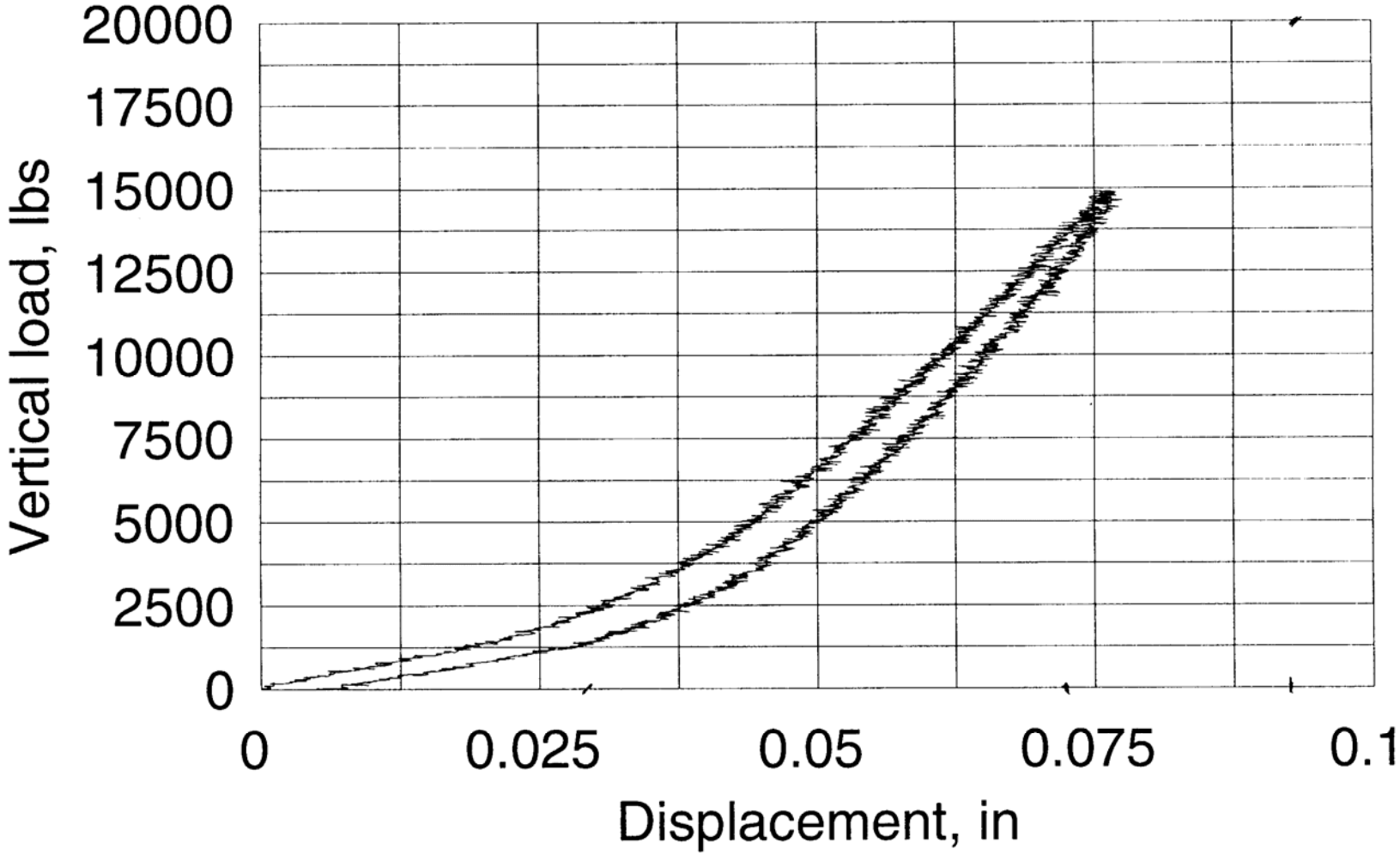

Bonded Plate 1, Quasi-static Single Fastener Characterization
222.41 kN (50 kip) Vertical
177.93 kN (40 kip) Vertical
133.45 kN (30 kip) Vertical
88.96 kN (20 kip) Vertical
44.48 kN (10 kip) Vertical
Lateral Load, kN
Base Lateral Displacement, mm
-80
-70
-60
-50
-40
-30
-20
-10
0
0
5
10
15
20
25
30

Bonded Plate 1, Quasi-static Single Fastener Characterization



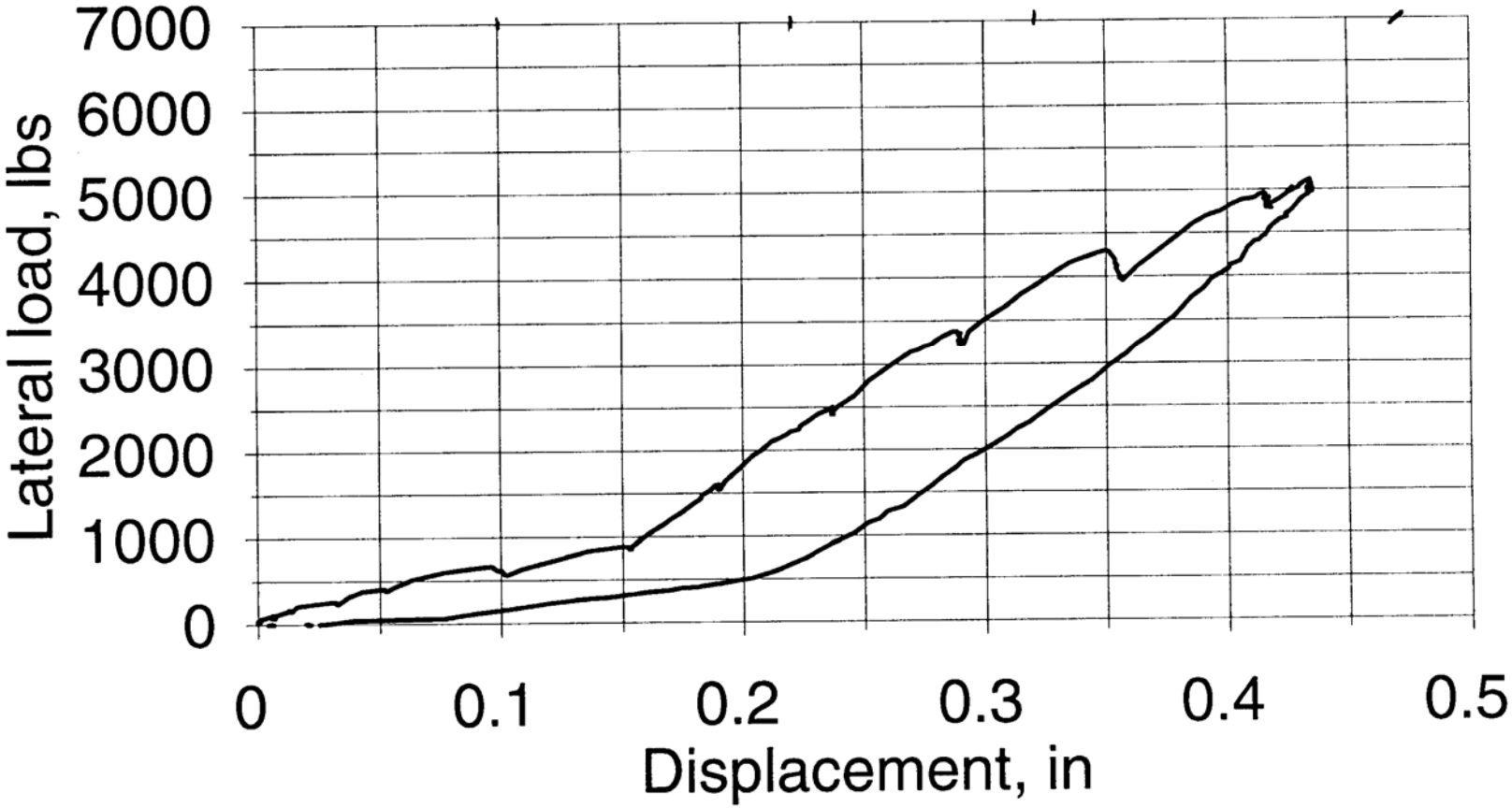

Bonded Plate 1, Dynamic Vertical Load
Vertical Load, kN
Vertical Displacement, mm
80
70
60
50
40
30
20
10
0
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

Fastener 10 Vertical Stiffness



Fastener 10 Lateral Stiffness

0 kip vertical load

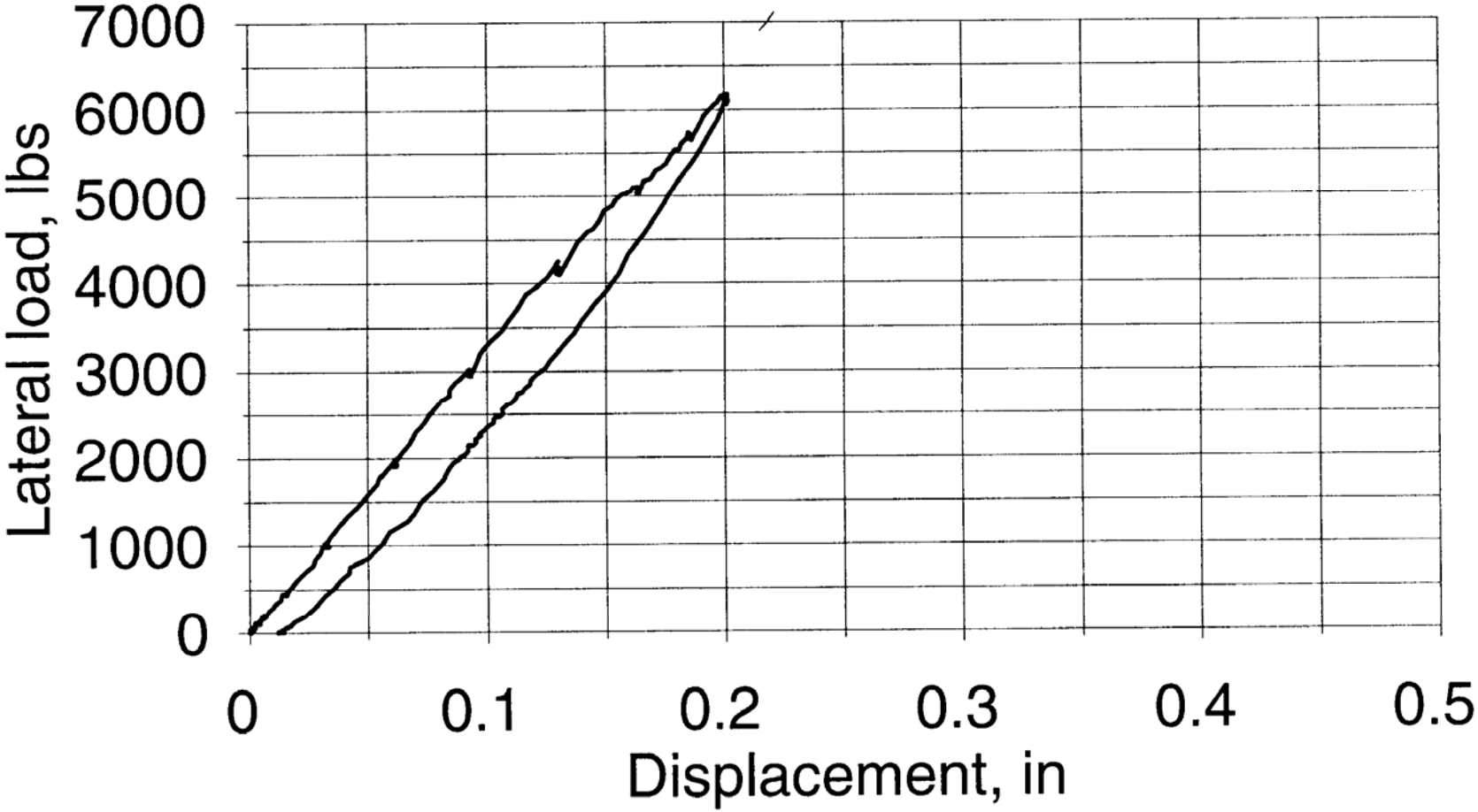


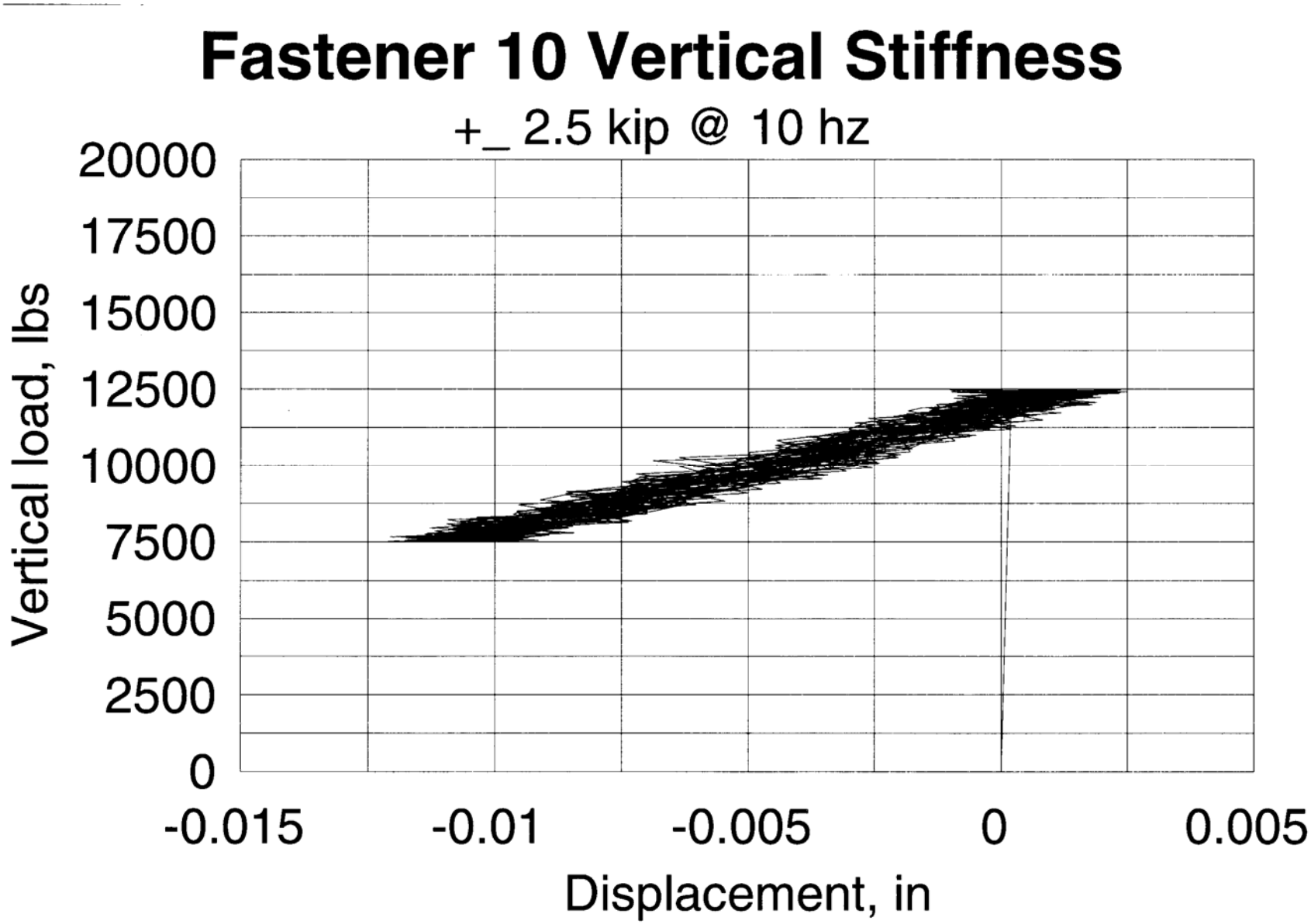
Fastener 10 Lateral Stiffness

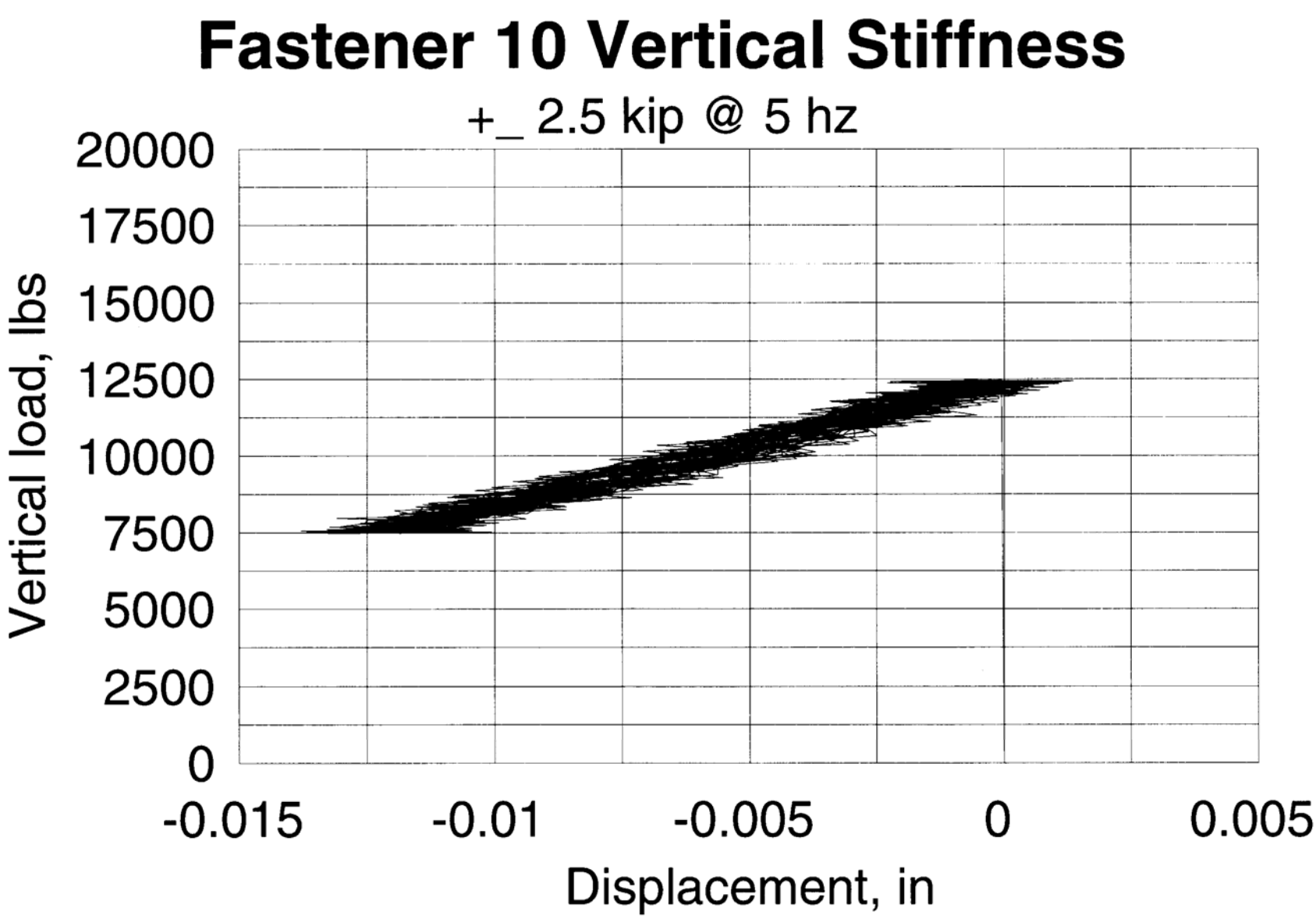
9 kip vertical load

Fastener 10 Lateral Stiffness

14 kip vertical load




Fastener 10 Vertical Stiffness
+_ 2.5 kip @ 10 hz
Vertical load, lbs
20000
17500
15000
12500
10000
7500
5000
2500
0
-0.015
-0.01
-0.005
0
0.005
Displacement, in


Fastener 10 Vertical Stiffness
+_ 2.5 kip @ 5 hz
Vertical load, lbs
20000
17500
15000
12500
10000
7500
5000
2500
0
-0.015
-0.01
-0.005
0
0.005
Displacement, in

Appendix E
Component Force versus Deflection Characterization

In a manner similar to the plots in Appendix D, the components that make up the embedded block system were tested. Plots of the test results are shown on the following pages of this appendix. Complete numeral test results are available upon request

The force versus deflection plots may be used to calculate the system stiffness and linearity in both the vertical and lateral directions by combining the results from the individual system components. Multiple samples were tested to judge variability between samples. Using a different elastomer formulation in a single component allows the development of alternate stiffnesses for each design. In this manner fasteners may be tailored for specific needs and wheelloads.

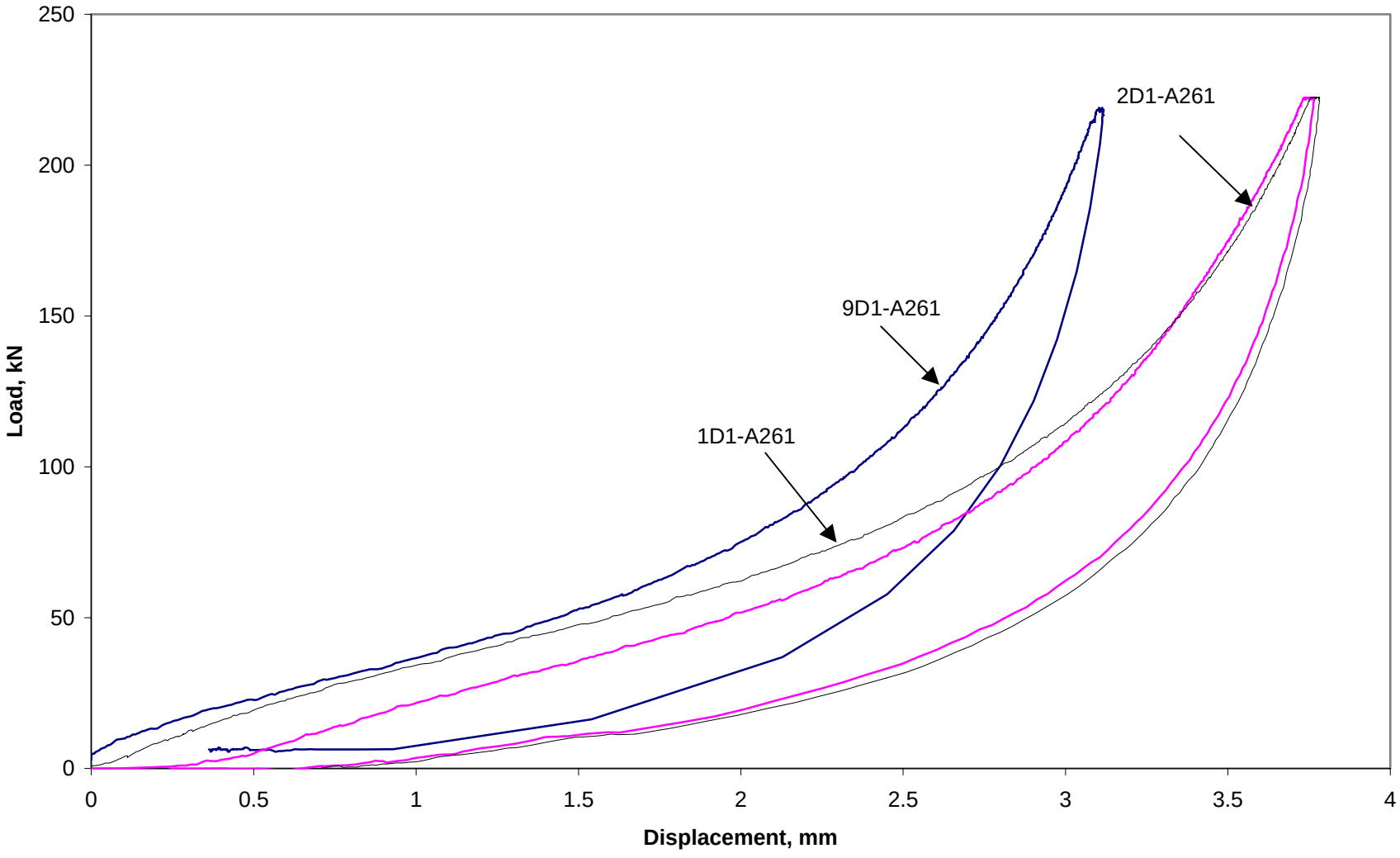


Figure E-1. Quasi-static load displacement behavior for Embedded block pad

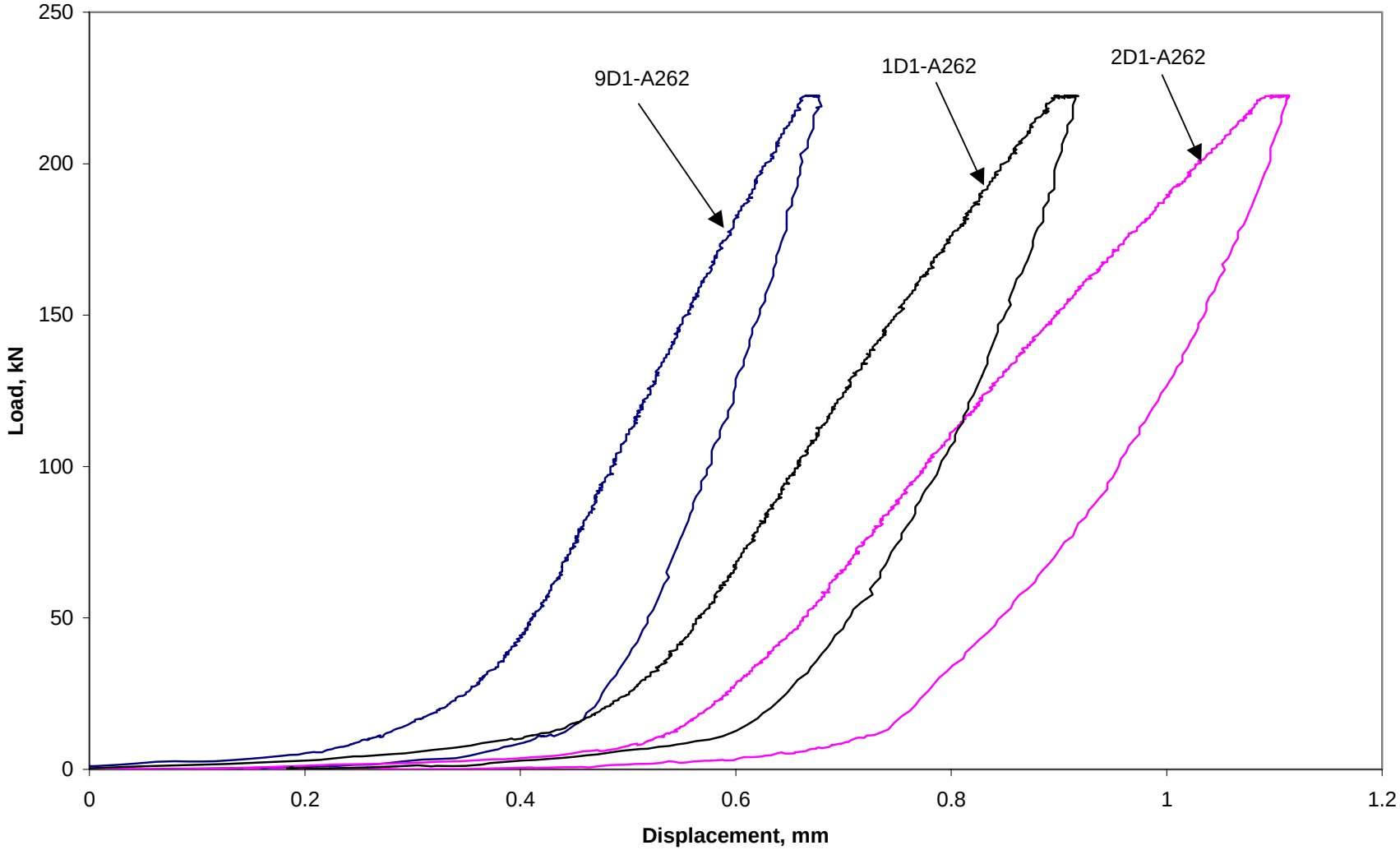


Figure E-2. Quasi-static load displacement behavior for embedded block rail pad

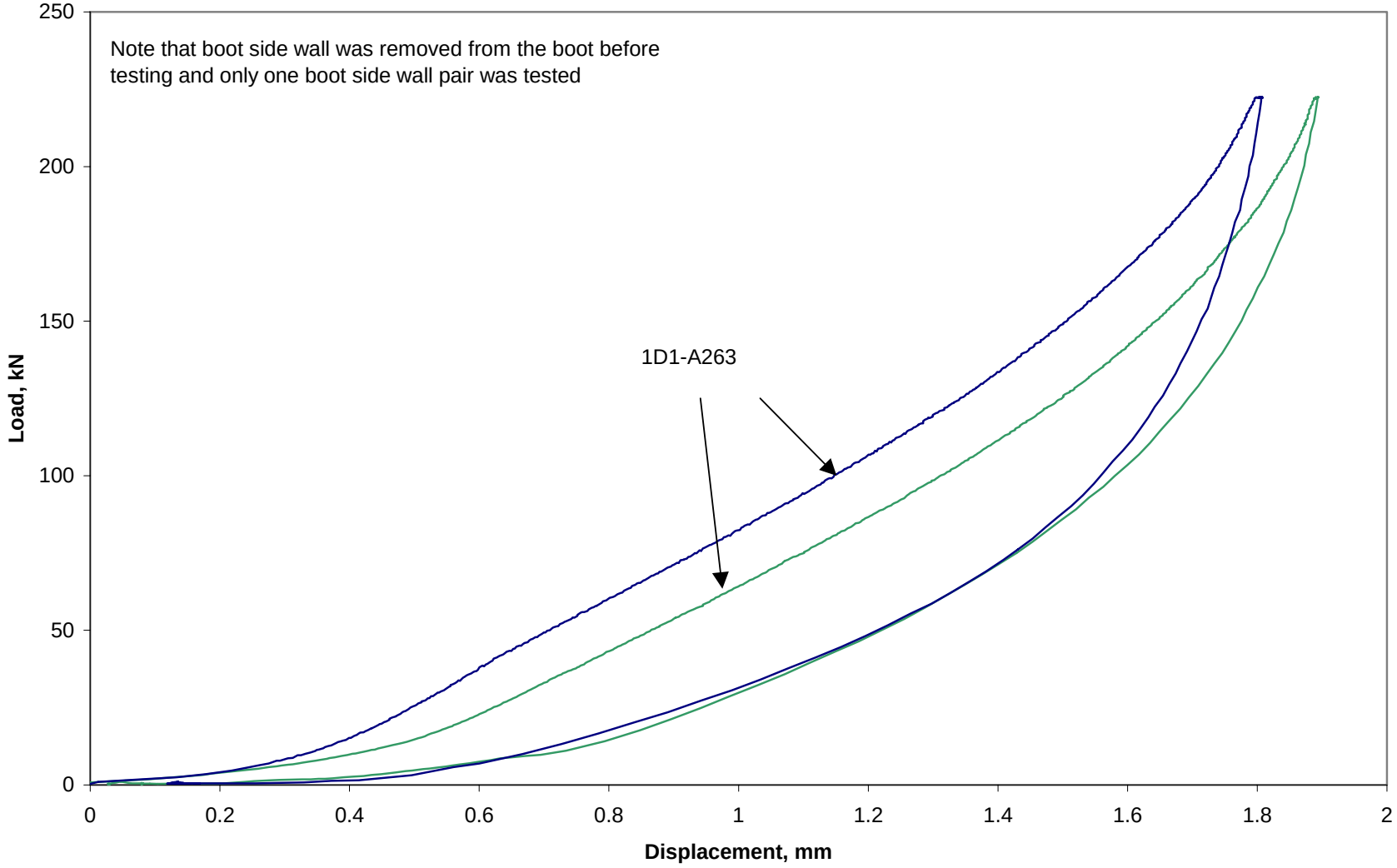


Figure E-3. Quasi-static load displacement behavior for embedded block boot sidewall

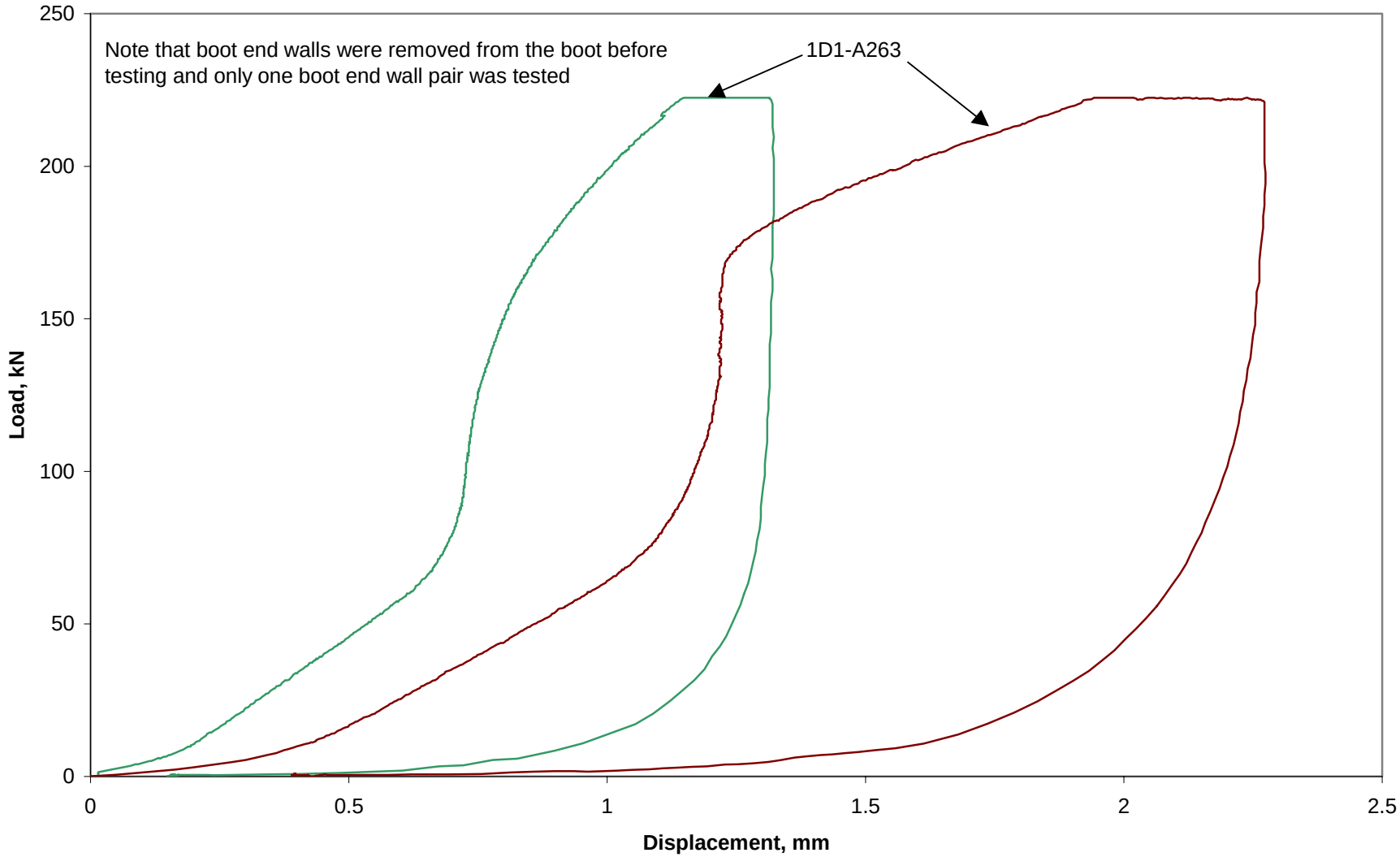


Figure E-4. Quasi-static load displacement behavior for embedded block boot endwall

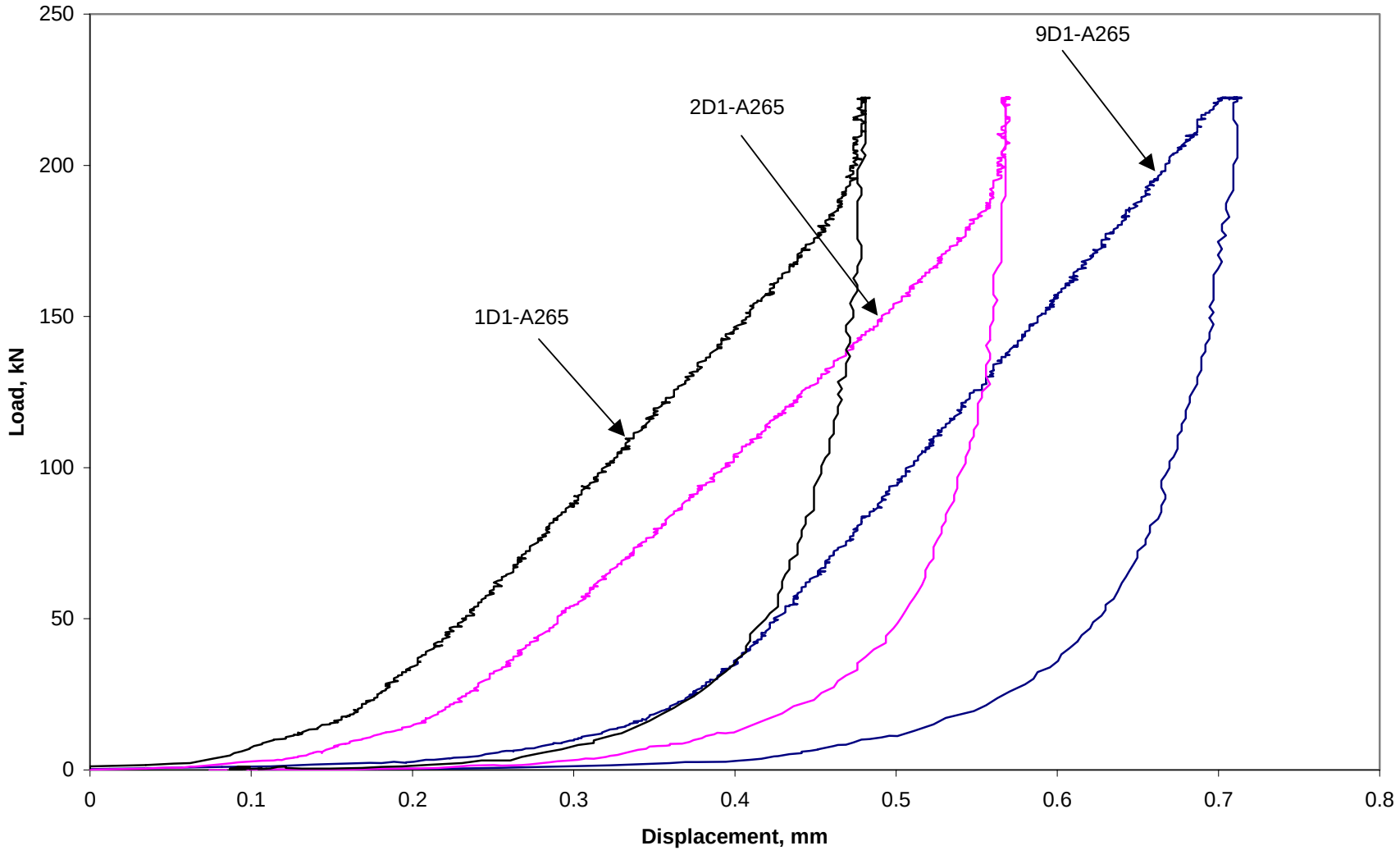


Figure E-5. Quasi-static load displacement behavior for embedded block boot bottom

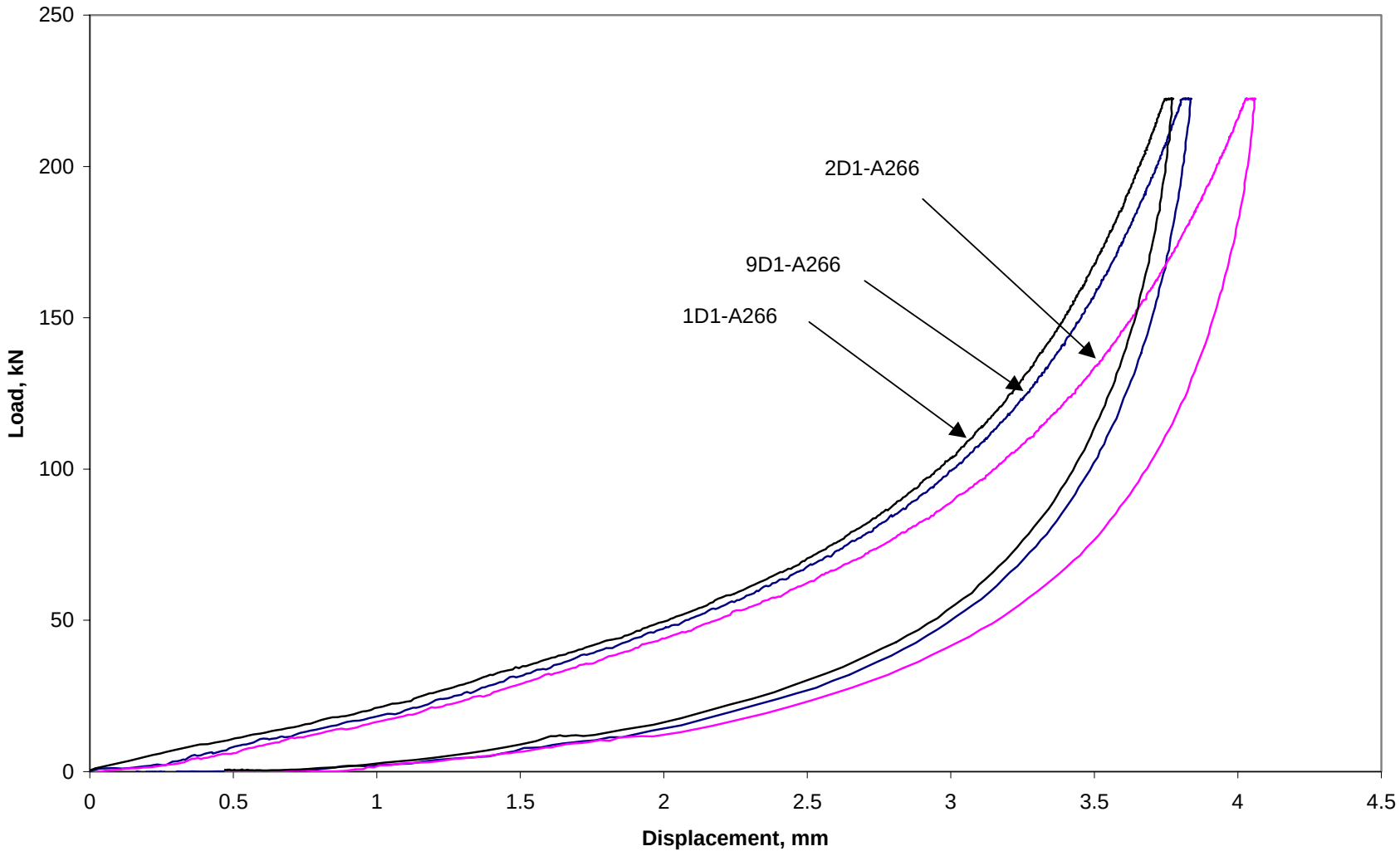


Figure E-6. Quasi-static load displacement behavior for embedded block boot and block pad

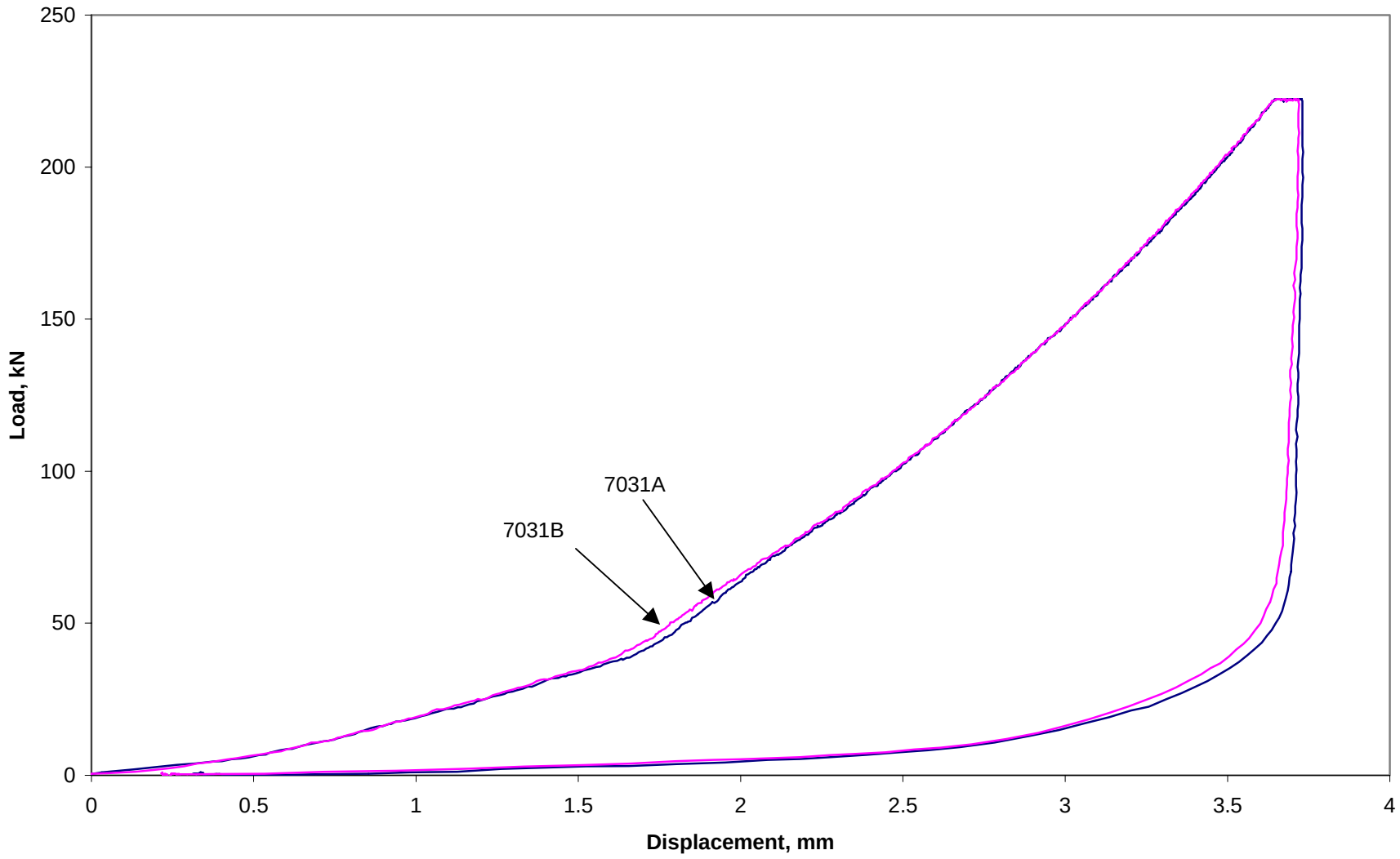


Figure E-7. Quasi-static load displacement behavior for 7031 rail pad

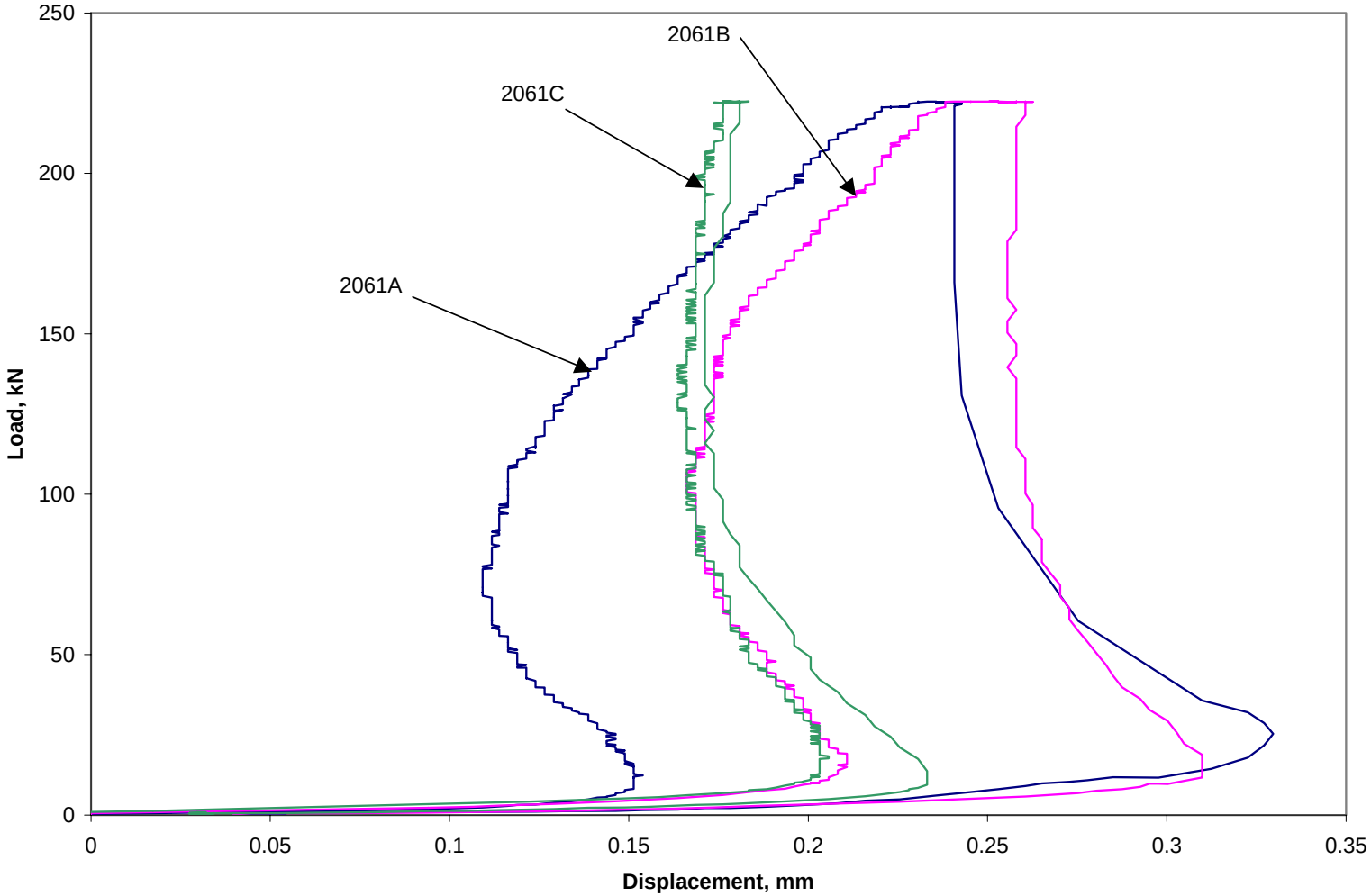


Figure E-8. Quasi-static load displacement behavior for 2061 rail pad

Appendix F
Repeatability Data Plots

A series of tests were run to evaluate the repeatability of the testing methodology after significant sample variation was observed in the testing presented in Appendix E. Selected components that make up the Embedded block system were tested multiple times to evaluate the repeatability of the test setup and execution. Plots of the test results are shown on the following pages of this appendix. Complete numeral test results are available upon request.

The force versus deflection plots may be used to calculate the system stiffness and linearity in both the vertical and lateral directions by combining the results from the individual system components. Multiple tests were executed to judge variability between tests.

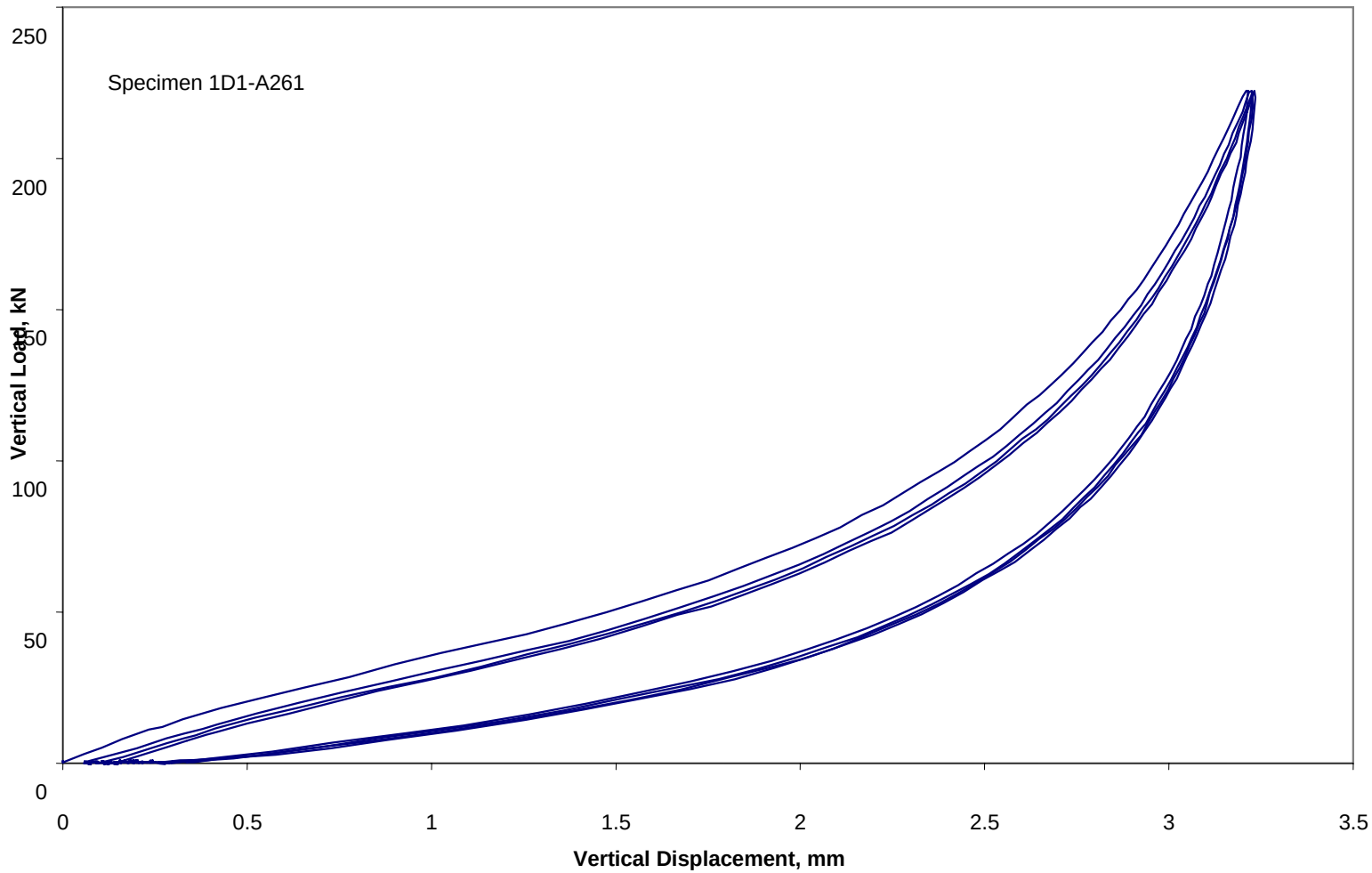


Figure F-1. Embedded block rail pad - Repeatability

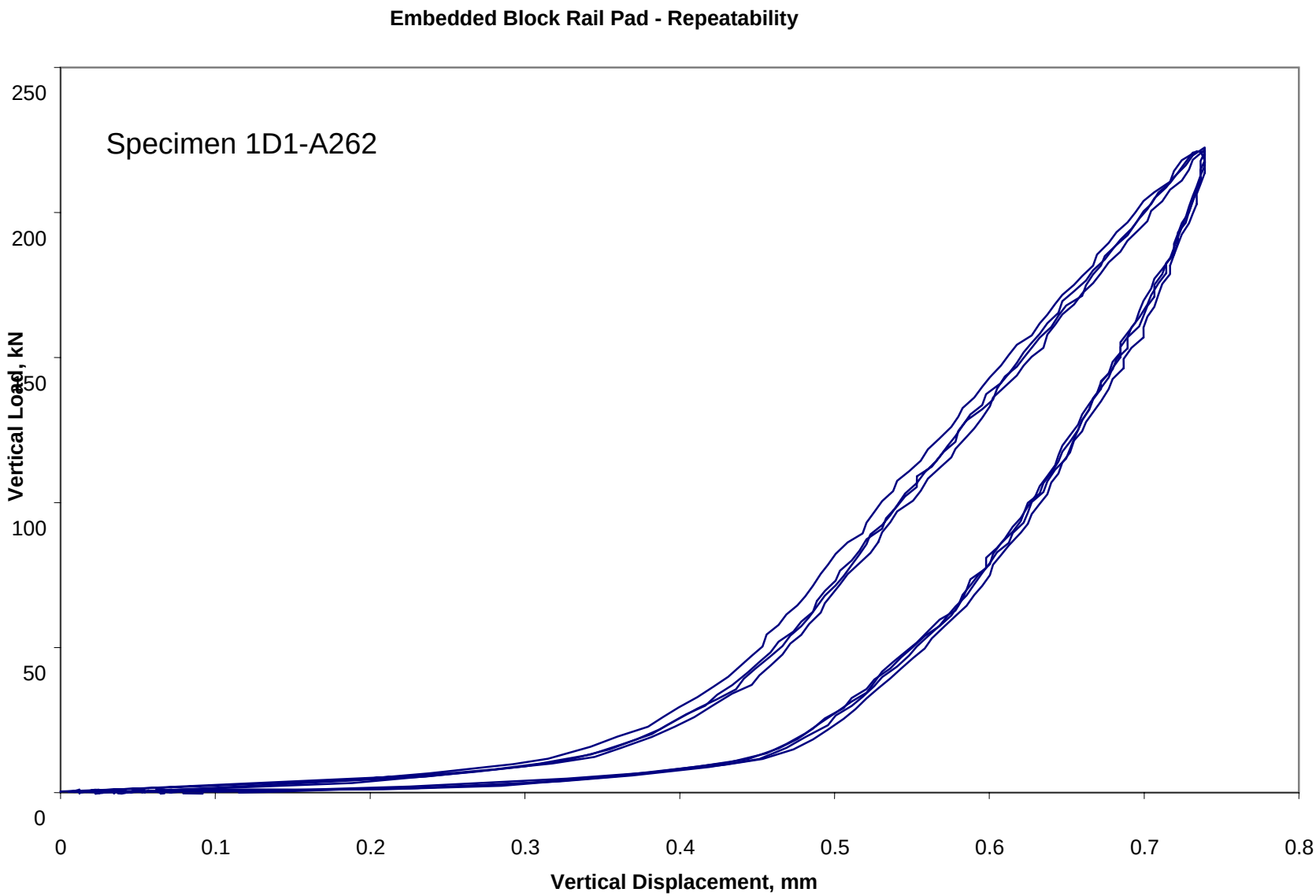


Figure F-2. Embedded block Rail Pad - Repeatability

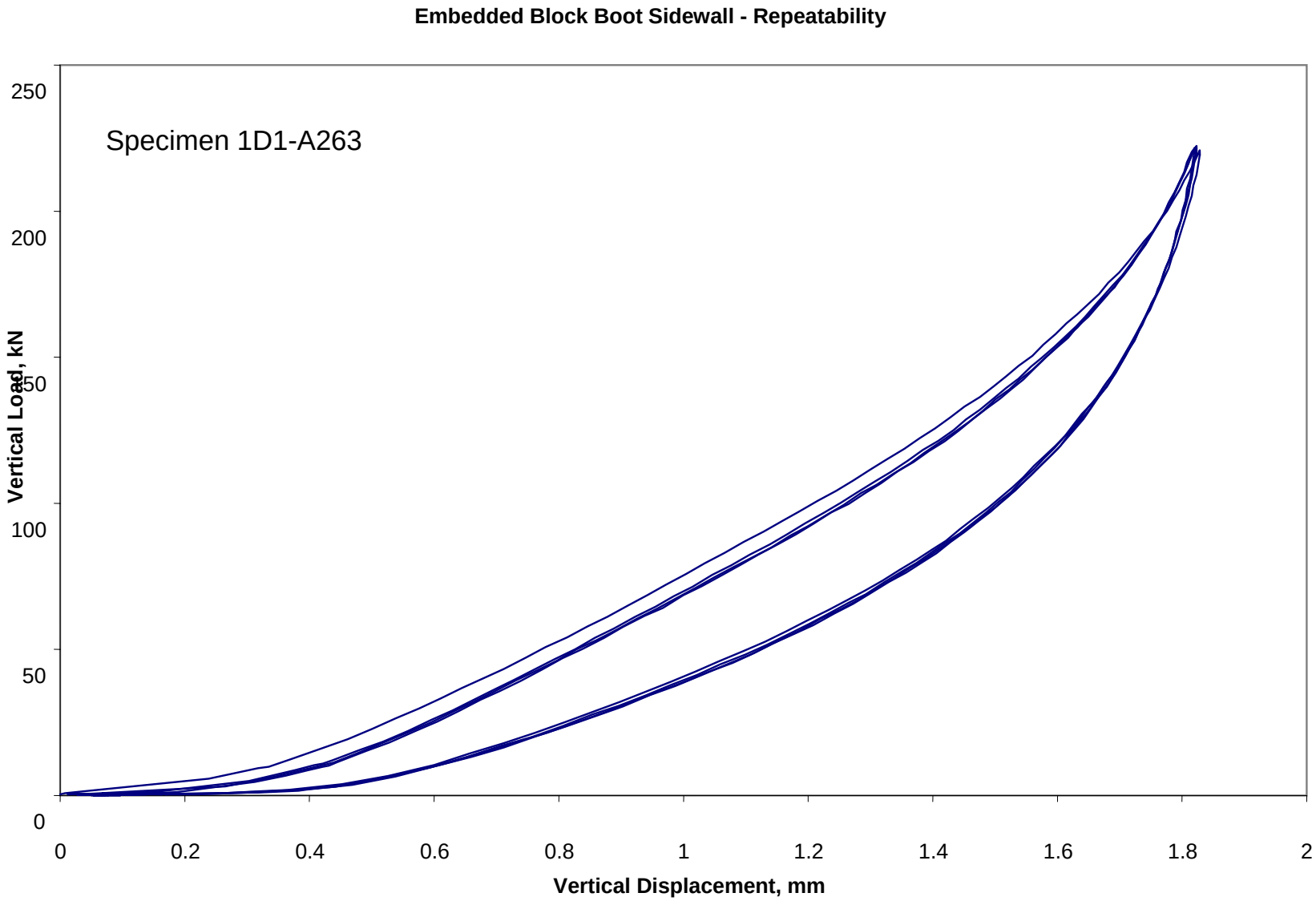


Figure F-3. Embedded block boot sidewall - Repeatability

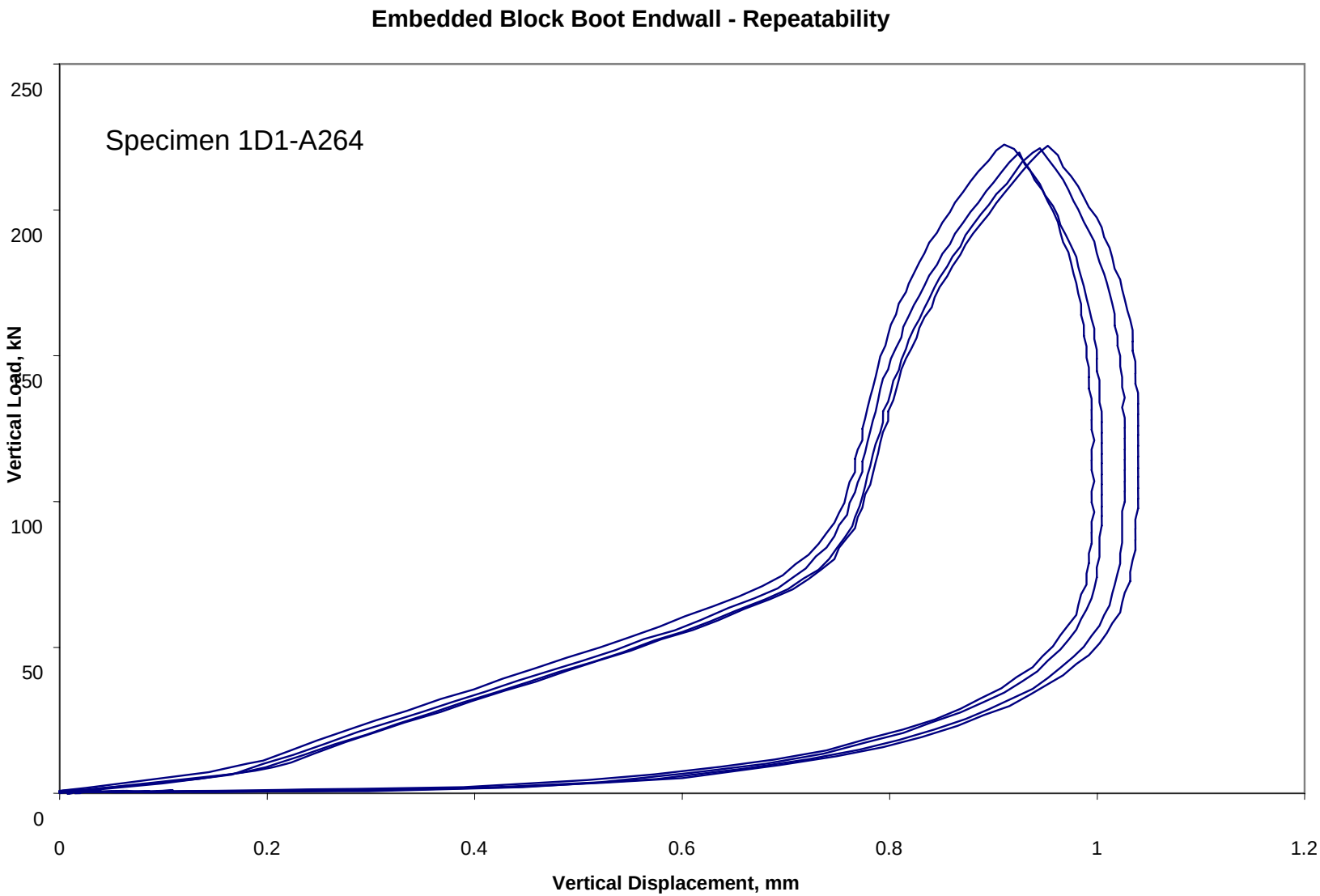


Figure F-4. Embedded block boot endwall - Repeatability

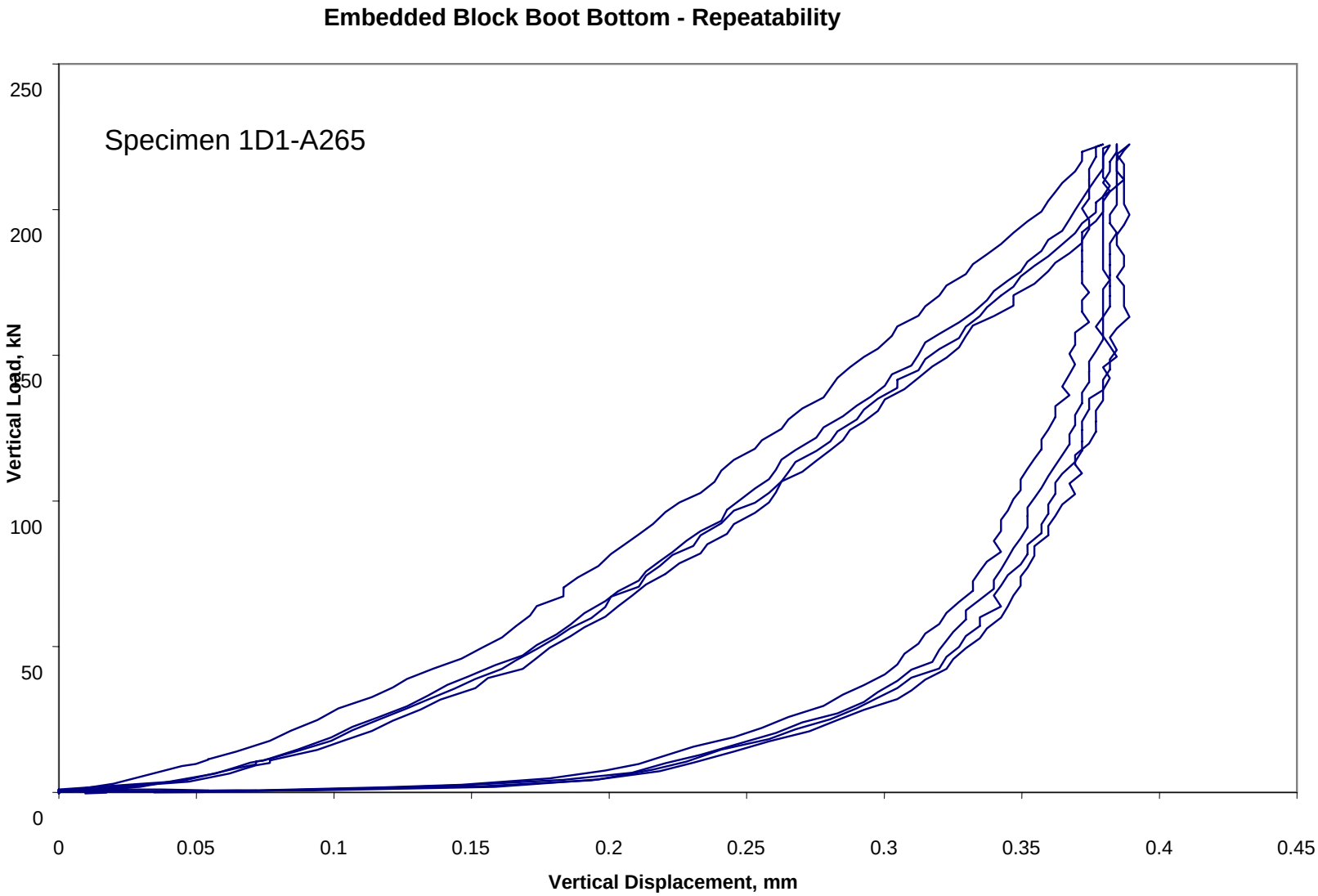


Figure F-5. Embedded block boot bottom - Repeatability

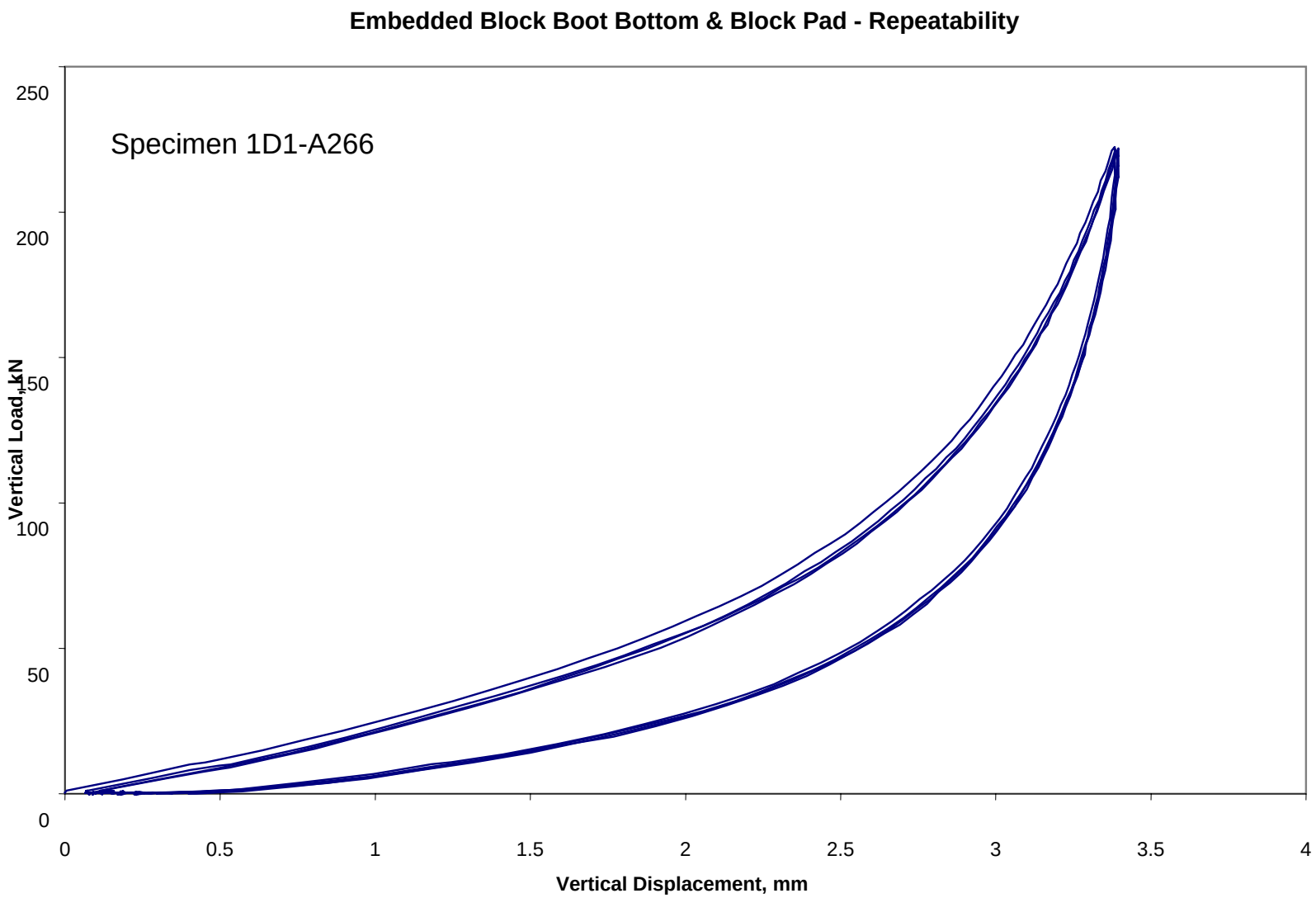


Figure F-6. Embedded block boot bottom and block pad - Repeatability

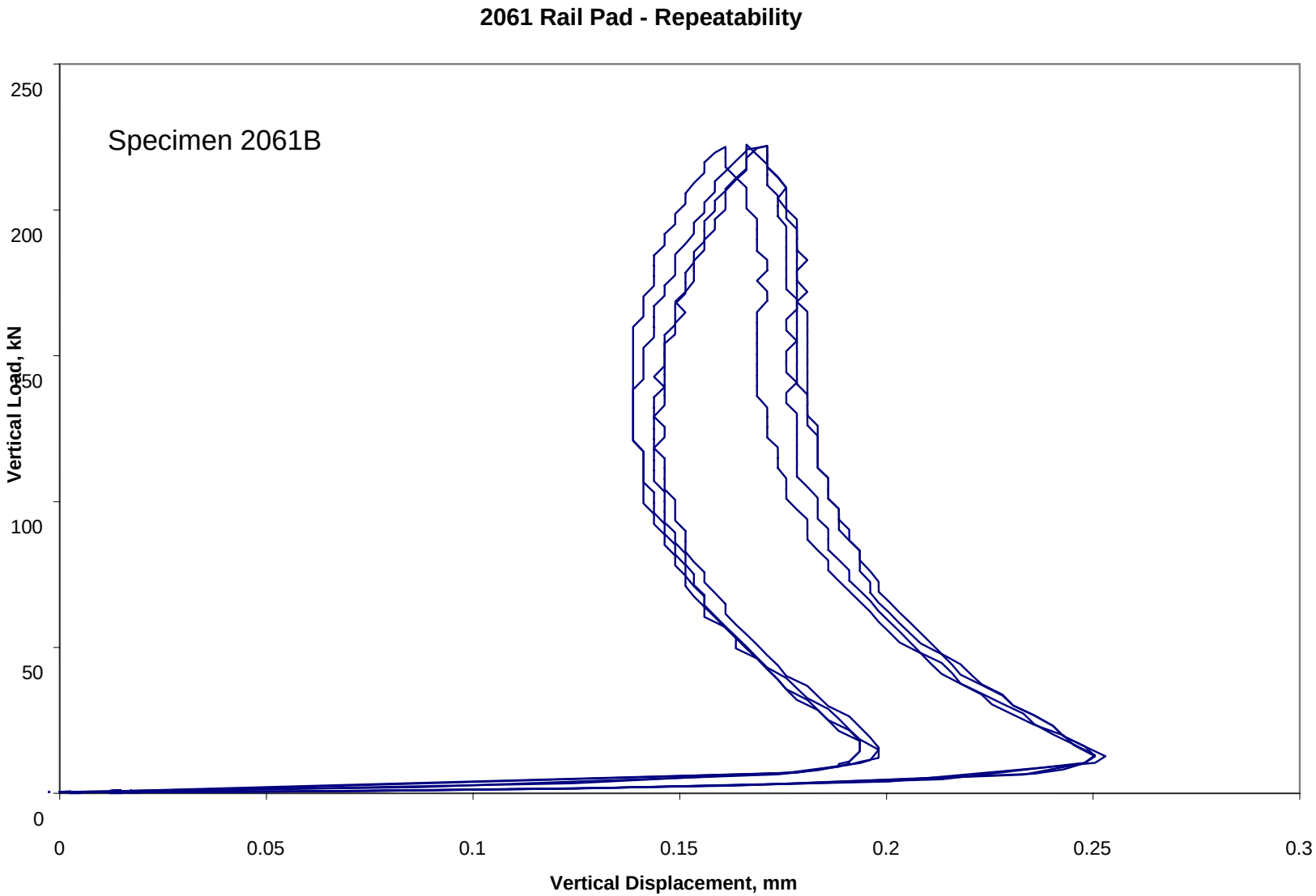


Figure F-7. 2061 Rail Pad - Repeatability

Appendix G
Stiffness versus Frequency Data Plots

A series of tests were run to evaluate the stiffness versus frequency for components of the Embedded block system. Selected components that make up the Embedded block system were tested at frequencies of 1, 5, 10, and 20 Hz to evaluate the change in stiffness at the different frequencies. The desired effect is to have as little variation with frequency as possible. Plots of the test results are shown on the following pages of this appendix. Complete numeral test results are included are available upon request.

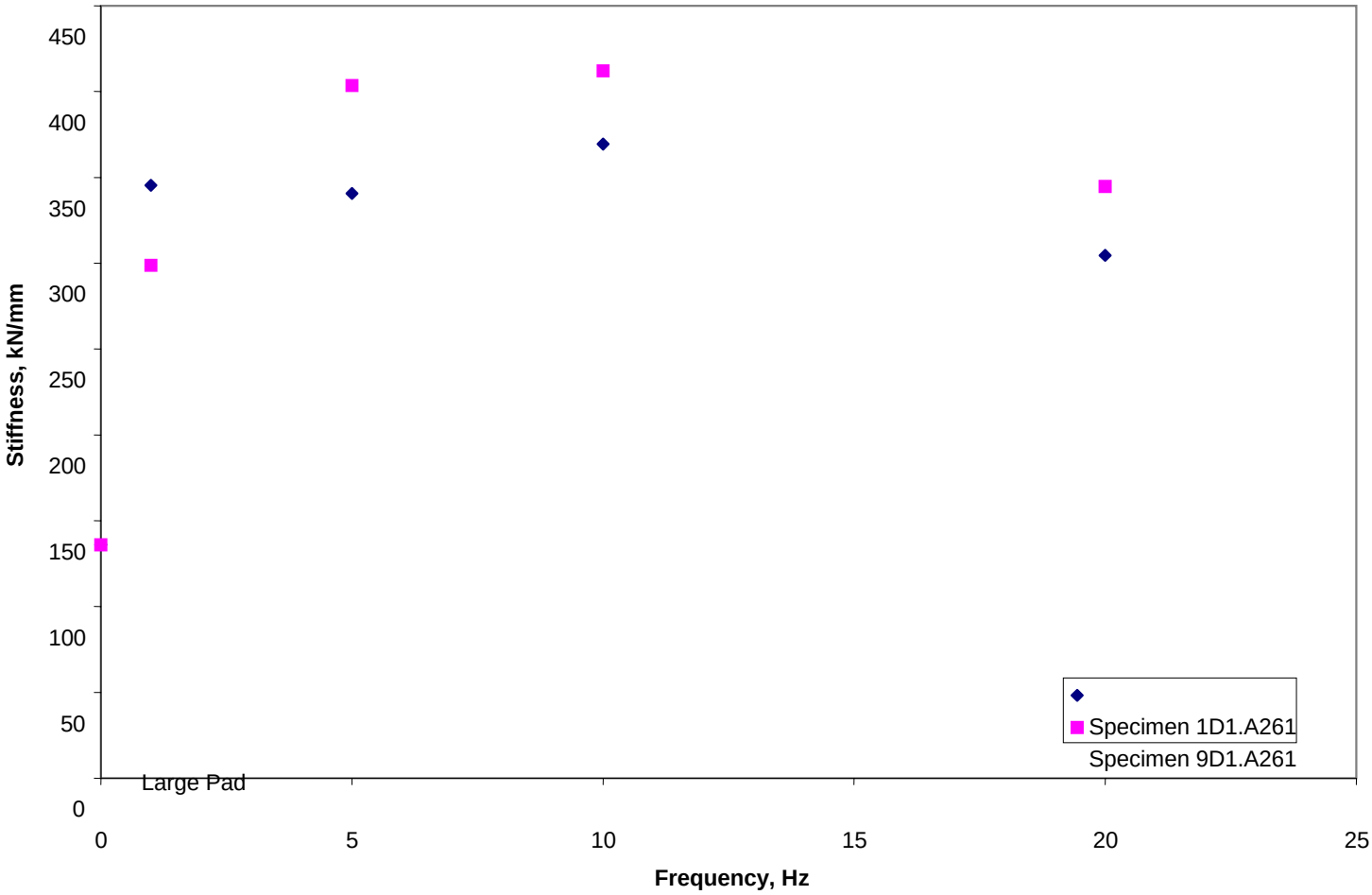


Figure G-1. Stiffness versus frequency for Embedded block pad at 133.4 kN (30 kip)

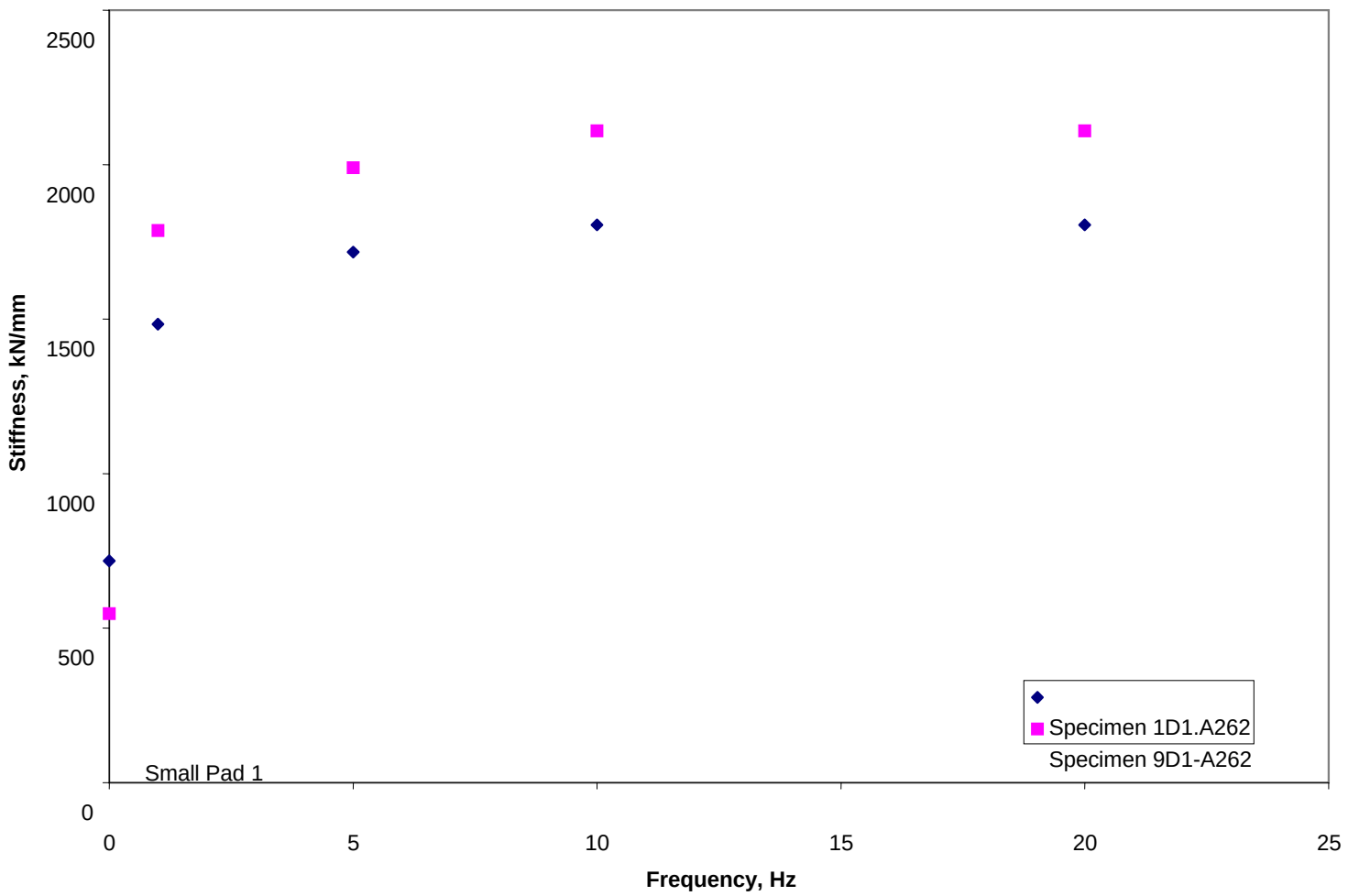


Figure G-2. Stiffness versus frequency for Embedded block rail pad at 133.4 kN (30 kip)

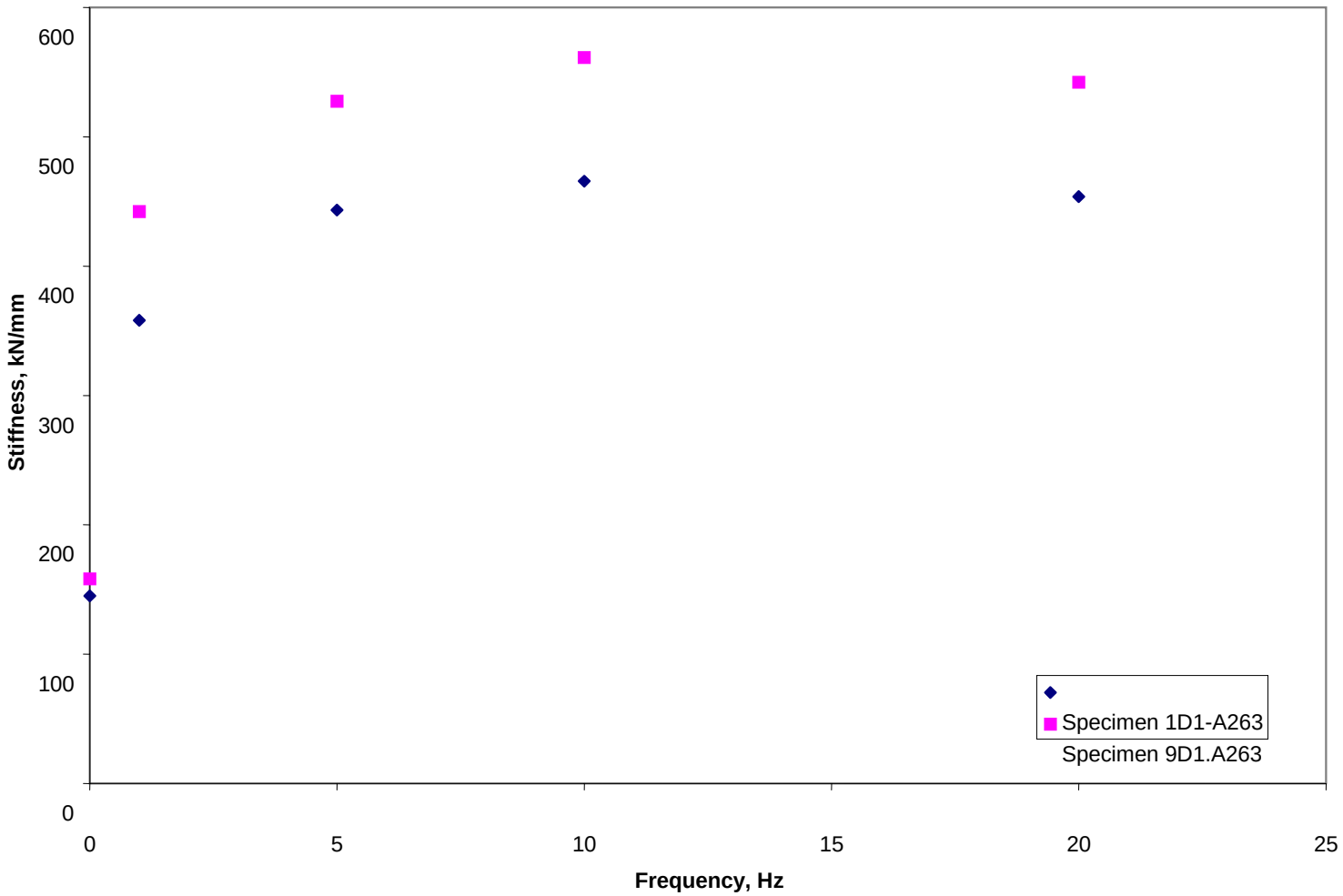


Figure G-3. Stiffness versus frequency for Embedded block boot sidewall at 133.4 kN (30 kip)

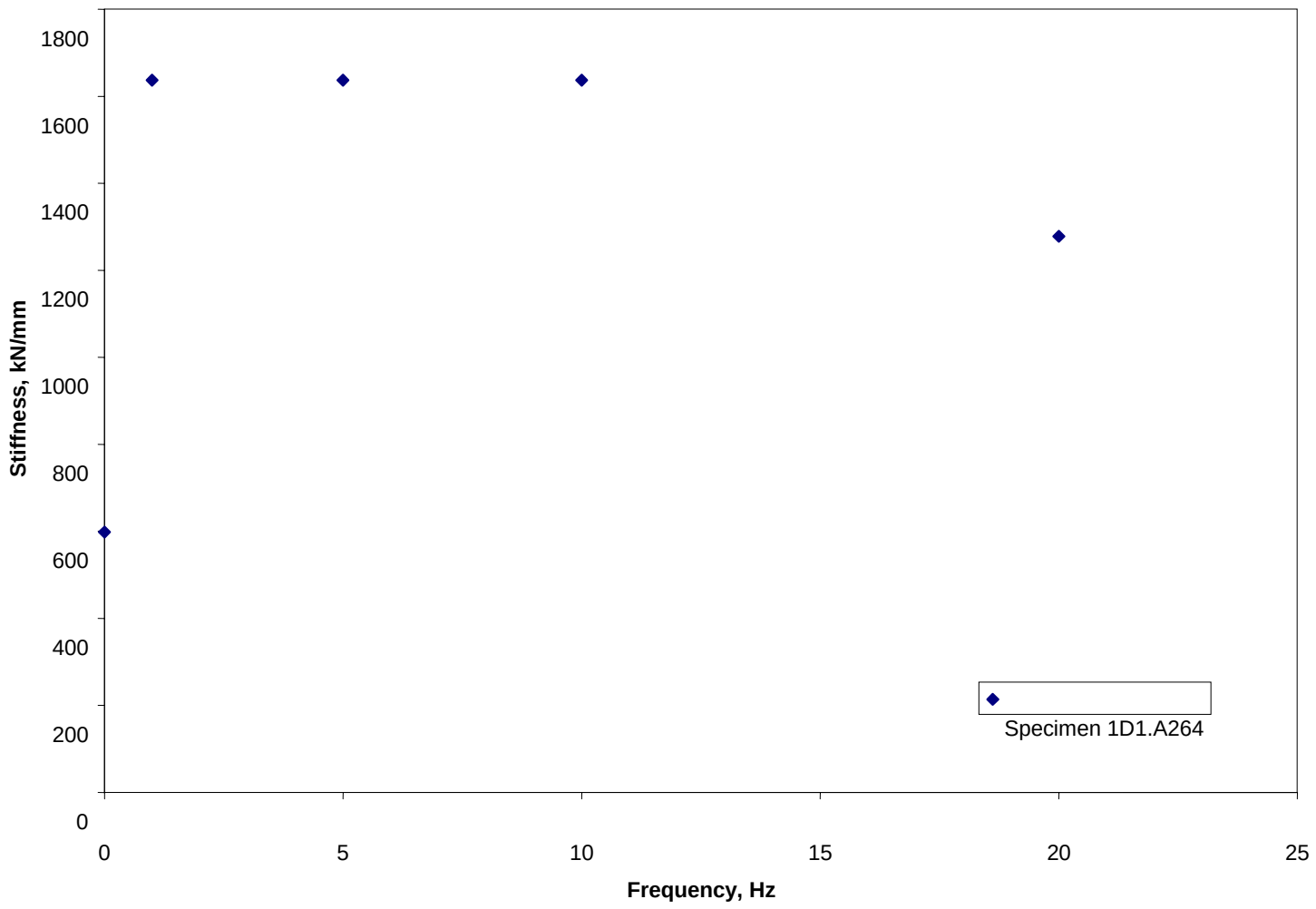


Figure G-4. Stiffness versus frequency for Embedded block boot endwall at 133.4 kN (30 kip)

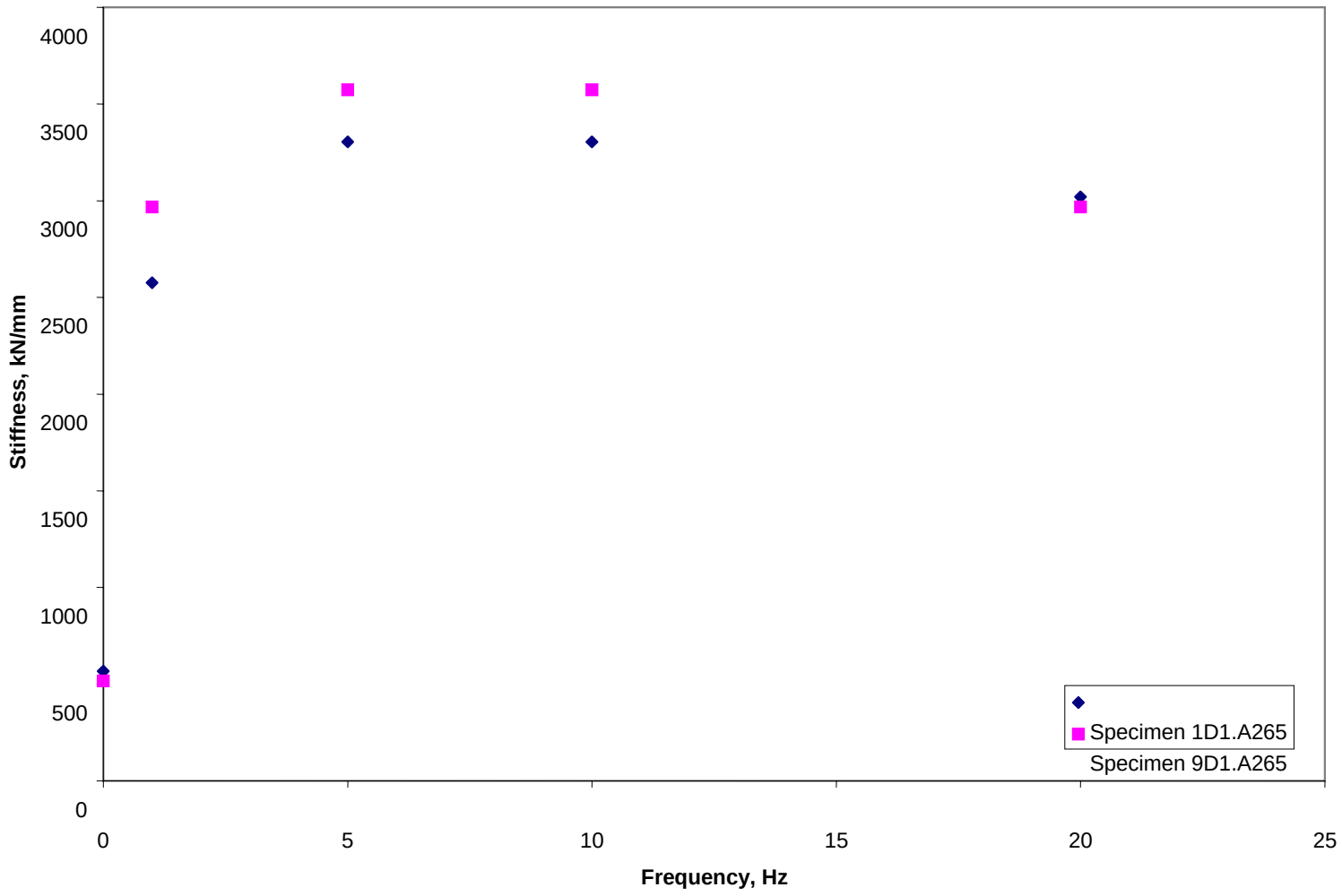


Figure G-5. Stiffness versus frequency for Embedded block boot bottom at 133.4 kN (30 kip)

Embedded Block Boot Bottom and Block Pad Quasi-static and Dynamic Stiffness at 133.4 kN (30 kip)

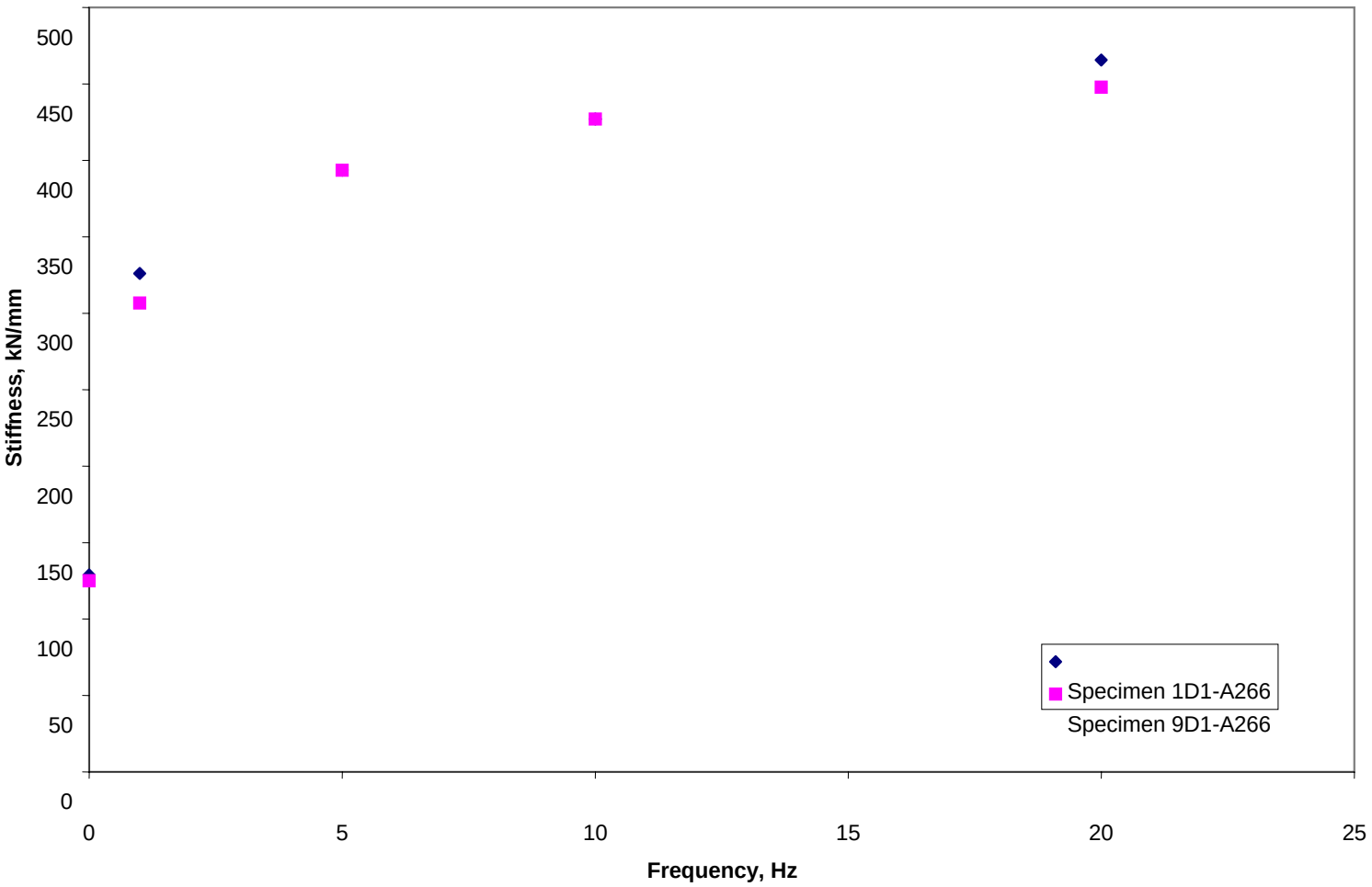


Figure G-6. Stiffness versus frequency for Embedded block boot and block pad at 133.4 kN (30 kip)

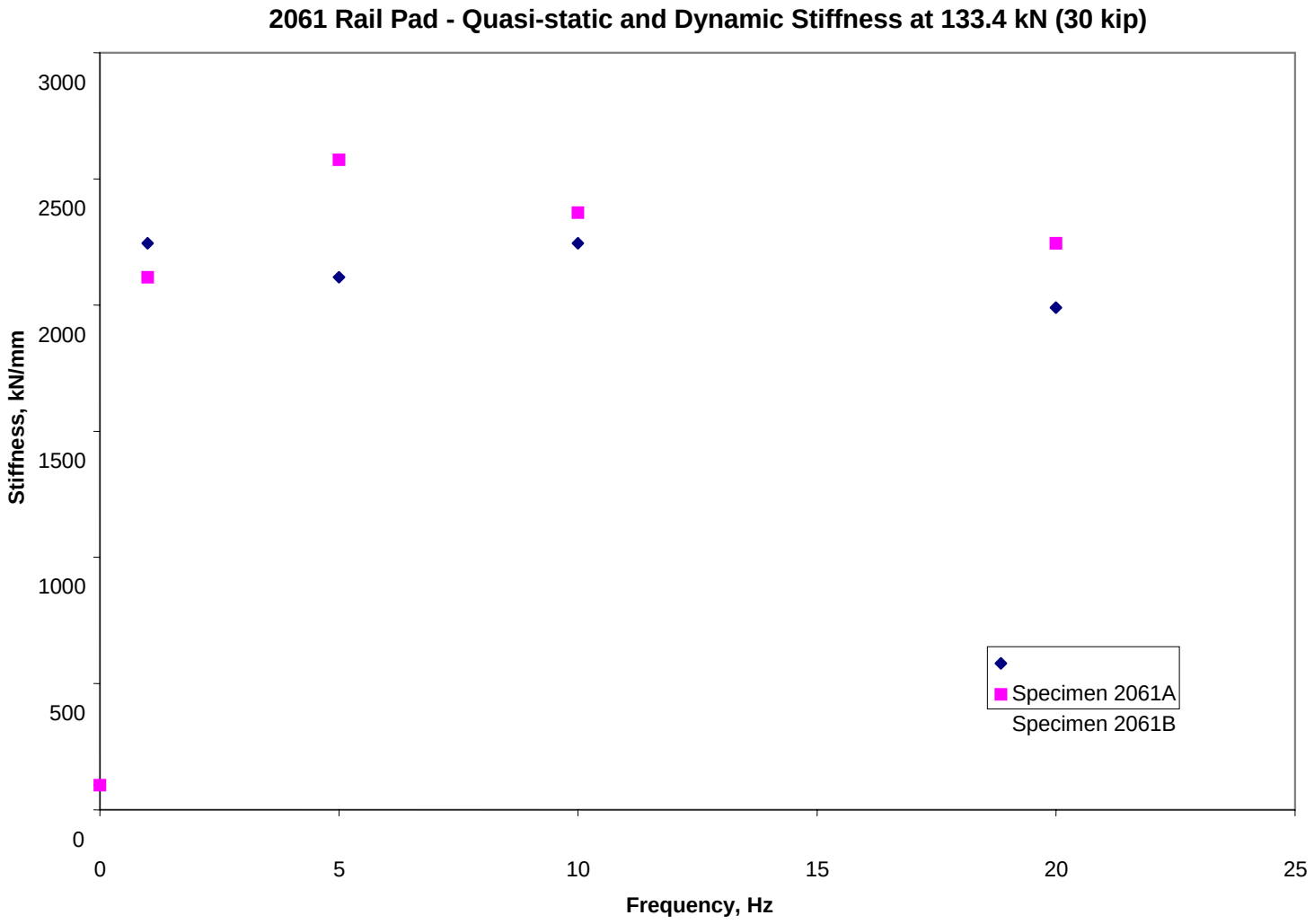


Figure G-7. Stiffness versus frequency for 2061 rail pad at 133.4 kN (30 kip)