Railroad Track Structure Performance Under Wheel Impact Loading

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Increased use of high-productivity railcars of 100- and 125-ton capacity has pushed current track structure designs to the limit. A number of heavy-haul railroads have turned to concrete-tie track to resist the extreme load environment. Two important factors must be addressed in the use of concrete-tie track. First, the higher axle loads result in a tighter "load tolerance" that requires closer control of wheel- or rail-induced impact loading. Second, the dynamic response of concrete ties and fastener systems to impact loading is quite different from that of traditional wood-tie track. In this paper, results of recent studies of concrete-tie track structural dynamics are discussed in the context of wheel and rail impact loading. These studies include a correlation between the experiments at the Facility for Accelerated Service Testing and revenue traffic load environments, an investigation of Northeast Corridor concrete-tie cracking problems, and recent work on extreme-value wheel loads due to freight car wheel profile geometries. The need for dynamic systems analysis in the design of track structures is emphasized by examples of tie, fastener, and insert response to impact loading.

The introduction over the past two decades of high-productivity freight cars of 100- and 125-ton capacity in unit train operations has pushed current wood-tie track structure designs to the limit. Some heavy-haul railroads have resorted to concrete-tie track to help resist the severe load environment. Concrete-tie track has now been installed on major portions of the high-speed Northeast Corridor (NEC) trackage; and a few North American freight railroads have installed substantial mileage in concrete ties. The merits of concrete-tie track are slowly gaining recognition and acceptance.

One important aspect of the design and use of concrete-tie track is the structural response to high dynamic loading due to irregularities in wheel and rail geometry. Damage due to rail joints and irregular weld surfaces has long been recognized by the heavy-haul railroads. Similar damage due to wheel profile irregularities (wheel flats, tread buildup, spalls, runout) has now been identified and quantified, both by computer prediction and actual measurement.

In this paper, the effects of vertical wheel impact loads on track structural response, particularly of concrete-tie track, are examined in the context of track component failure mechanisms.

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BACKGROUND

Recent studies (*1,2*) sponsored by the U. S. Department of Transportation's Federal Railroad Administration (FRA) have shown that damage, to both vehicle and track structures, can be caused by wheel tread irregularities that cannot be identified easily by traditional visual inspection techniques. These studies began in 1980 as an investigation of the causes of rail seat cracks in concrete crossties recently installed on the NEC high-speed track. At the same time, Amtrak noted problems with bearing cage and "hotbox" (hot bearing) failures on its older passenger cars. Wheel load data from instrumented track were used to trace these problems to longer-wavelength wheel profile "runout" geometry errors, primarily on these older cars (*3*).

A Wheel Impact Load Detector (WILD) was designed, fabricated, and installed on the NEC track (*4*) to measure peak wheel loads under each passing wheelset and to identify wheels causing dynamic loads in excess of preset limits. A number of these wheelsets were identified and removed from service by Amtrak and assembled in a test train. A series of test runs was made over an instrumented track section to gather impact load data on these specific wheels. Circumferential profiles were then measured and used as inputs to a vehicle-track interaction model to provide a direct comparison between predicted and measured load time-histories (*5*). An example of this comparison is given in Figure 1.

In addition to the wheel load and geometry measurements, extensive dynamic measurements of track component response to impulse loading were made, both in the laboratory and in the NEC track (*3,6*), for a wide range of loading conditions and for different component combinations. The results of these tests were used to evaluate the relationship between track component dynamic behavior and the observed problems of tie cracking, rail clip movement, and shoulder insert loosening. The results showed that improved track performance can be achieved by designing and combining track components in the context of their dynamic interactions—and, of course, by proper maintenance of the wheel and rail running surface conditions, which are the primary sources of high-impact loads.

LOAD ENVIRONMENT

The structural integrity of a vehicle or track component can be influenced strongly by the dynamic response to wheel-rail

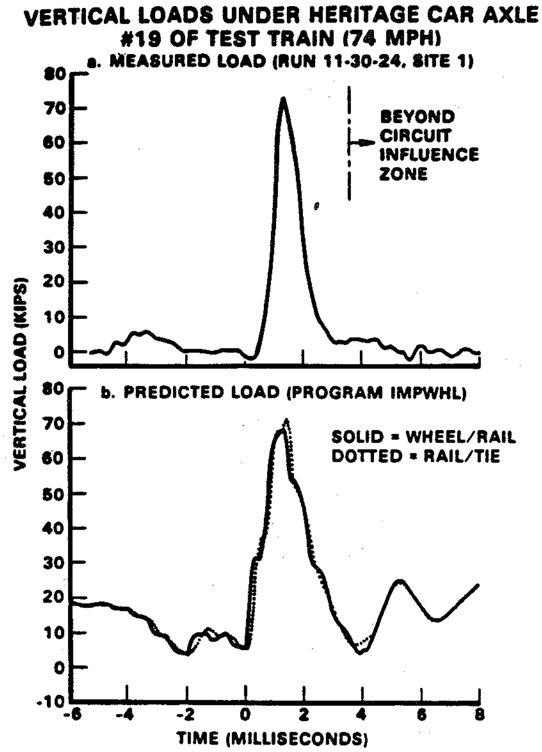

FIGURE 1 Comparison of predicted and measured load time-histories for Heritage car wheel tread anomaly.

impact loads. Consequently, a static evaluation of a component in general is incomplete and in many cases misleading. The first step in a dynamic evaluation is therefore the definition of the service load environment. This definition must include not only a statistical description of the load levels but also a descriptor of the frequency content of the load pulse.

Data from several major field measurement programs conducted over the past decade have provided statistical descriptions of the vertical and lateral wheel-rail load environment. In the early measurement programs on wood-tie track (*7*), data were analyzed within a 300-Hz bandwidth, which was deemed sufficient at that time to handle flat-wheel impact load events. Results from the concrete-tie cracking investigation, however, showed the importance of the higher-frequency (short-duration) impulse loads to which these ties and fasteners could respond. Data from this investigation clearly showed low-probability, high-amplitude vertical load events when the data analysis bandwidth was increased beyond 1000 Hz. For example, the "nominal" and dynamic vertical wheel loads under the mixed traffic on NEC track are compared in Figure 2, a typical "percent-level exceeded" statistical amplitude plot.

In one of the measurement programs (*8*), a major objective was the comparison of the wheel load environment at the Facility for Accelerated Service Testing (FAST) at the Transportation Test Center, Pueblo, Colorado, with the revenue service load environment of similar "real world" concrete-tie track structures. Four revenue service sites were chosen to be instrumented and monitored over a period of time. As expected, the vertical load environments at FAST and at the four revenue service sites were all significantly different because of a combination of factors including type of traffic, train speeds, and wheel tread conditions. The comparison is shown in the cumulative probability of exceedance plots of Figure 3. Note that the FAST load

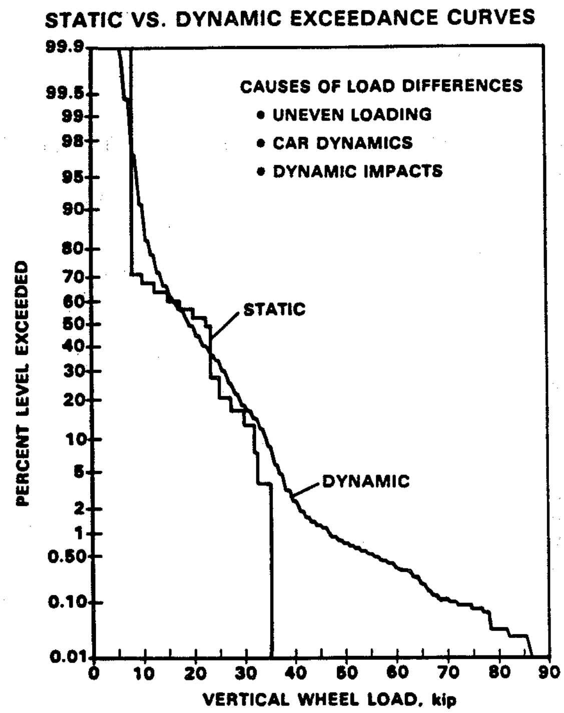

FIGURE 2 Cumulative probability curves of static and dynamic vertical wheel loads on Northeast Corridor concrete-tie track (all traffic).

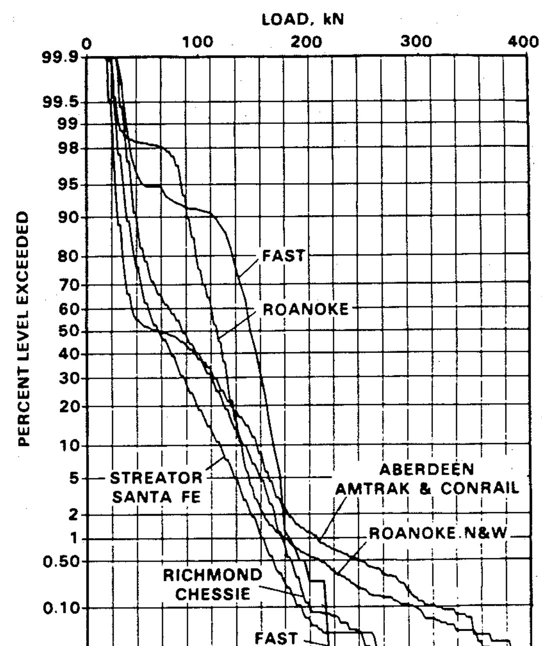

FIGURE 3 Statistical presentation of vertical wheel-rail loads at five correlation study measurement sites.

environment has the highest nominal wheel load, the 50 percent (median) level, because the trains consist primarily of loaded 100-ton cars. However, the plots are truncated at about 50,000 lb (222 kN) reflecting excellent (perhaps unrealistically good) wheel maintenance.

The development of the WILD has greatly enhanced the collection and monitoring of load environment data, particularly the low-probability, high-amplitude events most damaging to track structure. Examples of load statistics from the WILD are shown in Figure 4. Note that these extreme-value load events fall into a logarithmic distribution, which is similar to complex system failure statistics.

In addition to the amplitude statistics, the frequency content of the dynamic load is important in the definition of the load environment. The dynamic load is the vehicle-track interactive response to errors in geometry at the wheel-rail interface (neglecting for the moment other vehicle- and train-induced loads). Frequency content will therefore depend on shape of geometric error, wavelength, and passing speed. Response will also depend on the dynamic complexities of the vehicle (particularly the unsprung mass) and track structural components. Therefore the frequency description of the load environment tends to be quite site specific, in terms of the particular vehicle and particular track, and can require detailed analysis of each given case.

The importance of the frequency (as well as load amplitude) aspects of track dynamic response can be illustrated by recent track degradation experiments on the FAST track. Simulated "engine burn" geometry errors were ground into the rail surface in a section of NEC concrete ties. The largest of these divots produced impact loads under the FAST freight train greater than 90,000 lb (400 kN), sufficient (it was thought) to initiate tie cracking—determined from laboratory tests to be in the 75,000- to 90,000-lb (334- to 400-kN) range (*2*). However, track degradation was rather modest at 20 million gross tons (MGTs) of accumulated "traffic" — a few rail clips had fallen out and some ballast degradation had occurred, but no tie cracks or fastener insert failures were found. Why had this experiment "failed"? There are several possibilities:

- The frequency content of impact loads under the 40-mph (65-km/hr) FAST train was significantly different from that under 80- to 125-mph (130- to 200-km/hr) passenger trains, which was more closely matched to NEC track component frequencies;
- Symmetric (both-rail) geometry errors may have reduced the important asymmetric tie-bending response modes;
- An evolution in tie manufacturing techniques (different material mixes, cure times, etc.) may have increased tie strength; and
- Although "microcracks" were generated in the laboratory, substantially higher impact loads may be required under service conditions to create (and enlarge) "field" cracks.

Track dynamic response has long been assumed to be a primary factor in the generation of rail corrugations. Corrugation shapes artificially introduced on FAST rail surfaces have been observed to decrease in depth under accumulated tonnage, rather than grow, because of off-resonance frequency content.

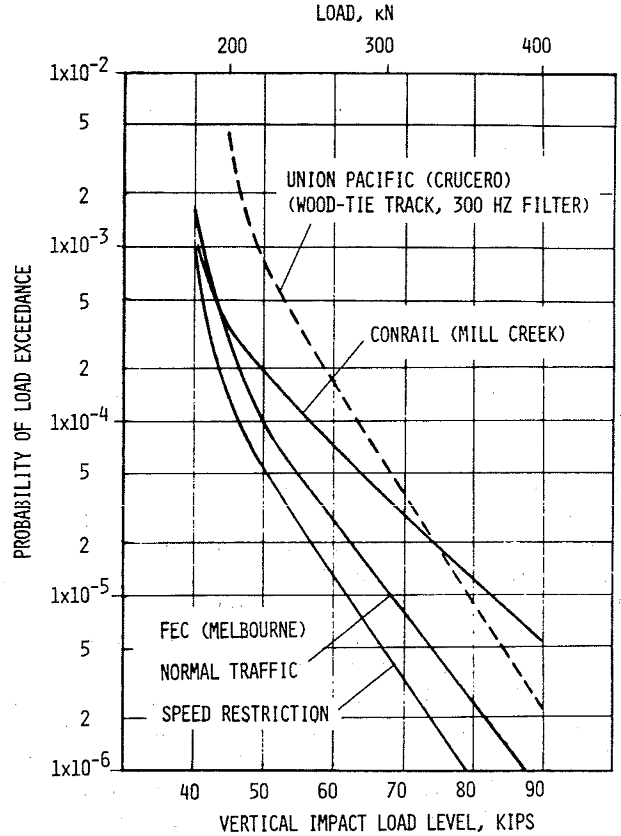

FIGURE 4 Probability of occurrence of wheel impact loads under freight traffic on concrete-tie, continuously welded rail track.

WHEEL AND RAIL SURFACE GEOMETRY

Studies on the NEC proved the existence of long-wavelength (10- to 16-in.) runout geometry errors on older passenger cars. At that time, similar profiles had not been measured on freight equipment. Since then, however, these profiles have been found to be rather typical of flat wheels on freight cars. During 1984 three WILD systems were installed on the concrete-tie track of the Florida East Coast (FEC) Railway. In the first few months of operation, load exceedance reports from the WILD allowed the FEC to "flag" a number of wheelsets that were producing impact loads of more than 70,000 lb (311 kN). Several were generating loads in excess of 100,000 lb (445 kN). Few of these wheels could be rejected from interchange service under the current Association of American Railroad (AAR) Interchange Rules (Rule 41), although some showed signs of distress such as chain spalling, rim spreading, and thrown bearing grease.

With the assistance of FEC personnel, profiles were measured on both wheels of six wheelsets taken from 100-ton freight cars. A special profilometer was used to measure the effective change in rolling radius with distance around the circumference. The wheelset was rotated cradled in its own bearings while these measurements were made. Five of these tread profiles are shown in Figure 5. Profile 1 appears to be a typical wheel flat; similar profiles were measured on two of the other wheels. Although this flat was 0.037 in. (almost 1 mm) in depth, the 6-in. (152-mm) wavelength made visual detection difficult. Profiles 2 and 4 have the well-developed long-wavelength geometry errors typical of older passenger equipment. Profile 5 was measured on the wheel opposite Profile 4. The only other case in which significant error was measured on the opposite wheel was a flat 0.027 in. (0.7 mm) deep directly across from the 0.062-in. (1.6-mm) error of Profile 3.

These five tread profiles were used as direct vertical geometry inputs to the computer model, IMPWHL, to predict peak loads on both concrete- and wood-tie track structures. Some results are shown in Figures 6 and 7. Peak loads versus speed on concrete-tie track are plotted in Figure 6, where a strong speed dependence can be seen for these long-wavelength shapes. In Figure 7 peak loads for concrete- and wood-tie track are compared for three of these profiles. The more resilient wood-tie structure in general produces somewhat lower peak loads, although at some speeds Profile 4 generates higher peak loads on wood-tie track. Note that Profile 5 with its longer (20- to 25-in., 500- to 600-mm), smoother shape produces relatively low dynamic loads in spite of its 0.070-in. (1.8-mm) depth.

In addition to wheel tread imperfections, load-producing geometry errors are also found on the rail running surface—rail joints, battered welds, engine burns, and so forth. These cause repetitive dynamic loads at a fixed point in the track and can produce rapid degradation of track components, ballast, and subgrade. Several engine-burn geometries were

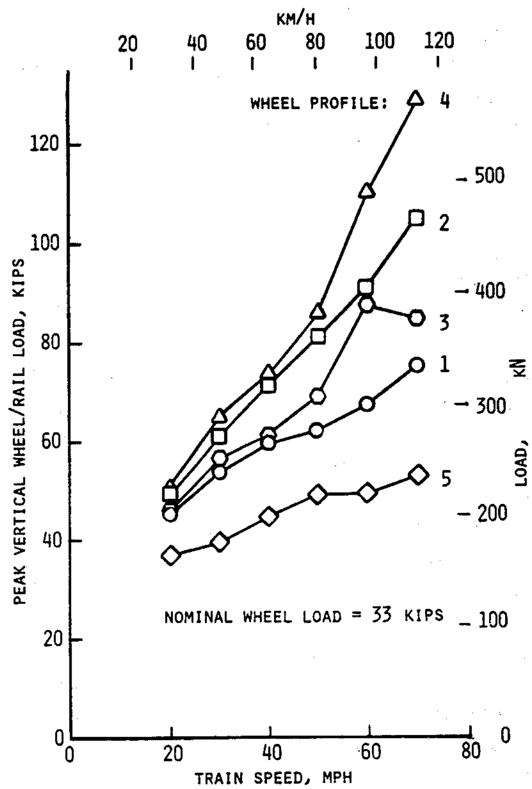

FIGURE 6 Peak vertical impact load versus speed for five wheel profiles on concrete-tie track (loaded 100-ton freight car).

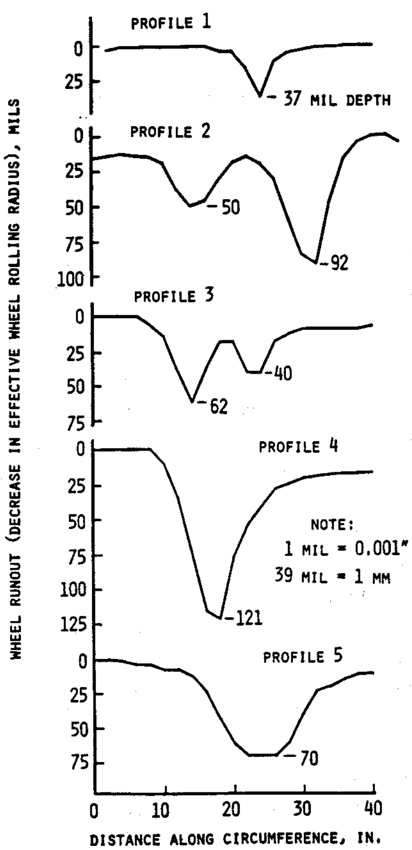

FIGURE 5 Five representative measured wheel circumferential tread profiles.

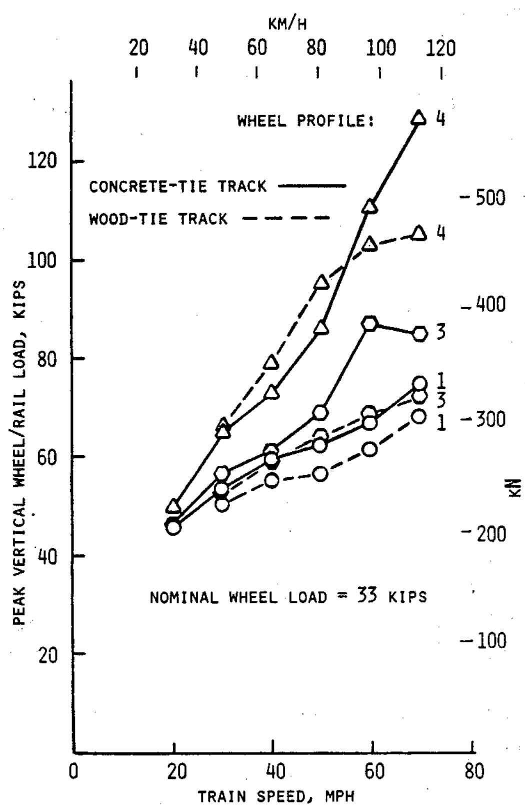

FIGURE 7 Peak vertical load on concrete-tie track versus good wood-tie track.

measured on the NEC using a precision-wheel profilometer to measure the change in vertical position of the wheel axis of rotation with longitudinal motion along the rail. With time, the rail surface profile in the vicinity of the engine burn assumes that of a low joint, as shown in Figure 8. This profile had a 0.090-in. (2.3-mm) depth over a 60-in. (1.5-m) span, with a pronounced dip at the engine burn itself. Rail clip fallout and loosened inserts were noted on the tie nearest the burn. A vertical dynamic load of 66,000 lb or 294 kN, (a 16,000-lb, 71-kN, static load) with a 3-msec pulse time duration was predicted under a passenger car wheel at 120 mph (194 km/hr) by using this profile in the computer model.

STRUCTURAL RESPONSE OF TRACK

Experimental studies were conducted both in the laboratory and on revenue track to investigate the dynamic response of the track to impact loading. Field tests were performed on the NEC concrete-tie track in Maryland in the fall of 1983. In addition to vertical wheel loads, the tie-bending strains; rail, tie, and ballast accelerations; and rail fastener displacements and strains were measured. Track response was measured under revenue traffic loading and under impact loads from an automated drop hammer designed to simulate a moderate flat-wheel impulse. Parameter variations in these tests included impact energy, fastener type, tie pad type, and different tie locations. Similar tests were performed in the laboratory on single ties and on a five-tie NEC track replica. Dynamic data were evaluated by fast fourier transform analyzers, which computed frequency spectra and transfer functions for selected signals (*3,6*).

Concrete-Tie Dynamics

The performance history of concrete ties in North America (*9*) has included tie failures that generally start with small cracks at the rail seat or the insert, as shown in Figure 9. The rail seat cracks progress upward to the top of the prestress strands and branch out, resulting in shear failure of the tie. This usually causes the insert to fail, thus reducing the gage-holding capacity of the tie. Rail seat cracks, and loss of adhesion around the fastener inserts, are related strongly to wheel-rail impact loads. Other cracks, such as the tie center flexural cracks in Figure 9, are less critical to the structural capacity and function of the tie.

Dynamic analyses of concrete ties have shown that these ties have several modes of vibration, which are strongly excited by wheel-rail impacts. The first three transverse beam-bending modes are shown in Figure 10a. The second

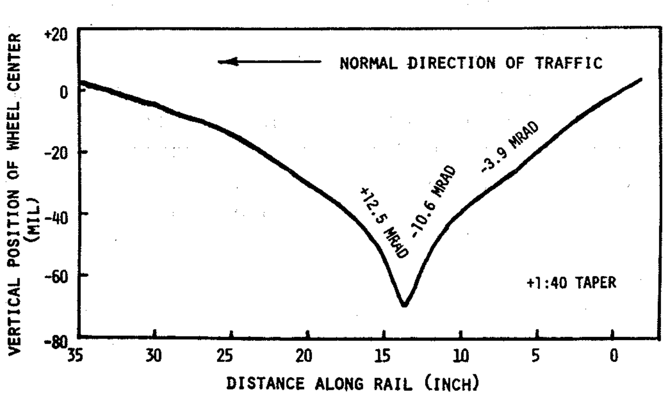

FIGURE 8 Measured rail running-surface profile near battered engine burn.

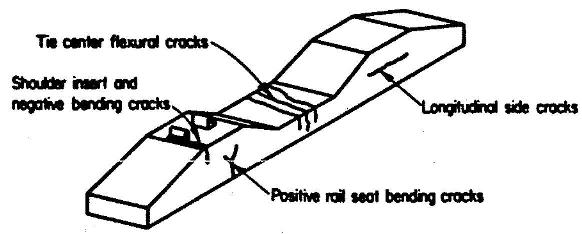

FIGURE 9 Typical flexural cracks in concrete ties.

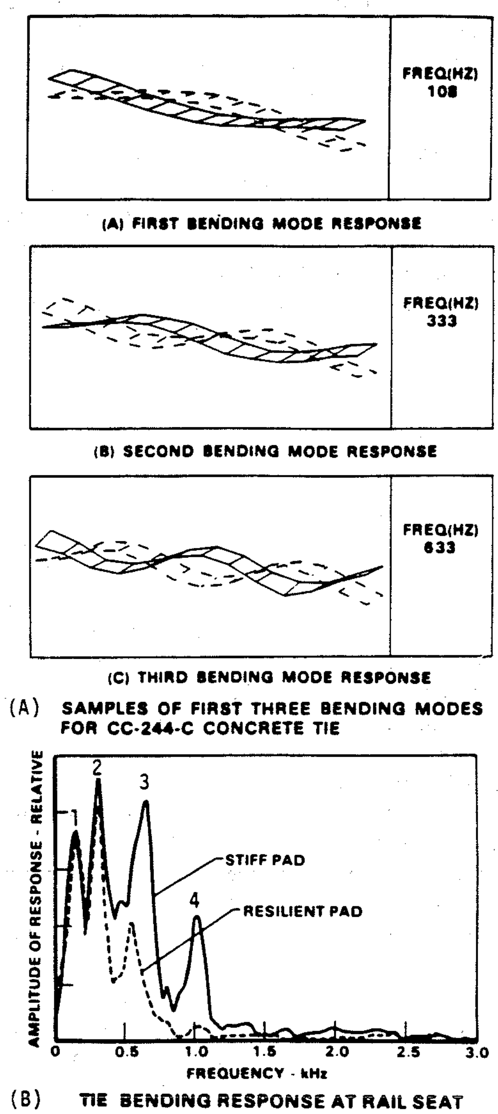

FIGURE 10 Attenuation of tie-bending response to impact loading with resilient rail-seat tie pad.

and third modes (333 and 633 Hz, respectively), in particular, generate large tensile strains at the bottom of the tie in the rail seat region. Because the second mode is asymmetric, large dynamic strains can occur by superposition under the rail seat opposite the struck rail. In the field, it has often been noted that rail seat cracks will occur opposite a joint, weld, or engine burn.

The primary load path into the tie for wheel-rail vertical impact loads is through the tie pads. Once excited, the tie — a very lightly damped element (typically less than 1 percent of critical damping in a given mode) — literally rings like a bell. Consequently, the dynamic characteristics of the tie pad are critical to tie performance. The pad must act as a low-pass mechanical filter with a "break frequency" low enough to attenuate most of the energy from the impact at the second and third tie-bending frequencies, reducing the effects of this excitation source. The original NEC ethyl vinyl acetate (EVA) pads proved far too stiff to perform this function. A more resilient pad with a dynamic stiffness of about 1,000 kips/in. (180 MN/m) was tested in the laboratory and in the NEC track. A comparison of tie bending moment response is shown in Figure 10b for this pad versus the standard EVA pad (a dynamic stiffness of 5,000 kips/in., 880 MN/m) under a typical impact load. A substantial reduction in response, particularly at the third bending mode, can be seen.

Field tests on the NEC were undertaken to confirm the results of laboratory tests. Two resilient synthetic rubber tie pads were tested sequentially in the same location under equivalent traffic conditions. Statistical plots of rail-seat bending moment in Figure 11 show a substantial reduction with the resilient pads. The 6.5-mm pad was chosen by Amtrak for new concrete-tie installations and for some retrofit installations on previously installed track.

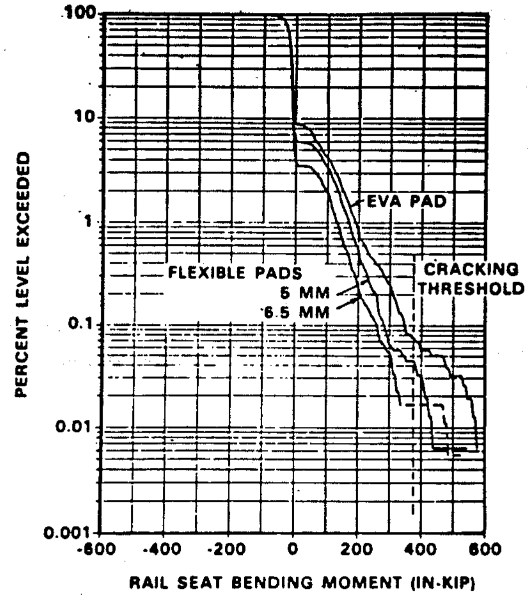

FIGURE 11 Statistical comparison of rail-seat bending moment under three different pads on NEC track.

The NEC track had experienced a small but significant number of clip fallouts. Three test sections were set up for an extensive track-walker survey over a 2-year period. Results from this survey were coded and stored in a computer library system called BASIS (*1*). Statistical analysis showed that on one section with older, rougher rail (mechanical joints, engine burns, etc.) 32 percent of fastener fallouts occurred within five ties of a known rail surface anomaly. Other sections had a more random pattern of clip fallouts.

Laboratory and field experiments were performed to investigate the clip fallout phenomenon. Tests included modal vibration analysis of free clips and repeated impact loading on the five-tie track section. Field tests on the NEC included drop hammer impact loading as well as measurements under revenue trains. Comparison of laboratory and field data showed that under impact loading the clips respond strongly to tie dynamics, particularly at frequencies near the third and fourth tie bending modes (633 and 1025 Hz, respectively). Further, clip resonant conditions in the 800- to 2000-Hz range are also excited and influence response in the longitudinal axis, the clip fallout direction. Typical longitudinal displacements of two different clip designs are shown in Figure 12: Type A, the current NEC design, and Type B, a somewhat stiffer design providing about 14 percent more preload. The dynamic behavior of the two in the longitudinal (fallout) direction is strikingly different: Type A exhibits a strong oscillation at 1050 Hz, which is near the fourth tie bending mode. In contrast, the response of Type B is more broadband and well damped. A number of the Type B clips have been installed on the NEC with no reported fallout problems.

The tie pad influences clip deflection response under traffic by its effect on the relative vertical and rocking motions between the rail and tie. Measurements of clip deflection response under traffic (including 100-ton cars) showed that rail-rocking displacements were actually smaller with the

Rail Fastener Dynamics

In concrete-tie track, the rail fastener system performs the tasks of both cut spike and rail anchor in wood-tie track: maintain track gage, prevent rail rollover, and provide longitudinal rail restraint under thermal and train traction and braking loads. Unlike the cut spike, concrete-tie fasteners provide positive restraint of rail uplift. On the NEC track, the fastener system consists of a Pandrol 601A rail clip and a cast-in clip insert with insulator. Several other types of fastener systems are currently in use or under test at FAST and on freight railroads.

For the current NEC clip design, progressive clip movement out of the insert is resisted only by the frictional forces at the clip-rail and clip-insert interfaces. Clip relative movement will occur when the net static and dynamic forces on the clip exceed the frictional "breakout" levels. Fluctuations in vertical preload occur in response to wheel-rail loads. For impact loads, the dynamic motions of the clip and tie may be sufficient to cause large momentary reductions in preload, which in turn may cause incremental movement of the clip out of the insert. Clip fallout therefore could result from repeated impact loads or from high vibration levels of rail and tie under traffic.

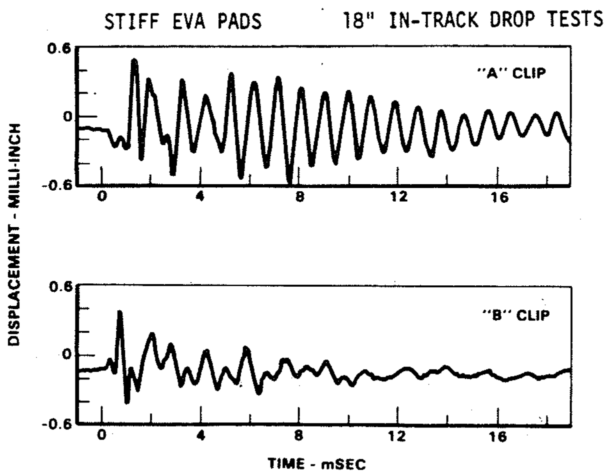

FIGURE 12 Comparison of clip longitudinal displacements at center leg for two clip designs.

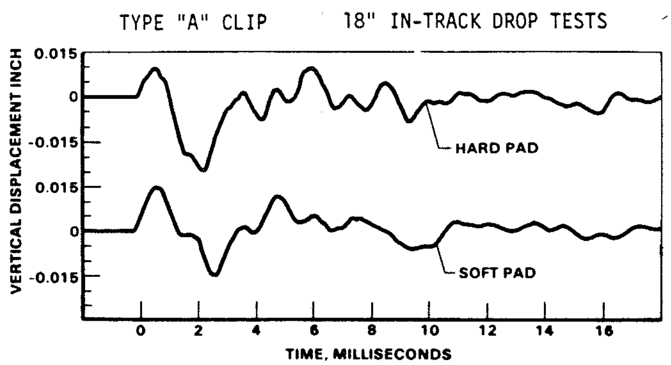

FIGURE 13 Comparison of clip (toe) displacements with stiff EVA and resilient tie pads.

resilient pads than with the very stiff pads (*3*). Similar measurements under impact loading are shown in Figure 13. Although the initial peak-to-peak clip deflections are comparable (0.030 to 0.035 in., 0.8 to 0.9 mm), the maximum clip-spreading deflection due to rail uplift relative to the tie is about 40 percent less with the resilient pad than with the stiff EVA pad. The reduction in preload corresponding to the maximum initial depression of the pad is, however, about 50 percent greater with the resilient pad. This is an important area to evaluate for 125-ton traffic because of the significantly higher nominal deflections under the heavier axle loads.

Tests were performed to explore the cause of bond loss between the cast-in fastener insert and the tie shoulder. Although the tests did not fully identify the failure mechanisms, observations and test results indicate that insert loosening can be caused by vertical impact loads smaller than necessary to crack a tie. Perhaps 100,000 impacts of moderate amplitude can loosen the insert. Vibration analyses of insert response to rail impact loading have revealed several modes of axial vibration (vertically oriented to the rail) in the 4- to 8-kHz range. When partly or fully constrained, the insert vibrates at 5 to 7 kHz, and, when unconstrained, the insert responds at 11 kHz. These complex modes are associated with compression ("standing") wave action. Although the amplitudes of motion at the steel-concrete interface are quite small, a microscopic pulverizing action may take place over time that results in gross loosening of the insert. Again, the more resilient tie pad will reduce the excitation energy at the tie, which reduces this vibrational response at the insert.

CONCLUSIONS

The results of these studies have shown that concrete-tie track, like any other complex mechanical system, requires an understanding of dynamic interactions between components to achieve an optimum design. On the basis of the results of these field and laboratory experiments, the following conclusions can be drawn about the dynamic performance of track components:

1. Concrete-tie track performance is strongly associated with the ability to withstand impact loads. Proper track design should therefore include dynamic analyses to optimize performance.
2. Laboratory evaluation of track components can be accomplished with the aid of a drop hammer that simulates the magnitude and frequency content of the impact loads found in revenue service.
3. Dynamic behavior of components should be evaluated to assure that no undesirable matching of responses takes place between components. For example, decreasing pad stiffness may increase dynamic wheel-rail contact forces, thus increasing the tendency toward initiation of rail corrugations.
4. A dynamically optimized track structure must still withstand the abuse of the largest impact loads actually found in service. An economic trade-off exists between building stronger (more expensive) track and maintaining more perfect wheel and rail running-surface geometries.
5. Impact load response of other vehicle and track components (e.g., wheel bearings and ballast) is not as well defined as concrete-tie-fastener response, but there are ample economic reasons for the dynamic analysis of these components as well. From the limited sample of wheels and bearings examined, there is a strong correlation between high load-producing wheel geometries and bearing damage (loss of grease, cage disintegration, race and roller distress). Wheel "thumpers" are at least a subset of the hotbox problem.

Design and evaluation techniques have been developed that can be applied to track that carries 125-ton cars. Because the 125-ton equipment is ever closer to the design limits of current rail, ties, and fasteners, wheel-rail impact loads caused by imperfections in either wheel or rail geometry become even more significant. Higher productivity is the purpose of using 125-ton cars. A matched higher productivity in track structures may require a greater investment in track design, in construction capital, and in both track and equipment maintenance techniques to meet the closer load tolerances of 125-ton operations.

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