

Effects of Track Parameters on Rail Joint Bar Stresses and Crack Growth

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Abstract

By their very nature, rail joints create discontinuities in the running surface of the rails. In addition to bending, thermal, and residual stresses, rail joints are also subjected to dynamic loads due to these discontinuities. Under normal track and load conditions, joint bars fail due to high cycle fatigue, which is evident from fatigue striations observed on broken bars. Accelerated track degradation increases deflections, which further increase joint bar stresses, possibly changing the failure from high cycle fatigue to low cycle fatigue and in some cases even yielding. The current joint bar design is meant to support only the railhead and base. This feature is of limited value in continuous welded rail (CWR) where resistance to longitudinal force loads is also desired.

Rail joint bar failures are a safety and reliability concern for railroads. Because of their redundancy (i.e. two bars in each joint), a failed joint bar is almost always found and replaced before an accident occurs. Rail joints are typically not one of the five leading track causes of accidents in the FRA accident database. However, the industry is experiencing some joint caused accidents.

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This paper discusses the effects that track parameters such as foundation configuration and track surface condition have on joint bar stresses. Joint bars were notched using the Electro-discharge machining (EDM) technique to initiate cracks and were tested under controlled conditions at the Facility for Accelerated Service Testing so that crack growth rates under simulated mainline heavy haul freight operations could be evaluated.

The tests provided the relevant data needed for developing more comprehensive models for joint bar fatigue life, crack growth, and inspection interval optimization.

The limited test data showed no significant difference between concrete and wood tie track in terms of joint bar stresses. However, joints installed in curved track showed a considerable increase in stress state and required more maintenance than joints installed in tangent track. Also, the data showed that standard joint bars experience higher stresses than insulated rail joints. Similarly, increasing the number of joint bar bolts and the magnitude of the bolt torque can have positive effects on joint performance. Limited thermal force data showed that insulated joints, once welded in place, behave like the surrounding rail and can develop considerably higher thermal stresses than standard rail joints. After cracks initiated from EDM notches at the bottom of the joint bars on tangent track, two joint bars out of eight broke within 35 million gross tons of traffic.

New joint bar designs are recommended. Other measures related to track foundations and materials properties, which could be adopted to reduce the likelihood of joint bar failures, are also discussed. This project is funded by the Federal Railroad Administration.

INTRODUCTION

There are essentially three different types of rail joints:

- Bolted joints
- Compromise joints
- Insulated joints

Bolted joints are used to join two rails in jointed rail territory. In continuous welded rail (CWR) territory, bolted joints are used to temporarily join rails before they are welded. Compromise bars are used to join two rails with differing sections. Insulated joints are further categorized as bonded or nonbonded joints. Bonded insulated joints are glued. Nonbonded insulated joints are basically bolted joints having some type of electrical insulating properties.

While these three types of rail joints perform differently and have different operational objectives, they share many similar design features. For example, they all use bolts and bars and create a discontinuity in the running surface of the rail. Bolts generally fail due to yielding, and bars usually fail due to fatigue. The discontinuity in the running surface of the rail creates conditions that can accelerate track degradation around the joint. At a minimum, the gap at the rail ends within the rail joint is a source of impact loading from passing wheels. Left unchecked, these impact loads increase rail end batter, thereby deteriorating the foundations, which further increase the impact forces generated by passing wheels.

This paper discusses the various types of loads insulated and standard joint bars are subjected to during their service lives. Also, the effects of various track parameters on different rail joint types are analyzed.

BACKGROUND

The standard bolted rail joint in service today in CWR territory is essentially the same joint that was designed in the early part of the last century to provide vertical and horizontal rail alignment but allow longitudinal movement to offset rail expansion and contraction due to temperature change. While the shapes of the bars have changed to better match the heavier rails now in service, the joint is still designed to minimize the contact area between the joint bar and the rail web in order to accommodate longitudinal rail movement. When used in CWR territory, this design feature is of limited value and can lead to excessive stresses under today's 286,000-pound and higher car weights.

In order to understand the magnitude of rail joint failures from a safety perspective, two sources of data are of interest. First is the Federal Railroad Administration (FRA) Railroad Accident database, which contains records of all railroad accidents above the reporting threshold of \$6,700 in damages or involving injuries. The second source of data is comprised of Joint Bar Failure Reports, which railroads are required to submit to FRA. In 2007, these reports were collected and analyzed by Transportation Technology Center, Inc. (TTCI).

According to FRA's accident data, a total of 242 accidents related to joint failures occurred from 2000 to 2009 (Figure 1). Most joint bar failures occurred due to cracks initiated from bolt holes or at the bottom or top edges of the joint bars. The number of accidents caused by joint bars was relatively consistent until 2007. The sharp decrease observed in 2008 and 2009 appears to be due to lower traffic and the overall downward industry trend in accidents.

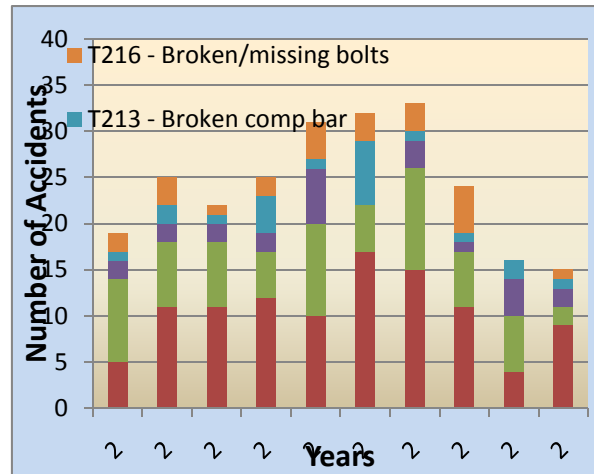


Figure 1. Joint bar related accidents by year, joint type, and failure mode

In 2007, the FRA required US railroads to submit Joint Bar Fracture Reports for all cracked and broken joint bars removed from track. Table 1 summarizes the joint bar failures by failure mode for both gage side (GS) and field side (FS) bars for tracks with more than 5 million gross tons (MGT) of traffic for all train operating speeds. Eighty-six percent were standard joint bars, 11 percent were compromise bars, and 3 percent were insulated joint bars. Sixty-two percent of the reports were for joint bars found broken on inspection, of which 10 percent had both GS and FS joint bars reported broken at the same inspection. Of all reported cracked joint bars, 29 percent had cracks on the top of the bar, and only 6 percent had cracks on the bottom of the bar.

TABLE 1. Joint Bar Failure Analysis

| | | Field Side % | Gage Side % | Total % |
|----------------|----------------------|--------------|-------------|------------|
| Broken | Joint bar Center | 26 | 31 | 62 |
| | Bolt hole | 1 | 2 | |
| | Other Break | 0 | 0 | |
| Cracked | Joint Bar Top Center | 16 | 13 | 38 |
| | Joint Bar Bottom | 3 | 3 | |
| | Bolt hole | 2 | 2 | |
| Total | | 48 | 52 | 100 |

The joint bar data presents more questions than answers. On inspection, why are more joint bars found broken than cracked? This is contrary to conventional wisdom. Why are more cracks found on the top of the bar where theoretically there are no tensile stresses? Yet, this data is consistent with conventional wisdom. Are most of the joint bar failures fatigue related? What is the role of residual stresses in joint bars in addition to bending and thermal forces? How do concrete tie track and wood tie track affect the different types of rail joints? How do deteriorated foundations affect joint bar service life? This paper discusses these and many other questions related to the joint bar load environment and joint bar failures.

TEST SETUP

To explore and quantify the effects of track condition on joint bar stresses, a series of experiments were conducted in the North American heavy axle load (HAL) environment. A total of 24 rail joints were installed on different track geometry and track types: 16 rail joints were installed at the Facility for Accelerated Service Testing (FAST) and eight rail joints were installed in revenue service (Tables 2 and 3 show details). Each joint bar has two strain gage circuits: one on the bottom of the joint bar to quantify tensile bending stresses and one on top of the joint bar to quantify compressive stresses.

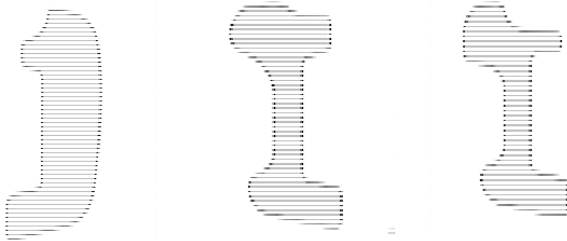
TABLE 2. Rail Joint Test Matrix

| Locations | Track Geometry | Tie/Fastener | Joint Type | Site |
|-----------|----------------|---------------------------|------------|------------------|
| 1 | Tangent | Wood/cut spikes | A,B,C,D | FAST HTL |
| 2 | Tangent | Concrete/elastic fastener | A,B,C,D | FAST HTL |
| 3 | 5-degree Curve | Wood/cut spikes | A,B,C,D | FAST HTL |
| 4 | 5-degree Curve | Concrete | A,B,C,D | FAST HTL |
| 5 | Tangent | Wood/cut spikes | B,D | Eastern railroad |
| 6 | 7-degree Curve | Wood/cut spikes | B,D | Eastern railroad |
| 7 | Tangent | Wood/cut spikes | B,D | Western railroad |
| 8 | 4-degree Curve | Concrete | B,D | Western railroad |

Joint Bar Types

- A 8-hole, bonded IJ, 48-inch long, 3/8-inch end post
 B 6-hole, bonded IJ, 36-inch long, 3/8-inch end post
 C 8-hole, high relief joint, 1-1/16-inch bolts tightened to 800 ft-lb.
 D 6-hole, standard joint, 1-inch bolt tightened to 600 ft-lb

TABLE 3. Cross-sectional Properties of Joint Bars

|  | | | | | |
|--|--|-------------------------------------|-------------------------------------|--|-----------------------------|
| | (a) | (b) | (c) | | |
| Joint bar type | Cross-sectional Area - in ² | Moment of Inertia - in ⁴ | Section Modulus-top in ³ | Section Modulus-Bottom in ³ | Neutral Axis from Top - in. |
| (a) IJ | 6.27 | 12.25 | 4.81 | 4.99 | 1.53 |
| (b) Standard | 5.89 | 16.14 | 6.68 | 6.11 | 2.41 |
| (c) High Relief | 5.64 | 14.04 | 5.55 | 5.6 | 2.53 |

Insulated joints (Types A and B) were installed in 20-foot-long plugs in four locations on the High Tonnage Loop (HTL) at FAST. Standard joint bars (Types C and D) were installed by

cutting the existing rails to make new joints (Figures 2 and 3 show test locations). Bending strains from joints at FAST were measured at 25 to 30 MGT intervals. To quantify foundation degradation, static deflections under loaded HAL car wheels were also measured at these intervals. Joint foundations were only surfaced when required to maintain operational requirements for the train at FAST. No longitudinal force circuits were installed on the rail joints installed at FAST. Rail temperature was recorded when the rail joints were installed.

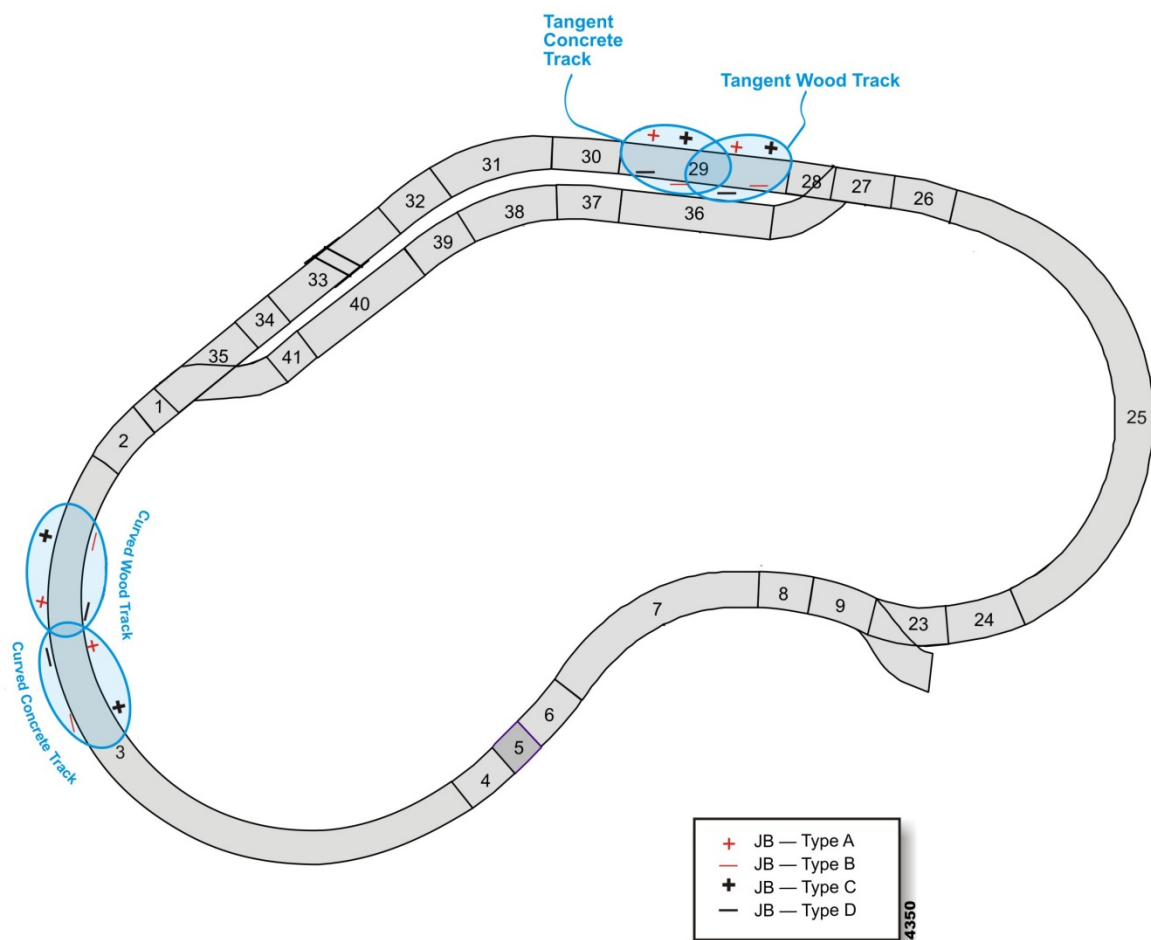


Figure 2. Four joint bar test locations at FAST HTL

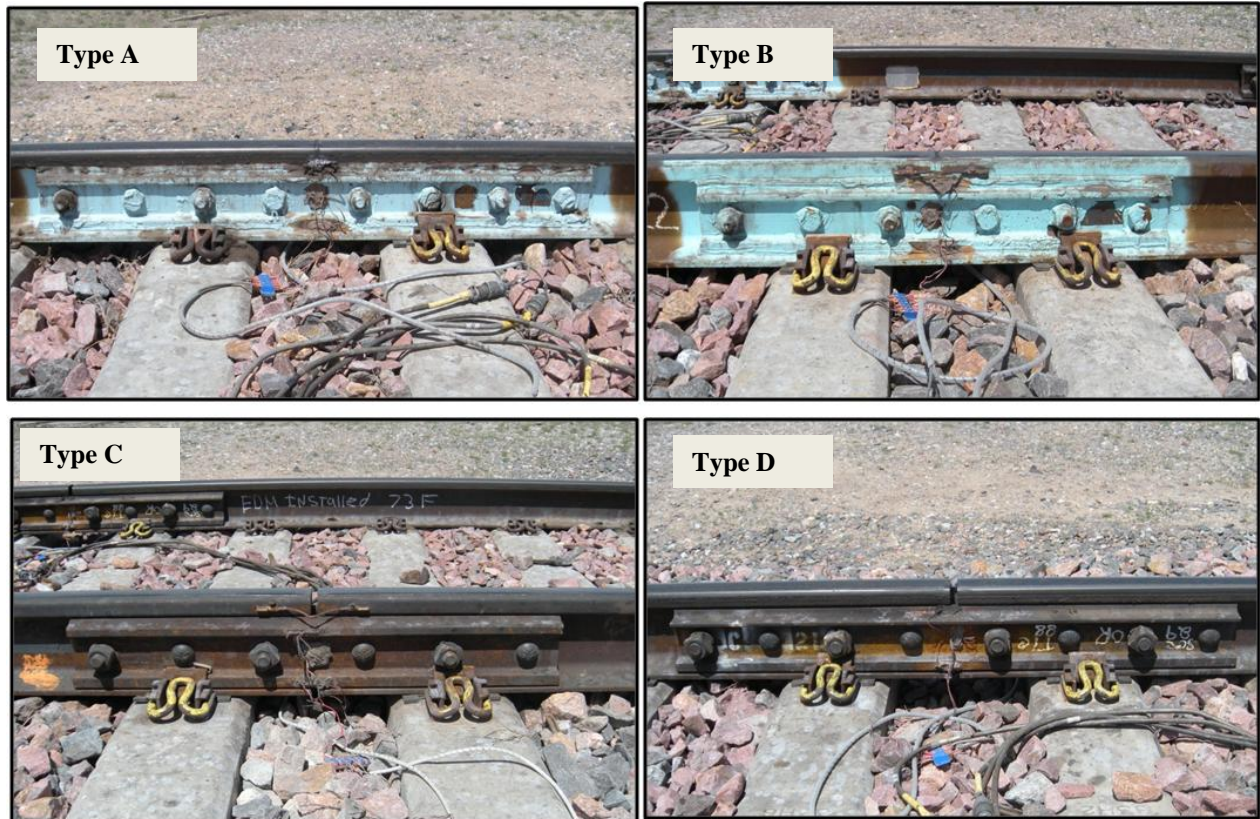


Figure 3. Typical test joints clockwise from top left — 8-hole insulated joint (Type A), 6-hole insulated joint (Type B), 8-hole standard joint (Type C), and 8-hole high relief joint (Type D)

Two pairs of Types B and D joints were installed on a tangent track section and in a 7-degree curve on an eastern railroad's track. Two pairs were also installed on a tangent track section and in a 4-degree curve on a western railroad's track. In addition to bending strain gage circuits, longitudinal force circuits were installed on each of the joint bars and on each of the rails. Temperature and corresponding thermal strains from these circuits is automatically collected every half hour using solar-powered data loggers.

Rail Joint Maintenance History

Rail joints normally require three types of maintenance during service:

- Surfacing due to ballast degradation

- Grinding due to metal flow at the rail ends
- Replacement of broken bolts or broken joint bars

Of the current test joints at FAST, those on curved concrete tie track required the most maintenance, joints on wood tie track required some maintenance, and joints on tangent concrete and wood tie track did not require any maintenance (Figure 4 shows details).

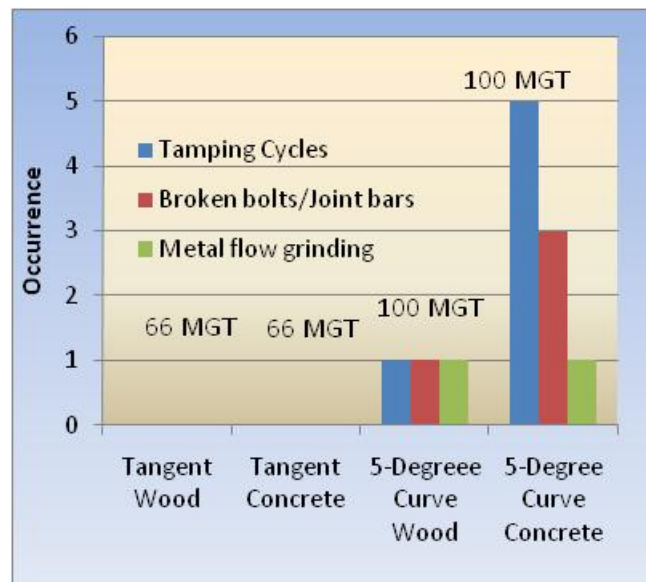


Figure 4. Maintenance history of test joints at FAST

Among the four joints on curved concrete tie track, standard joints required more track surfacing, which is understandable. The gaps between rail ends increase when the rail is in tension. Larger gaps increase impacts, accelerating track surface degradation.

Degraded ballast increased vertical deflections of joints, which overstressed and fractured joint bars. Two joint bars and one bolt broke in curved concrete tie track, and one joint bar broke on curved wood tie track.

Static Data Measurement

After the rail joints at FAST had accumulated 5 MGT of HAL traffic, vertical deflections and bending strains in the joint bars were measured on undisturbed track under a static wheel load produced by a fully loaded 315,000-pound car. Vertical deflection is defined as the deflection at the end post when the load is right over it. Strain gages were installed on joint bars close to the end post.

After measurements were made on undisturbed track, the ballast under and around the joints was disturbed by dragging a chain twice under the ties. The objective was to simulate a degraded foundation condition under the joints and five to seven ties on both sides of the joints. Then, static vertical deflections and bending strain measurements were repeated. Three measurements, one from undisturbed track and two from disturbed track, were obtained for each joint. Figure 5 shows 48 data points for all 16 joints.

In curved track, deflection strain data from the joints installed on the low rail was increased by 18 percent, and data from joints installed on the high rail was reduced by the same percentage to account for the effects of superelevation.

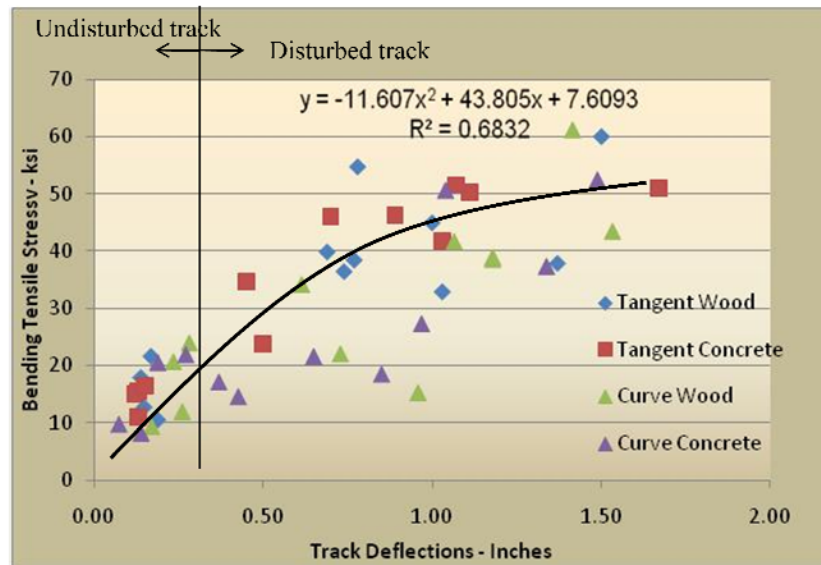


Figure 5. Static stress-deflection relationship of joints on simulated degraded foundations

Dynamic Bending Strain Measurements

Bending strains on the top and bottom of all of the joint bars were collected during train operations at FAST at regular intervals with the objective of understanding the response of the joints as their foundations degraded under HAL traffic. Figure 6 shows the 99th percentile data calculated for the stress history of each joint.

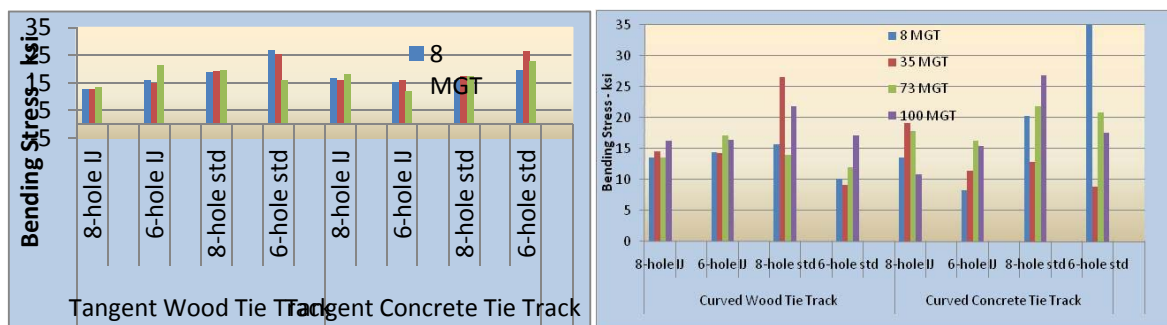


Figure 6. 99th percentile tensile bending stress in the bottom — average of the field and gage side joint bars, tangent track (left), curved track (right)

In general, bending stress levels increased with increases in joint deflection. This suggests that the stress amplitude may increase over time, reducing the fatigue life of the joint bars. Similarly,

higher deflections related to increases in stress can also increase crack growth rates. On curved track where higher maintenance was needed, especially for standard joints, the large difference in strains was due to variations in deflections caused by degradation-surfacing cycles.

Longitudinal Force Measurements

Longitudinal forces in rails and joint bars are being measured in revenue service at an eastern railroad and a western railroad. One pair of insulated joints and one pair of standard joints were installed in a 7-degree curve and the other pair was installed in a tangent track section. Each joint had four strain gage circuits to measure longitudinal force: one on each rail and each joint bar. Joints are three to five ties apart on adjacent rails. Standard joints were installed the way they are normally installed in revenue service track with the middle two holes left blank. At the eastern site, no pulling force was applied during installation of the joints. The rail temperature was 62 degrees F, which is also the neutral temperature of the track. The standard joints and insulated joints were installed on same day. The insulated joints were initially bolted into the track, but were welded into the rail at a later date. Figure 7 shows the data collected over 60 days.

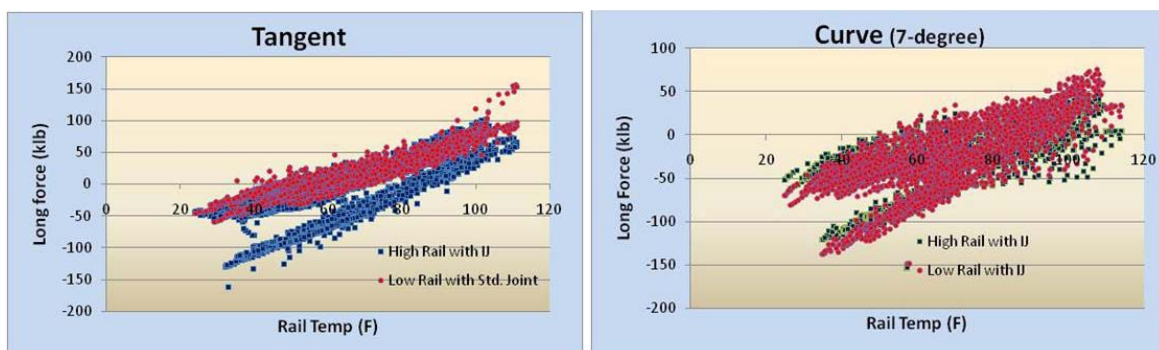


Figure 7. Temperature-thermal force relationship of rail on curve and tangent from joints installed on an eastern railroad's track

On the tangent track section prior to the insulated joints being welded to the rails, the slope of the trend line was similar to the standard joints. After the insulated joints were welded to the rails,

the thermal force increased about three times compared to the standard joint. There appears to be no difference in the temperature-force relationship for rail on tangent and curved track; however, at a given temperature, the force data for curved track has a wider envelope as compared to the tangent track data, which is probably due to “breathing” of the curve.

Crack Propagation Rates

From the inspection records submitted by railways and compiled by FRA, it appears that many reports are for broken, not just cracked joint bars. This suggests that the current inspection regimen is unable to find the majority of cracked components before they progress to fracture.

Three factors may affect this result:

- Terminology — many track inspectors would consider a cracked joint bar to be fractured or broken. From the track maintainer’s point of view, there is little to distinguish a crack from a break; both require replacement of the component.
- Limited inspectability — the entire joint bar is difficult to inspect with automated inspection systems, which currently target the top of the joint bar.
- Inspection sensitivity — current inspections are visual. This requires the defect to be visible from outside the joint. However, most defects originate at the rail-bar interface or at the toe (bottom) of the bar. These defects are not detectable with the current automated inspection systems until they have grown quite large. When the defects have reached this size, crack growth can be quite rapid, limiting the number of inspection opportunities possible.

An optimum track inspection period is desirable to locate and replace joint bars with cracks before they break. It requires a detailed study of crack growth rates for different joint bar designs and a variety of environmental and load conditions. This research will help determine how to

extend crack growth life so that more flaws can be found with existing inspection technologies prior to joint failure.

Besides alternating stress amplitude, which is dependent on foundation conditions, other factors that affect crack growth are thermal forces and joint bar residual stresses. Residual stresses are induced in joint bars during manufacturing processes. Tensile stresses up to 25 ksi in the bottom and compressive stresses up to 20 ksi were measured on a limited sample of joint bars. The magnitude of thermal and residual stresses varies considerably so the crack growth rates for joint bars are expected to vary as well.

In order to estimate crack propagation rates, eight joint bars were notched on the bottom and top edges and installed on the gage side of the rail. During train operations, joint bars were inspected on a daily basis. All joint bar holes had bolts that were tightened to the manufacturer's recommended full torque. Notch sizes were estimated based on the load environment reported earlier in this paper. The notched joint bars were installed when rail temperature was between 80 and 90 degrees F. This is the prevailing rail temperature during summer and fall in Colorado when the train at FAST normally operates. Thus, these joint bars are subjected to variations in rail temperature, which is typically over 40 degrees F. This temperature corresponds to a thermal force of about 100,000 pounds on tangent track. A lesser thermal force may be assumed in curved track, where the track can "breathe" due to the rail temperature variation.

One 8-hole joint bar installed on a concrete tie tangent track section and one 6-hole joint bar installed on a wood tie tangent track section broke at 27 and 36 MGT respectively. One crack on the top of the joint bar located in a curved track section grew slightly and then became dormant. Electro-discharge machining (EDM) notches on the other five joint bars had not initiated any cracks at the time of this writing (Figure 8).

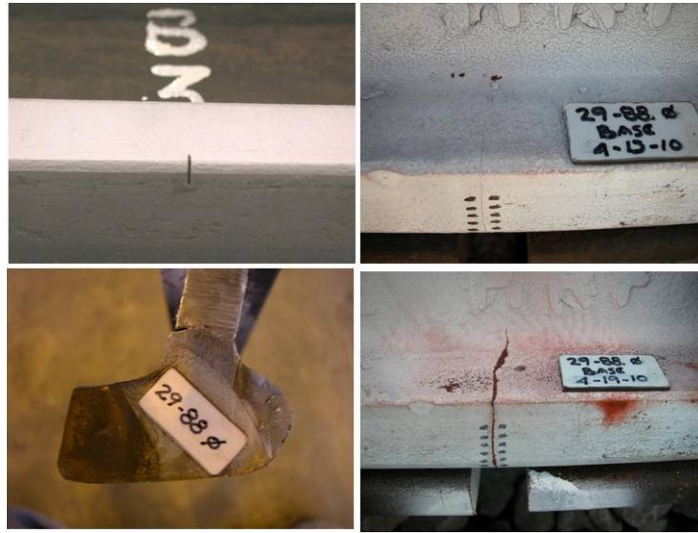


Figure 8. Crack growth of one broken joint bar. Clockwise from top left corner — joint bar with EDM notch, crack propagation after 20 MGT, after 25 MGT, and broken joint bar after 27 MGT

DISCUSSION AND CONCLUSIONS

Effects of Track Type and Geometry

No significant differences in joint bar stresses were observed between concrete tie and wood tie track. Also, static measurements taken on tangent and curved track did not show any measureable differences in joint stress. Therefore, at lower train operating speeds, joints on tangent and curved track may show similar performance. The dynamic bending stress history measured over 100 MGT at FAST showed that joints, particularly standard joints on curved track, experienced higher stresses sufficient to break joint bars.

Several factors are likely to contribute to increased bending stresses in the curved concrete tie track test zone at FAST, which is adjacent to wood tie track. Wood tie track typically has lower lateral stability than concrete tie track.¹ Therefore, the concrete tie section with joints has track with higher lateral stability on one end and lower lateral stability on the other end. This may cause lateral movement of whole track panel. Rounded ballast and powdery ballast surface conditions were observed in this area, which is indicative of higher levels of ballast degradation.

The tangent concrete tie track location did not have this problem. Another factor is that the train at FAST operates above the balance speed of the curves. At 42 mph, the wheels on the high rail of the curve can load the rail 10 percent more than on the low rail of the curve.

Insulated joint bar designs vary from supplier to supplier, so there is no standard fastening system for insulated joints. TTCI's track crew used a combination of fastening systems to install the insulated joints used in this test that either broke or became loose soon after installation. It probably resulted in joint twist, creating additional stresses due to torsion.

Effects of Deflections on Stresses

As Figure 5 shows, up to about 0.5-inch deflection, the stresses in the joint bar increase proportionally with deflection. Beyond 0.5-inch deflection, the level of stress tends to flatten out, suggesting that further deflections may cause little or no additional bending stresses in the joint bars. Using regression analysis, joint deflection can explain 68 percent of the variation seen in bending stresses.

Stress State of Insulated Joints and Standard Joint Bars

Under static loads, insulated joints and standard joint bars experienced similar levels of stress, but not under dynamic loads. Each joint has gage side and field side bars. Figure 9 shows the average dynamic bending stress of two joint bars on each joint. Tensile bending stresses on the bottom of the 8-hole and 6-hole standard joints were up to 60 percent higher than the stresses measured on the insulated joints.

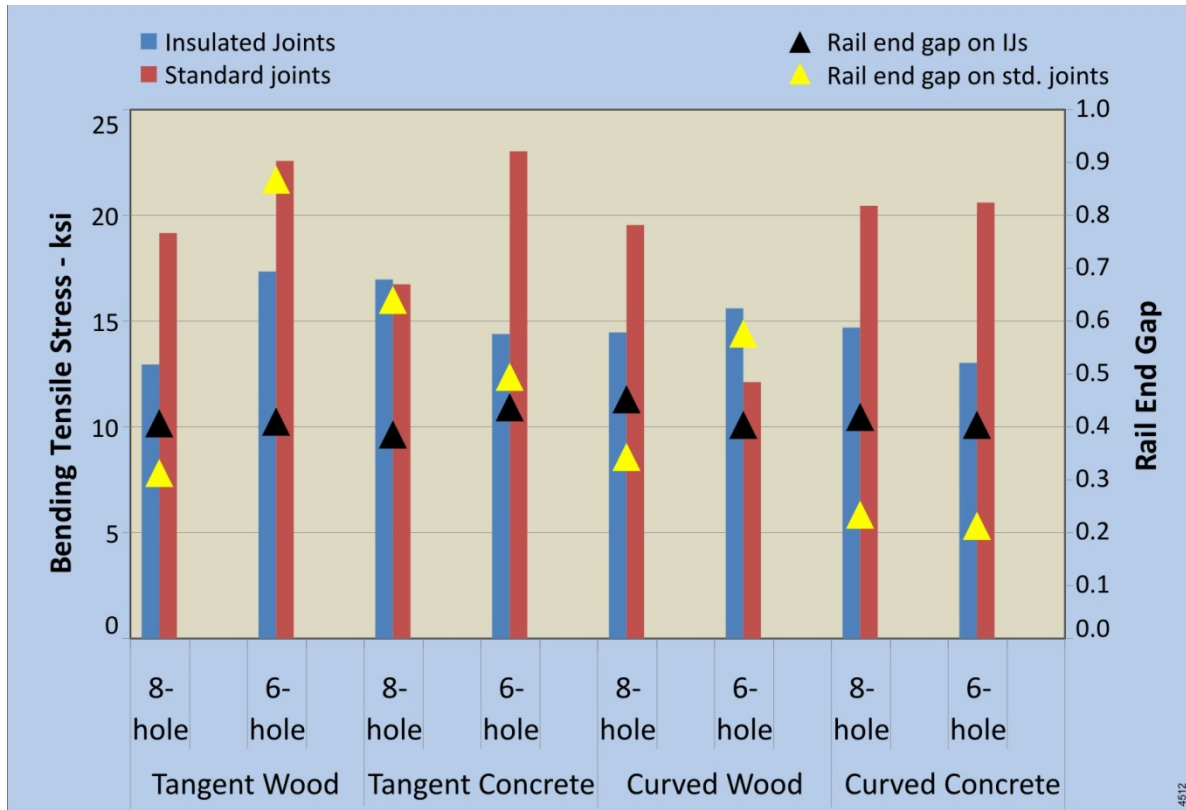


Figure 9. Stress-deflection-rail end gap relationship of joints

Although the moment of inertia of insulated joint bars is quantitatively lower than that of standard joint bars, stresses are lower in the latter. Being bonded together, insulated joint bars are more efficient in carrying the bending moment than standard joint bars.

Another likely reason for the higher stresses observed in standard joint bars is that the rail end gap (defined here as the distance between the bases of the two rails in the joint) in standard joints can grow significantly, resulting in increased dynamic loads compared to insulated joints.

Effects of Torque and Number of Bolts on Standard Joints

Generally in CWR, the middle two bolts of the joint are not installed (to facilitate field welding), and the bolts are not usually tightened to the recommended torque value. This practice was evaluated against a case when all bolts were installed and tightened to the recommended torque value. Data showed that joints assembled with the recommended bolt torque value experienced

up to 40 percent lower stresses than joints assembled with half the recommended bolt torque value.

Effects of Joint Bar Length on Stresses

Within the standard joint bar group, 8-hole joint bars have a lower bottom section modulus than 6-hole joint bars, yet the bending tensile stresses in the bottom of the latter on tangent track appear to be up to 40 percent higher than the former. The 8-hole joint bars used 1-1/16-inch diameter bolts as compared to 1-inch diameter bolts used in the 6-hole joint bars. Torque applied to the 8-hole joint bars was 800 foot-pounds as compared to 600 foot-pounds in the 6-hole joint bars. The higher torque most likely increases the moment of inertia of the 8-hole joint bars, reducing the stresses when compared with the 6-hole joint bar assembly. It confirms the results of static measurements where joints assembled with the recommended bolt torque value had lower stresses than joints assembled with half the recommended bolt torque value.

In general, 36- and 48-inch-long insulated joint bars that had the same cross section showed no significant difference in stresses.

Cracking on the Top of Joint Bars

Figure 10 shows the stress history of some cars of a train measured on a 6-hole joint bar on concrete tie track with elastic fasteners and on wood tie track with cut spikes at FAST. In both cases, the strain gages were located on the top of the joint bar where compressive stresses are expected when the bar is loaded. However, due to negative bending, caused when wheels are on either side of the joint, the strain gages showed some tension as well. The 99th percentile of this tension ranged from 2-8 ksi for the joints on both concrete tie and wood tie track. In both cases, this stress was too low to initiate a crack in material with a 70 to 90 ksi yield strength. Thus, cracking on the top of the joint bar is likely a design-related issue rather than a service load

environment issue. The sharp corners of the rail ends make notches and cause metal flow on the joint bar, which may serve as crack initiation sites. AREMA recommends a relief on a joint bar to address this problem. Also, it appears that wood tie track with cut spikes shows higher tension stress due to reverse bending than concrete tie track.

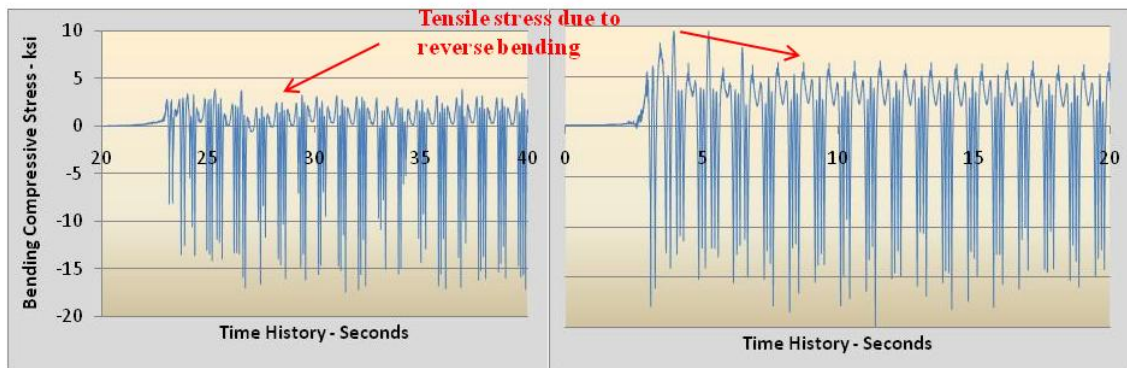


Figure 10. Stress history of a standard joint bar at FAST — concrete tie track (left), wood tie track (right)

Joint Bar Failure Modes

Dynamic bending strain data collected at FAST was converted to stress and plotted against mean stress on a Goodman diagram (Figure 11). Residual and thermal stresses both increase the mean stress and affect fatigue life. Higher and lower mean stresses are likely to cause yielding or fatigue failures, respectively. Because the loads in revenue service are lower than those generated at FAST, the possibility of joint bars failing due to fatigue cracking, instead of yielding, is higher in revenue service than at FAST. In order to get infinite fatigue life, the endurance limit needs to be increased or the mean stresses need to be limited to approximately 10 ksi.

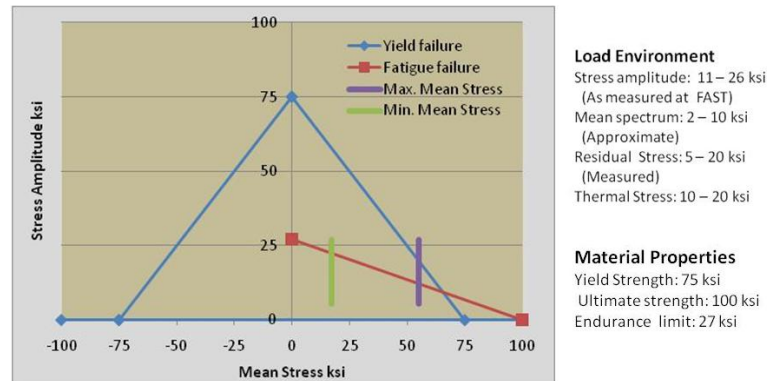


Figure 11. Goodman diagram showing failure modes under different mean stresses

Strategies to Improve Rail Joint Bar Service Life

The following strategies may potentially improve the service life of rail joint bars:

1. In CWR, the most undesirable design feature of joint bars is the ability to allow longitudinal movement of the rails. In winter, rail movement increases gaps, causing bolts to bend and break and the material in the head of the rail to flow and chip. Wider rail gaps can also increase dynamic loads, accelerating foundation degradation and further distressing the joint bars. Thus, a new joint bar design that does not allow longitudinal rail movement is essential.
2. Better foundations for rail joints need to be designed. The improved foundations should have the ability to dampen dynamic loads. Alternatively, the improved foundations should reduce ballast pressure under the joint to the pressure under regular track.
3. Joint bar strength should be at least equal to the surrounding rail. Strength can be increased either by using higher strength materials or by increasing the cross section of joint bars.
4. Joint bars have high residual stresses induced during manufacturing processes. Controlling residual stresses can be useful. Residual stresses should be tensile or compressive on joint bar locations where service loads induce compressive or tensile

bending stresses respectively. This approach will not only increase joint bar load capacity, but also increase fatigue life.

5. Higher bolt torque can increase bending stiffness of rail joints. Use of larger bolts with higher torque is recommended. Current joint bars make contact with the rail on the sloped location of the top and bottom of the bars. Optimum torque needs to be designed to avoid web splitting.

Reference

1. Li, Dingqing, William Shust, and Semih Kalay. February 1997. "Track Panel Shift due to Repeated Passes of Lateral Axle Loads." *Technology Digest* TD-97-006, Association of American Railroads, Transportation Technology Center, Inc., Pueblo, CO.

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