

# Continuous-Welded Rail on BART Aerial Structures

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## ABSTRACT

A review and description are presented of the design approach and development of materials needed to directly attach continuous-welded rail (CWR) to prestressed concrete aerial structures on the San Francisco Bay Area Rapid Transit (BART) Project. The methods used to calculate the interaction forces and movements between the CWR and aerial structure are defined and the results are illustrated. Special designs for track crossovers and anchor abutments are described. BART's construction of 24 route miles of aerial track was the first large-scale installation of CWR directly affixed to concrete girders in North America. The design concepts and hardware developed for BART established a basis for the design of all subsequent new transit projects.

The San Francisco Bay Area Rapid Transit (BART) Project, which was authorized in 1962 and placed in systemwide operation in 1974, has been the subject of articles and discussions describing the many interesting engineering and construction issues. Few of these papers have covered issues relating to trackwork, although significant work was accomplished in such areas as direct-fixation rail fasteners, concrete cross ties, and the installation of continuous-welded rail (CWR) on aerial structures. The latter issue is (a) of continuing importance in the transit field and (b) of growing importance to railroads. It is, therefore, the subject of this paper.

Early on in the Project's design, the following three basic decisions were made that controlled track and structure design:

1. CWR would be used to the maximum extent possible to reduce track maintenance costs and to minimize noise and vibration.

2. Aerial structures would be simple-span prestressed or post-tensioned concrete girders supported on T-shaped concrete piers. A standard design would be used systemwide for (a) single grade separations longer than 200 ft (61.00 m) and (b) long viaduct-type structures, the longest of which is 10 mi (16.1 km). Ballast deck bridges would be used for all grade separations shorter than 200 ft.

3. Track construction on aerial structures would be by direct attachment of rail to concrete girders to minimize dead load, thus contributing to the aesthetics of minimum girder depth and pier diameter. In addition, the rail fastener design would incorporate sound and vibration absorption, electrical insulation, and a means for adjusting the line and grade of the track.

Individually, these requirements did not break new ground in engineering design. Knowledge and experience were available in the railroad applications of CWR, in post-tensioned concrete bridges, and in rapid-transit applications of direct-rail fastening. However, the combination of these requirements presented a challenge that few engineers had ever faced before on a domestic railroad or rapid transit project. How this challenge was met is the subject of the following sections, each of which describes a component or aspect of the track-aerial structure system.

## BART AERIAL STRUCTURE

The standard BART aerial structure consists of two lines of precast, post-tensioned, concrete box girders, spaced 14 ft (4.27 m) apart, and supported on 5 ft (1.525 m) hexagonal concrete T-shaped piers (1). Simple support is used for spans up to 100 ft (30.5 m) and continuous supports or composite steel girders with cast-in-place concrete deck, or both, are used for longer spans.

The standard box girder is trapezoid-shaped, 4 ft (1.22 m) deep with an overhanging deck-slab 11 ft 8 in. (3.556 m) wide to support the 5-ft 6-in. (1.6775-m) gage track. Figure 1 shows a typical girder in the casting yard. The aerial girder deck provides a

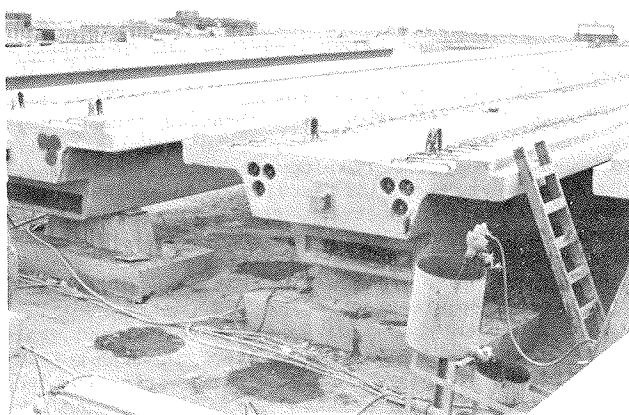


FIGURE 1 Aerial girder in casting yard in Richmond, California.

continuous, 31-in. (78.7-cm) wide by 3-in. (7.6-cm) deep block-out under each rail to receive a second pour of reinforced concrete to support the rail fasteners. Stirrups project up into each block-out on 10 in. (25.4 cm) centers to anchor the second pour concrete to the girder.

The design of aerial structure was controlled by stringent criteria covering expected loadings in the Bay area, aesthetic considerations, and BART operat-

ing requirements. Of these requirements, the following are of particular interest to the track engineer:

1. Longitudinal thermal interaction forces between the CWR and the simple-span structures were mathematically simulated and found to be significant on the first three piers from an abutment or the end of an aerial crossover. Design interaction loads of 17,000 lb (75 650 N) per rail were applied to each of these piers.

2. Girder lengths were controlled and a uniform pattern of girder fixed or free (or both) end support was adopted to minimize the relative thermal movement between the rail and structure. These requirements, along with rail fastener requirements, avoided the use of such special devices as rail-free fasteners and rail expansion joints.

3. Transverse loading due to CWR of 11,000/ radius lb/ft (1 604 918 N/m) of rail was applied to all curved structures.

4. All girders were cambered to compensate for deflections due to dead and live load including impact. Actual camber values were subject to wide variations; however, the typical 70-ft (21.35-m) girder was designed for initial midspan camber of 0.23 in. (5.8 mm), which would grow to 0.56 in. (14.2 mm) over the long term. Designed live load plus impact deflection on the same girder was 0.34 in. (8.6 mm). The top of the rail was installed at the profile grade, without regard to the camber of each girder.

5. All girders were designed with notch ends to minimize the distance from the bearing surface to the top of the rail. This feature increased the stability of the girder under lateral loads and reduced the relative longitudinal push-pull movement between rail and girder due to girder end rotation produced by live-load deflection. This push-pull movement produced fatigue loading on the rail fastener and was introduced as a laboratory test requirement during the fastener development program.

#### RAIL FASTENER DEVELOPMENT

A BART rail fastener development program, initiated in January 1966, by the AAR Research Center, consisted of (a) a detailed investigation of existing rail fasteners to attach rail to concrete, (b) mechanical and fatigue testing of selected rail fasteners, and (c) sound and vibration studies (2). Concurrent with the effort, seven supplier firms were working on the development of new rail fasteners to meet the BART service requirements. This cooperative effort between the engineers and the suppliers provided an excellent climate for the development of rail fasteners that could (a) be manufactured at a reasonable cost and (b) satisfy BART service requirements.

All input to this program was gathered and evaluated during the first half of 1967. In August 1967, BART issued a performance-type specification for direct-fixation rail fasteners that included the following principal requirements:

1. General requirements:
  - (a) Single design for all concrete trackbeds.
  - (b) One-man installation.
  - (c) Transverse adjustment of plus or minus 1 in. (2.5 cm) in 1/8-in. (3.2-mm) increments.
  - (d) Maximum thickness of 1 1/2 in. (3.81 cm).
2. Rubber component tests in a hostile environment.
3. Laboratory test requirements:
  - (a) Static longitudinal load versus deflection. The load at 0.1-in. (2.5-mm) deflection

must be between 1,800 and 3,600 lb (8,000 and 16,020 N).

(b) Static lateral versus deflection. The deflection at a lateral load of 3,000 lb (13,350 N) must not exceed 0.33 in. (8.47 mm).

(c) Minimum direct current resistance of 100 megohms.

(d) Minimum alternating current impedance of 10,000 ohms to frequencies between 20 Hz and 10 kHz.

(e) Repetitive push-pull test of plus and minus 1/8 in. (3.2 mm) for 1.5 million cycles.

(f) Repetitive tie-wear tests of a 14,500-lb (64,525-N) vertical load with a lateral load that varied from 5,000 lb (22,250 N) on the gage side to 2,600 lb (11,750 N) on the field side applied to the railhead for 3 million cycles.

(g) Heat aging at 212°F for 70 hr before longitudinal and lateral static tests.

4. Qualification--laboratory test reports were required before production to prove conformance.

5. Quality control--additional laboratory tests were conducted at random during production to ensure quality.

Three bids were received in December 1967 ranging from \$9.05 to \$10.90 per fastener. However, these bids were rejected and the responsibility of furnishing rail fasteners was transferred to the track installation contractors. Using this method, the contractor would select the fastener with the lowest total cost for furnishing and installation.

The first trackwork contract was awarded in April 1968 to Dravo Corporation. The contractor elected to furnish and install the Landis fastener. This fastener was also furnished in the four subsequent trackwork contracts that were split between Dravo Corporation and the William A. Smith Contracting Company, Inc. Figure 2 shows a Landis rail fastener installed on a BART aerial structure.

The rail fastener is a sandwich-type pad consisting of a 1/4-in. (6.4-mm) thick, steel lower plate and a 1/2-in. (12.7-mm) thick, steel upper plate bonded together by a 3/4-in. (19.1-mm) thick elastomer pad. The rail is clamped to the upper plate with cast steel clips and high-strength bolts and the lower plate is anchored to the concrete deck by two 7/8-in. (22.2-mm) diameter high-strength bolts threaded into embedded inserts in the concrete. The elastomer provides electrical resistance, vertical elasticity to dampen sound and vibration, and longi-

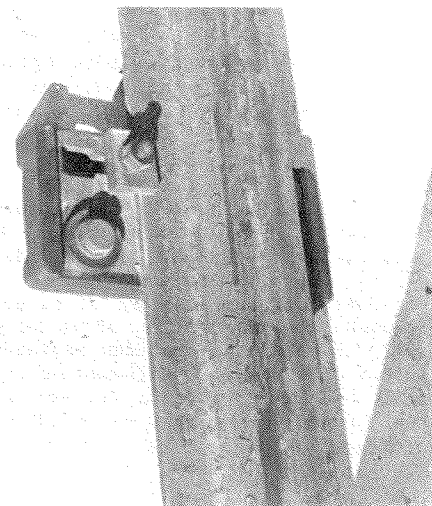


FIGURE 2 Landis rail fastener installed on BART aerial structure.

tudinal elasticity to accommodate rail structure interaction movements. Transverse elasticity is restricted because of the design of the pad. The elasticity constants of the fabricated fasteners are as follows:

1. Vertical--421 kips/in. (735,827 N/cm).
2. Longitudinal (new)--23 to 36 kips/in. (40,295 to 63,071 N/cm).
3. Longitudinal (worn)--28 kips/in. (49,055 N/cm). This spring rate is almost constant to the point of rail slip, which varies between 5 and 7 kips (22,250 and 31,150 N) of longitudinal load. These are laboratory values determined on a single fastener.
4. Maximum allowable longitudinal shear movement-- $1/3$  in. (8.4 mm) limited by the elastomer.

#### AERIAL TRACK DESIGN

The concept of BART aerial track was set by two decisions described previously (i.e., the use of CWR and the direct attachment of rail to the concrete deck of simple-span, concrete girders).

Aerial track consists of three components: rails, rail fasteners, and the direct connection details. They are as follows:

1. Rails for the BART mainline are 119 lb/yd (59.24 kg/m) American Railway Engineering Association (AREA) section.
2. Rail fastener development and the selected rail fastener were described in a previous section. The adjustment features were of particular importance for rail fasteners on aerial structures. Vertical and horizontal adjustment capacity were required during construction to compensate for errors and structural tolerances, and during operation to compensate for rail wear, long-term creep in the concrete girders, and for differential settlement of the supporting piers. The rail fastener provided for lateral horizontal adjustment by moveable rail clips on a serrated base plate. Vertical adjustment was obtained by varying the  $3/8$ -in. (9.5-mm) nominal thickness polyethylene shim installed between the rail fastener and track concrete.
3. Direct connection detail was a second pour of track concrete placed in the continuous block-outs of the aerial girders. The function of this track concrete was to transmit wheel forces to the girder; to support the rail fastener in proper elevation, cant, and superelevation; to embed the threaded anchor bolt inserts in the proper positions; and to allow for girder construction tolerances. The track concrete varied in thickness from 3.5 in. (8.9 cm) to 8.5 in. (21.6 cm) depending on the girder construction tolerances and the positive camber of the girder. The track concrete was reinforced for temperature and load distribution with three longitudinal No. 5 bars and No. 5 transverse hook bars at 12-in. (30.5-cm) centers. The specified concrete mix was similar to that used for thin precast slabs using small aggregate ( $\sim 5$  in.) ( $\sim 12.7$  mm), high-cement content (6.5 sacks per  $\text{yd}^3$ ), 3-in. (7.6-cm) average slump, and moist curing. The mix provided strength and workability for the difficult placement around forms, rail fasteners, embedded inserts, and reinforcing bars. The surface between the track concrete and the girder deck was considered a construction joint and therefore required surface preparation by sand blasting or other means. Curing by water or membrane methods was required to protect against drying on the exposed aerial girders. Figure 3 shows the jig used to form the track concrete.

The fastening of CWR was controlled by the speci-

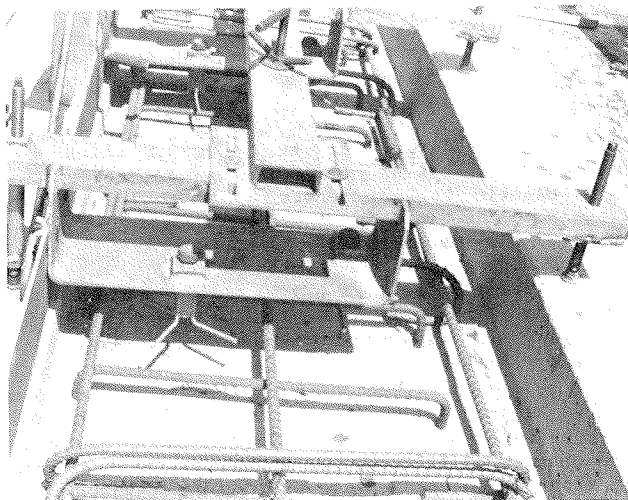


FIGURE 3 Jig used to form the track concrete.

fication to prevent the build-up of excess rail-structure interaction forces produced by temperature change. Rail fastener advance on each rail was staggered five girder lengths from any other rail on the same structure during periods of rapid temperature change or if the fastening operation was interrupted for 3 hr or more. No restrictions applied during a uniform rate of advance and a constant rail temperature.

The specifications required the actual rail temperature at zero thermal stress to be within  $\pm 10^\circ\text{F}$  of a temperature  $10^\circ\text{F}$  below the median of the long-term temperature extremes of the region. This requirement was set to protect the thermit-type rail welds from pull-apart failure, while recognizing that high-temperature sun kinks were almost impossible on aerial structures. Rail was normally laid at a temperature lower than the required range and then stretched by hydraulic rams (before field welding and fastening down) to shift the actual zero stress temperature to within the allowable range. Field records of the rail temperature and the amount stretched were used to calculate the theoretical zero stress temperature. Figure 4 shows the completed aerial track.

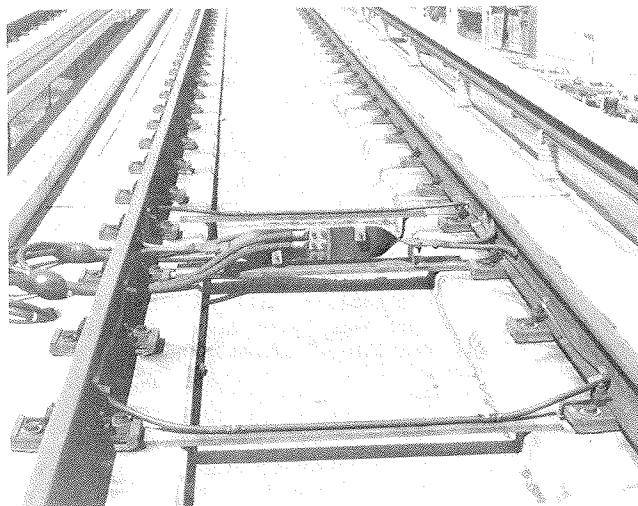


FIGURE 4 Completed aerial track.

## RAIL-STRUCTURE INTERACTION

A structural system is formed when CWR track is installed on an aerial structure. The major components of this system are

1. Long, elastic CWR, the ends of which are anchored in the ballasted track beyond the abutments.
2. Elastic rail fasteners to attach the rails directly to the girders.
3. Simple-span elastic girders.
4. Elastic bearing pads.
5. Elastic piers anchored to rigid foundations.

Forces and movements between the components (called rail-structure interaction) are produced when the system is subjected to loads from its own weight, moving trains, and temperature changes. The largest loads on the system are induced by temperature changes of the components. In the San Francisco Bay area, these changes amount to plus or minus 30°F from the no-load temperature of concrete structures, and plus or minus 50°F from the no-load temperature of the rails.

Temperature changes affect the system in two ways. First, a uniform internal force is developed in the end-restrained rail in direct proportion to the temperature change. For a 50°F change in 119-lb/yd (59.24-kg/m) rail, a force of 113,200 lb (503,740 N) is developed. If the end restraint is sufficient to resist this force, the rail will not move. Note that this force exceeds the nominal 100,000-lb (445,000-N) capacity of a bolted rail joint.

Second, the change in temperature causes longitudinal expansion or contraction in each girder. This movement produces moments in the elastic rail fasteners, which, in turn, create the following:

1. A longitudinal shear movement in the elastomer of each rail fastener.
2. Longitudinal forces on the rails that produce local stretching or compressing. This situation can be demonstrated with a rubber band that is stretched to simulate the uniform internal thermal force in a rail. If a series of opposing longitudinal forces is applied to the rubber band, the original tension is locally reduced or increased depending on the placement and direction of the applied forces.
3. Longitudinal reaction forces acting on the girder are transmitted to a pier through the fixed-girder connections.

Because the major components are elastic members, the structural system can be analyzed and the interactions determined for specific loadings. The complete analysis was complex because of the large number of members, and required a high-capacity computer and program such as ICES-STRUDL.

Interaction studies on the typical BART aerial structure of 70-ft (21.35-m), simple-span concrete girders were conducted throughout the design phase. Early studies defined the basic approach to be followed throughout the structure and track design. (This approach is shown in Figure 5 with plots of relative rail and fastener forces.) Further studies were conducted to establish rail fastener criteria and to determine maximum loads and deflections in the system (2). Results of these studies are summarized as follows:

1. Longitudinal elasticity of rail fastener. The maximum modulus was set at 36,000 lb/in. (63,071 N/cm) to limit the interaction forces acting in the CWR and on the piers. The minimum modulus was set at 18,000 lb/in. (31,535 N/cm) to limit rail break gap to a target value of 1 in. (2.54 cm).

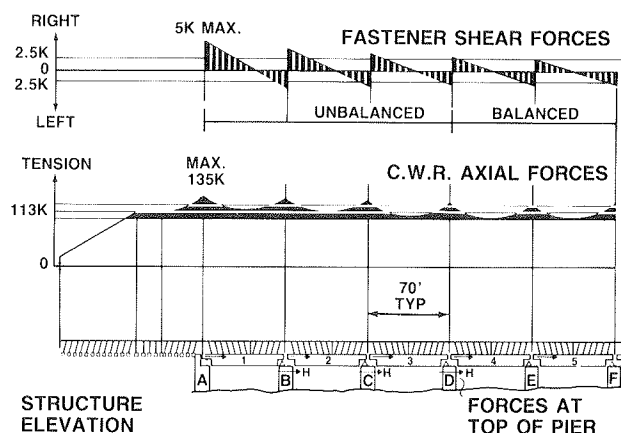


FIGURE 5 Standard aerial structure.

2. Longitudinal shear movement of rail fastener. Studies indicated that shear movements up to 0.15 in. (3.8 mm) would occur on typical systems [50-ft (21.35-m) spans] and up to 0.25 in. (6.4 mm) on special long span systems [170-ft (51.85-m) maximum spans].

3. Spacing of rail fasteners. The 36-in. (91.4-cm) spacing was determined by analysis of rail bending stresses, interaction forces on the rail and rail fasteners, and the amount of pull-apart at a weld failure. The light static wheel loads (12,500 lb) and the stiff rail (the moment of inertia is 71.4 in.<sup>4</sup>) contributed to the relatively large spacing.

4. Total axial rail stress. The studies indicated locations of peak rail stress. Field welding by thermit methods was prohibited at these locations of high rail stress.

5. Interaction forces on abutments and piers. The three piers nearest an abutment and an aerial crossover were designed to withstand a longitudinal interaction force of 17,000 lb (75,650 N) per rail applied at the top of the pier. Interaction forces were not applied to standard abutments because girders were not fixed to the abutments. Exact solutions at the abutments cannot be computed because the end restraint of the CWR in crosstie and ballast track is neither elastic nor rigid and is subject to variation as a result of maintenance practices.

Additional interaction studies were conducted throughout the design phase to check special structures such as long-span girders, high piers, changes in girder support patterns, aerial crossovers, and CWR anchor abutments. As valuable as these studies were to the design of BART's structures and track, the identification and location of high-stress components is equally valuable to the BART operating staff.

## AERIAL CROSSOVERS

BART operating criteria required main line crossovers to be located throughout the system to facilitate single-track operation during maintenance and emergency situations. These crossovers normally consist of two, single No. 10 crossovers between main tracks that are 14 ft (4.27 m) apart. The special work included No. 10 rail-bound manganese frogs and 19-ft 6-in. (5.948-m) curved switches. All rails and special trackwork items were connected with American Railway Engineering Association (AREA) bolted joints for ease of replacement. Five of these crossover locations are on aerial structures.

Two special problems were encountered during the

design of these aerial crossovers. The first was the method of attachment of the frog and switch to the concrete girders. Direct attachment, which was similar to the standard aerial track, was a possibility; however, this was discarded because of the lack of available hardware and service experience. Short timber ties embedded in concrete and supporting standard turn-out hardware were selected.

Special flat top girders were designed to support the crossovers. These girders were set 6 in. (15.24 cm) lower than the adjacent standard girders to accommodate the concrete-embedded short ties. In addition, a poured-in-place closure deck was constructed between each pair of girders to support the crossover track. The structural layout was designed to minimize the girder thermal movement under the switch and all bolted rail joints. Each single crossover was supported by three 76.4-ft (23.302-m) pier spans or four 57.3-ft (17.477-m) pier spans depending on local conditions.

The second special problem was how to avoid excessive rail-structure interaction forces caused by the interruption of CWR at the crossovers. Previous studies indicated that the CWR thermal and interaction forces can exceed the capacity of AREA bolted rail joints. In addition, the interruption of two or more CWR at one location caused by joint failure could overstress the aerial structure under normal Bay-area temperature changes.

The initial approach was to avoid any rail joints by welding in reinforced frogs and stock rail and by designing a structural load transfer member between the curved stock rail and the straight closure rail. This has been done successfully on British Railways (3). However, this approach was rejected because of the lack of domestic hardware and service experience.

The alternative was to solve the rail-structure interaction problem within the design of the aerial structure and avoid the use of the track components as structural members. This allowed the use of standard track hardware including bolted rail joints. This alternative was selected and the BART "tie bar" was developed.

The concept of the tie bar is quite simple. The CWR is interrupted at the crossover and the rail ends are attached as rigidly as possible to special "AXO" girders adjacent to the outer ends of the pair of single crossovers. (The AXO girders are similar to standard girders except for the addition of embedded steel plate for the welded attachment of the tie bar.) The tie bar, a structural steel member of cross section that is equal to two rails, is located on the centerline of each track and is welded to the embedded plates on the centerline of the two AXO girders. The tie bar is approximately 550 ft (167.75 m) long and rests on Teflon bearing pads directly on the concrete deck. Figure 6 shows a tie bar installed on an aerial crossover.

During a temperature change, the thermal force built up at the end of each pair of CWR strings is transferred to an AXO girder through a group of 20 standard rail fasteners spaced at 20 in. on centers. An equal and opposite thermal force is developed in the tie bar and transferred to the AXO girder through a welded connection. Therefore, the net longitudinal thermal force on the AXO girder is zero. The CWR thermal force is directed through the tie bar instead of down into the piers where structural damage could result or into the jointed special work where track bolt damage could result.

The tie bar presented many design challenges. The location of the tie bar in the girder drainage channel required the use of rust-resistant ASTM A441 steel. The 2- by 24-in. (5.08- by 60.96-cm) cross section and the long length required many heavy butt field welds during fabrication. The operation of the

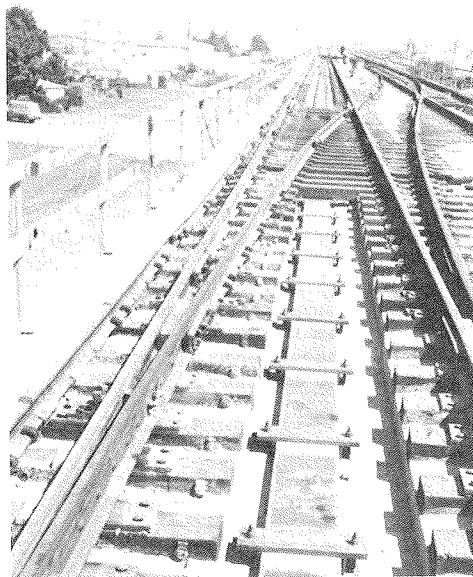


FIGURE 6 Tie bar on aerial crossover.

tie bar in compression as well as tension, required the placement of hold-down devices every 4 ft (1.22 m) to prevent buckling during hot weather. Ideally, the tie bar should be completely free of the supporting crossover girders; therefore, low-friction Teflon bearing pads were used on all contact surfaces. Train control designers required insulated joints at each end of the tie bar to minimize interference with the control system. Finally, the 6-in. (15.24-cm) step between the deck of the AXO girder and the crossover girder required an eccentric connection.

#### CONCLUSION

In summary, the BART design and construction of CWR on aerial structure has provided the following benefits:

1. A concrete aerial structure design that does not induce unacceptable local stresses in the rail.
2. A single-rail fastener design that is elastic enough to allow for relative movement between rail and structures for standard spans up to 100 ft (30.5 m) and special spans up to 160 ft (48.80 m). In addition, the fastener conforms to a number of other mechanical, electrical, and vibration absorption requirements.
3. Aerial track design, which proved to be constructible and substantial enough to withstand and distribute the imposed loads.
4. Structural crossover tie bar details that are sufficient to transmit interaction loads around the track special work and avoid overstressing the bolted rail joints.
5. Special anchor abutments that are able to withstand the full thermal and interaction loads that can be developed in the rail.

In operation for 13 years, the rail-structure system has functioned as expected and without any adverse incidents. A BART Rail Fastener Report issued in 1983 (4) indicated no failure in 10 years of service, and no deterioration of physical properties of the fasteners after 5 years of service. The latter conclusion was based on a repeat set of laboratory

qualification tests and a comparison of results between used and unused fasteners. BART's conclusion was

...the useful life of a BART fastener will in all likelihood not be a factor of the loads on the rail system under normal services conditions and may well depend on other conditions, such as environmental deterioration, heat, ozone, sunlight, or some unknown type of failure. However, from visual inspection and from the electrical tests, none of these factors has caused significant harm to these fasteners to date.

In conclusion, the BART challenge to install CWR on aerial structures was successfully met by a practical design that has been confirmed by 13 years of experience.

#### REFERENCES

1. L.W. Riggs. 27 Miles of BART Aerial Structure. *Railway Track and Structures*, July 1966, pp. 17-21.
2. Report of Rail-Structure Interaction Studies for Aerial Structures. Tudor Engineering Company, Nov. 1970.
3. A. Paterson. Preparing British Railways Track for High Speed Running. *The Railway Gazette*, June 7, 1968, pp. 413-416.
4. V.P. Mahon. BART's Experience with Direct Fixation Fasteners. Presented at the UMTA Direct Fixation Fastener Workshop, Boston, Mass., Feb. 1983.

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## Manufacturing, Reclamation, and Explosive Depth Hardening of Rail-Bound and Self-Guarded Manganese Frogs on the Chessie System

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#### ABSTRACT

Rail-bound and self-guarded manganese frogs have been used on the Chessie System for many years. For the past half-century, they have been manufactured or reclaimed at shops operated by the railroad. In May 1961, explosive depth hardening was initiated and the policy established whereby this process was applied to all rail-bound manganese frogs, self-guarded frogs, and one-piece manganese guard rails manufactured or reclaimed by the railroad. This amounts to approximately 90 percent of the systems requirements. In addition, any of these components purchased complete from outside suppliers are sent to the Chessie System and are explosive depth hardened before being put into service. Tests indicate that this process extends the service life of products manufactured from austenitic manganese steel and also acts as a quality control check on the integrity of the products exposed to this process.

In the case of rail-bound manganese frogs, the components are acquired from various sources and the finished products put together at the Chessie System plants in Martinsburg and Barboursville, West Virginia. Although the word "manufacturing" is more commonly used to describe the activity, "assembling" would be a more accurate term.

#### MANUFACTURING FROGS

Rail-bound manganese frogs are used primarily on heavy density lines where traffic is approximately equal on both sides of the frog. Figure 1 shows the names of detail parts of a rail-bound manganese frog per American Railway Engineering Association (AREA) Plan 690-52 in the Portfolio of Trackwork Plans. The major components are the manganese insert, wing rails, leg rails, filler blocks, and necessary high-grade bolts of sundry lengths. The inserts are purchased from various sources. Head and toe filler blocks and necessary bolts are likewise obtained