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Federal Railroad Administration

Load Environment of Rail Joint Bars – Phase I

Effects of Track Parameters on Rail Joint Stresses and Crack Growth

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13. ABSTRACT (Maximum 200 words)

The load environment of joint bars was assessed under a variety of loading and track conditions. Bending stresses, thermal stresses, and residual stresses were measured on commonly used joint bars. Crack growth rates from artificially induced cracks were also monitored. This study provides the relevant data and analysis results needed for developing more comprehensive models for joint bar failure, fatigue life, crack growth, and inspection interval optimization. The data provided will also help railroads to design more reliable and safer joint bar designs.

Bending stresses in joint bars vary widely in local foundation and loading conditions. Stresses too low to cause fatigue damage and stresses large enough to cause joint bar breakage were measured. Thermal stresses in insulated joint bars are similar to those found in rail. Data also shows that once one joint bar of a standard joint is broken because of fatigue or manufacturing defect, the other joint bar carries all of the longitudinal and bending loads from the broken bar. This puts high stresses on the remaining bar, which sometimes breaks. This is consistent with the fact that in many cases both joint bars are found broken on inspection. The data also shows that thermal stresses can increase significantly because of maintenance operations, such as surfacing and under cutting.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

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1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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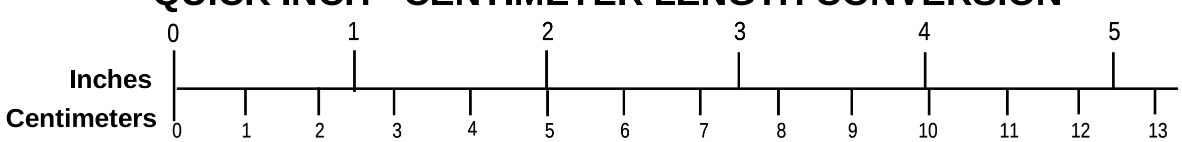
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

Transportation Technology Center, Inc. (TTCI), assessed the load environment of joint bars under a variety of loading and track conditions at the Transportation Technology Center (TTC), Pueblo, CO, under a federally funded project. TTCI measured bending stresses, thermal stresses, and residual stresses on commonly used joint bars. Crack growth rates from artificially induced cracks were also measured. This study provides the relevant data and analysis results needed for developing more comprehensive models for joint bar failure, fatigue life, crack growth, and inspection interval optimization. Railroads and suppliers will be able to use the data to design more reliable and safer joint bars.

Data collected from test joints at the Facility for Accelerated Service Testing (FAST), Pueblo, CO, and in revenue service shows that bending stresses in joint bars vary widely from local foundation and loading conditions. Stresses too low to cause fatigue damage and stresses large enough to cause joint bar breakage were measured. Bending stresses in standard joint bars are higher than those in insulated joint (IJ) bars. The analysis shows that bending stresses can be reduced at least by using longer standard joint bars and surfacing of rail joint foundations. In revenue service, joint bars on concrete tie track experienced higher stresses than the joint bars on wood tie track.

Thermal forces in IJ bars are similar to those found in the rail. Data also shows that once one joint bar on a standard joint is broken from fatigue or manufacturing defect, the other joint bar distresses and sometimes breaks. This is consistent with the fact that many times both joint bars are found broken on inspection. The data also shows that thermal stresses can increase significantly from maintenance operations, such as surfacing and undercutting.

The residual stresses in the bottom of the joint bars are tensile and approximately equal to the magnitude of bending stresses from live loads. Neutralizing or reversing the residual stresses can increase the bending strength of joint bars.

Crack growth monitoring was conducted by artificially inducing cracks in the bottom and top of joint bars. Although some joint bars broke early during service life, others did not see any crack growth. The ones that broke had cracks that propagated from the bottom notch. Other unnotched test and nontest joint bars at FAST, which broke during the duration of this study, broke from cracks that initiated at the bottom of the joint bars.

Measures that may be taken to reduce the number of joint bar service failures include redesigning of joint bars for current loading, using high-strength materials, maintenance of foundations, and more reliable inspections tools.

Other forces that joint bars may be subjected to but not measured during this test include contact, shear, and torsion stresses. These stresses in joint bars are difficult to measure. Thus, TTCI recommends a detailed finite element analysis, which may use as input measured bending, thermal, and residual stress data to calculate these stresses. TTCI also recommends that a more detailed statistical analysis of the collected data be conducted to identify the most common stress levels that should be used for newer design purposes.

1. Introduction

Conversion of jointed rail to continuously welded rail (CWR) has induced considerable thermal forces in rail. In addition, axle loads have increased significantly during the past three to four decades. New rail sections have been designed to accommodate these changes in load environment. Joint bar cross section has usually increased to match the increasing rail sizes, but the basic design has remained the same. Unlike other track components, in which component-caused accidents have gradually been reduced from design improvements, the number of joint bar-related accidents remained the same until 2007.

Rail joints are used to join two rails. As illustrated below, rail joints can be classified as insulated or bolted joints. IJs are further categorized as bonded or nonbonded joints. Bonded IJs have the joint bars epoxied to the rail. Nonbonded IJs are basically bolted joints having some type of electrical insulating properties.

Bolted rail joints are further classified into compromise and standard joints (Figure 1). Standard joints are used to join two similar rail sections. Compromise joints are used to join two dissimilar rail sections. Standard joints are only temporary in CWR territory and permanent in jointed rail territory.

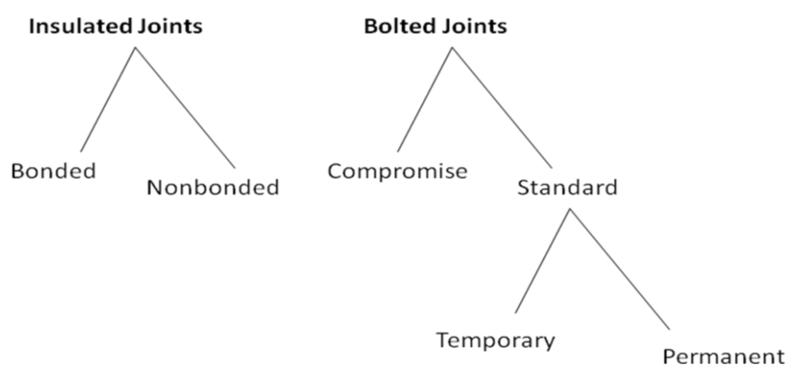


Figure 1. Classifications of Insulated and Bolted Rail Joints

Insulated and standard rail joints perform differently and have different operational objectives, but they share many similar design features. For example, they both have butt joints that use bolts and bars to connect the two rails. This creates a discontinuity or gap in the running surface of the track on each rail. 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. Like other special trackwork components, rail joints have lower service life than the parent rail. At the same location, a rail joint may be replaced many times during the service life of the surrounding rail.

Rail joints are a safety and reliability issue for the railroads. Rail joint failures may cause derailments and accidents. At the minimum, joint failure causes increased maintenance and traffic delays.

The type and level of stresses induced into rail joints attributable to live and environmental loads are not very well understood. This report summarizes the load environment data collected from standard and bonded IJs in different track conditions.

1.1 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 allows longitudinal movement to offset rail expansion and contraction as a result of temperature change. Although 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 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 (lb) and higher car weights.

To understand the magnitude of rail joint failures from a safety perspective, the Federal Railroad Administration (FRA) has databases that contain records of all railroad accidents above the reporting threshold of $6,700 in damages or involving injuries and joint bar fracture reports that railroads are required to submit (1). In 2007, these reports were collected and analyzed by TTCI (2).

According to FRA's accident data, 249 accidents related to joint failures that occurred from 2000 to 2010 (Figure 2). Most joint bar failures occurred from 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 through 2010 appears to be due to improvements in inspection procedures and capabilities. This improvement is due, at least in part, to FRA mandated frequent inspections of rail joints that came into effect in 2007.

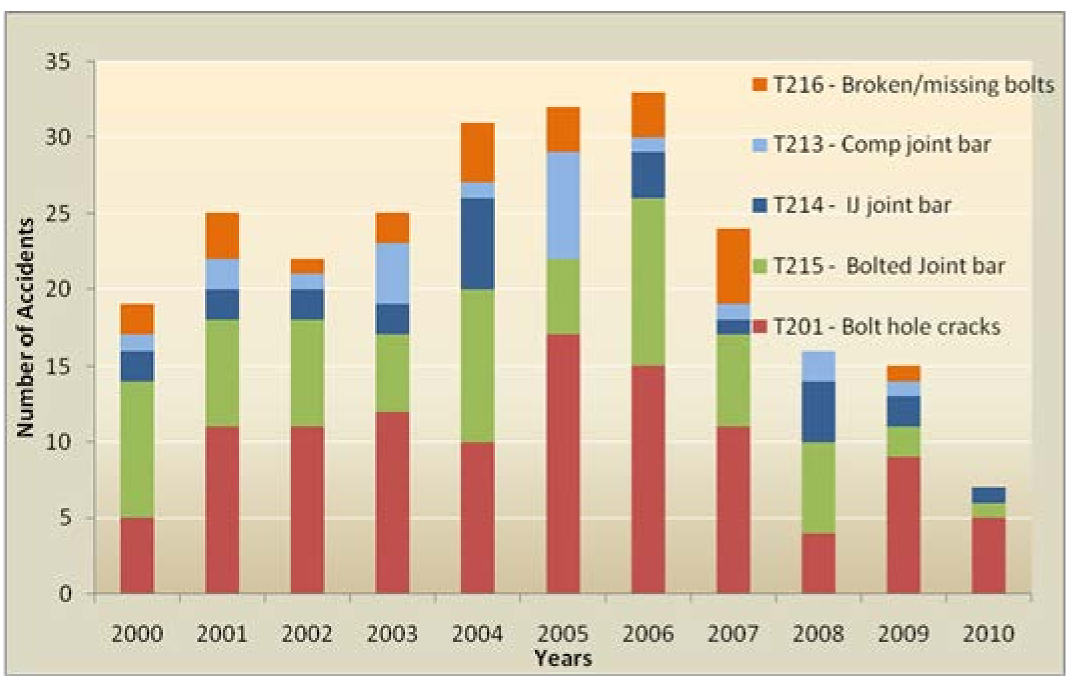


Figure 2. Frequency of Rail Joint Bar Accidents during the Last 11 Years

FRA requires U.S. 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 based on reports submitted during the first half of 2007 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 IJ 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, 29/38 (75%) had cracks on top of the bar and 6/38 (15%) had cracks on the bottom (3).

Table 1. Failure Mode Analysis of Joint Bars

Failure Mode	Location	Field Side %	Gage Side %	Total %
Broken	Center	26	31	62
	Bolt hole	1	2	
Cracked	Top Center	16	13	38
	Bottom Center	3	3	
	Bolt hole	2	2	

1.2 Objectives

One objective of this study was to measure the load environment that joint bars are subjected to under different loading, weather, and geographical conditions. This includes bending and thermal strains.

Measurement of service loads will help understand the failure modes of joint bars. Also, a better understanding of service loads will allow development of methods to reduce stress levels in joint bars.

Another objective of this study was to measure crack growth rate. Crack growth rate will allow railroads to optimize the track inspection intervals. Using optimum inspection periods will help railroads schedule the removal of cracked joint bars from track before they break.

1.3 Overall Approach

To meet the objectives, several most commonly installed IJs and standard joints were installed at FAST (Figure 3) and in two revenue service locations.

At FAST, static and dynamics bending strains data was collected at approximately 25 MGT intervals under fully loaded cars for more than 100 MGT of traffic to measure the joint bar response to gradually deteriorating foundations.

In revenue service locations, bending strains were measured under unit- and mixed-freight trains. In addition to bending strains, longitudinal strains due to thermal changes were measured in rail, standard joints, and IJs.

Standard joint bars were artificially notched at FAST to monitor real-time crack growth. Crack growth rate in IJ bars was not measured because very few (3 percent of 2007 failure reports were IJ bars) failed from crack growth.

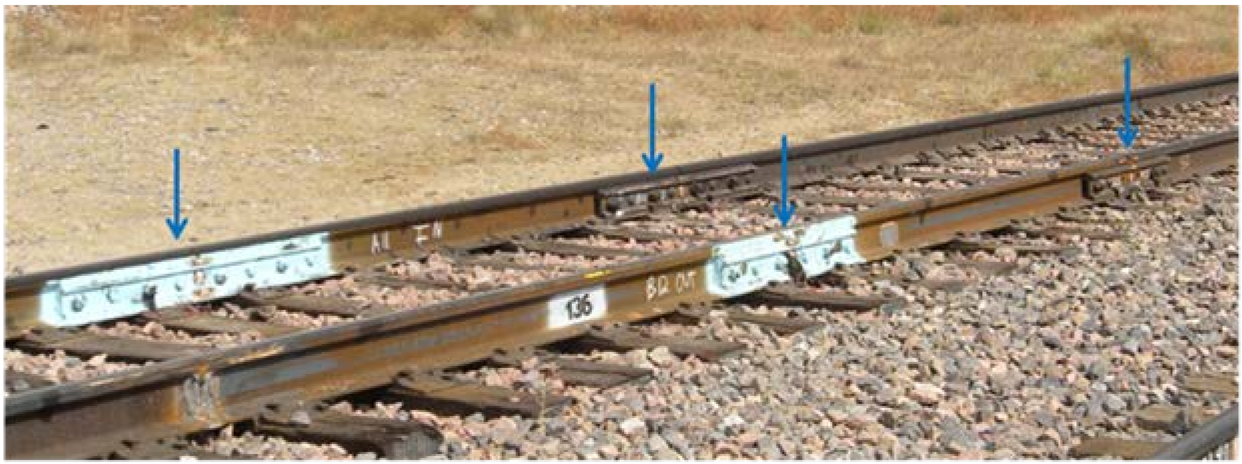


Figure 3. Insulated and Standard Joints installed as Part of the Test

2. Description of Test Methods

To explore and quantify the effects of track conditions on joint bar stresses, data was collected from the most common rail joints. A total of 24 rail joints were installed on different track geometry and track types: 16 rail joints were installed at FAST in the High Tonnage Loop (HTL) and 8 were installed in revenue service (see Tables 2 and 3). Each joint bar had two strain gage circuits: one on the bottom of the joint bar to measure tensile bending stresses and one on top of the joint bar to measure compressive stresses.

Table 2. Test Matrix

Locations	Track Geometry	Tie/Fastener	Joint Type	Circuit Type	Site
1	Tangent	Wood/spikes	A,B,C,D	Bending	FAST HTL
2	Tangent	Concrete	A,B,C,D	Bending	FAST HTL
3	5-degree curve	Wood/spikes	A,B,C,D	Bending	FAST HTL
4	5-degree curve	Concrete	A,B,C,D	Bending	FAST HTL
5	Tangent	Wood/spikes	B,D	Bending/Thermal	Eastern RR
6	7-degree Curve	Wood/spikes	B,D	Bending/Thermal	Eastern RR
7	Tangent	Wood/spikes	B,D	Bending/Thermal	Western RR
8	4-degree Curve	Concrete	B,D	Bending/Thermal	Western RR

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 Tested (4)

Joint Bar/Rail Type	Cross-Sectional Area	Moment of Inertia	Section Modulus Top	Section Modulus Bottom
Units	Inches^2	Inches^4	Inches^3	Inches^3
Insulated joint bar	12.54	24.5	9.62	9.98
Standard joint bar	11.78	32.28	13.36	12.22
136RE rail	13.32	94.2	23.7	28.2

IJs (Types A and B) were installed in 20-foot-long plugs at four locations on the HTL at FAST (Figure). Standard joint bars (Types C and D) were installed by cutting the existing rails to make new joints (Figure 4). Bending strains from joints at FAST were measured at 25–30 MGT intervals. To quantify foundation degradation, static deflections were measured under loaded heavy-axle load (HAL) car wheels at the same intervals. Joint foundations were only surfaced when required to maintain operational requirements for the train at FAST. No longitudinal force measurements were made on the rail joints at FAST; however, rail temperature was recorded when the rail joints were installed.

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, thermal force circuits were installed on each of the joint bars and on each of the rails. Temperature and corresponding thermal strains from these circuits are automatically collected every half hour using solar-powered data loggers.

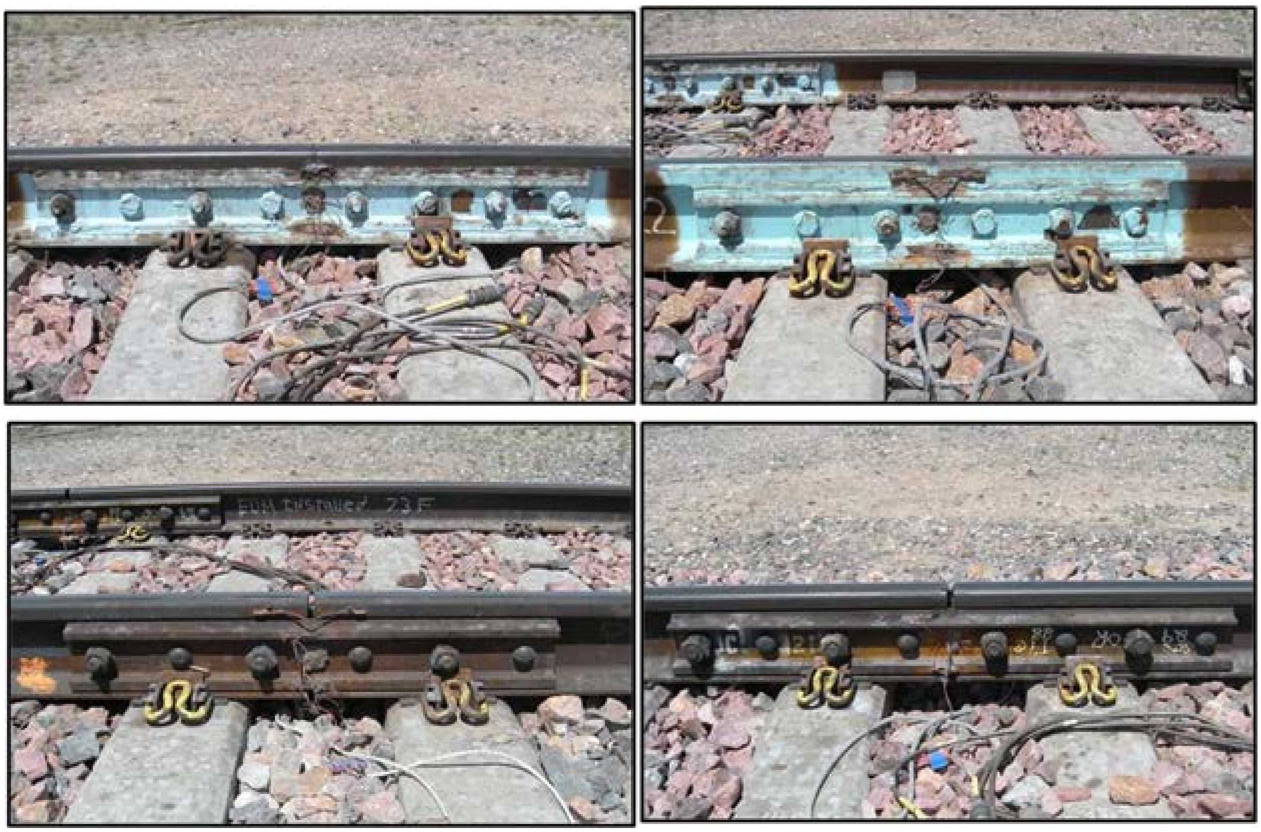


Figure 4. Typical Test Joints Clockwise (from top left) 8-Hole IJ (Type A), 6-Hole IJ (Type B), 8-Hole Standard Joint (Type C), and 6-Hole High Relief Joint (Type D)

2.1 Static Bending Stress

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 net deflection at the end post when the wheel of the loaded and empty car is right over the joint bar. Strain gages were placed close to the end posts of the joint bars.

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 five to seven ties around 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, as Figures 5 and 6 show.

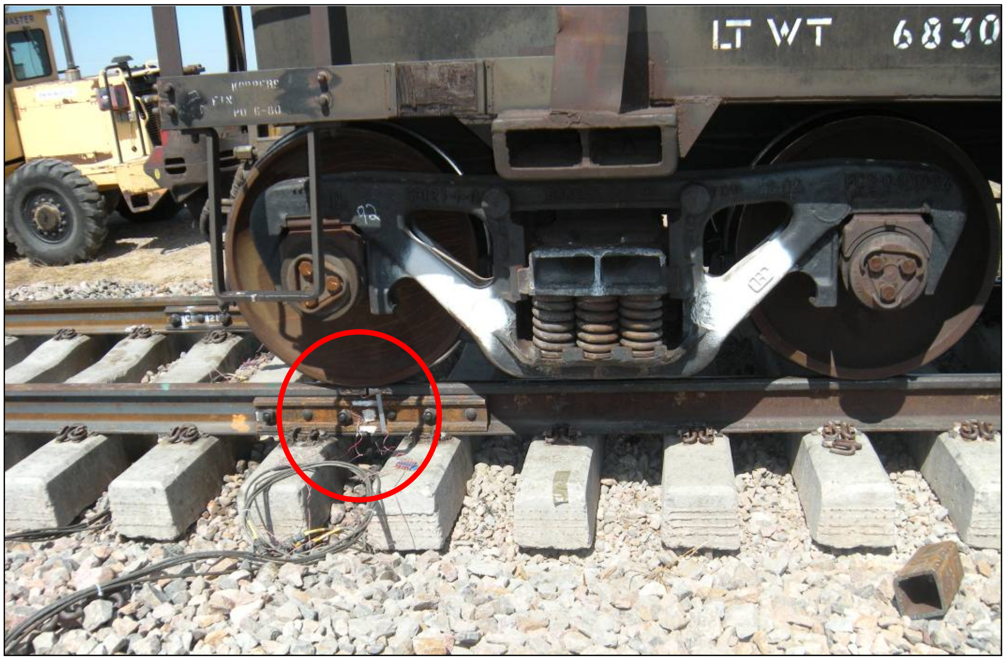


Figure 5. Car Wheel on the Joint Center during Static Data Collection (photo shows joint with disturbed foundation)

Figure 6. Ballast Being Disturbed and Removed from under the Ties

2.2 Dynamic Bending Stresses

Bending strains on the top and bottom of all of the joint bars were collected during train operations at FAST. The data collection was conducted at regular intervals of approximately 25 MGT with the objective of understanding the response of the joints as their foundations degraded under HAL traffic. Train speed was 40–45 miles per hour (mph). The train consisted of about 100 loaded (315,000 lb gross weight) cars. Static deflections of each joint were also measured at every interval. Figure 7 shows the typical time history of a few cars of the train.

In revenue service, bending strains were measured from rail joints only right after installation. No vertical deflections were measured. Trains were either coal unit trains or mixed freight. Train speed varied from 35 to 45 mph.

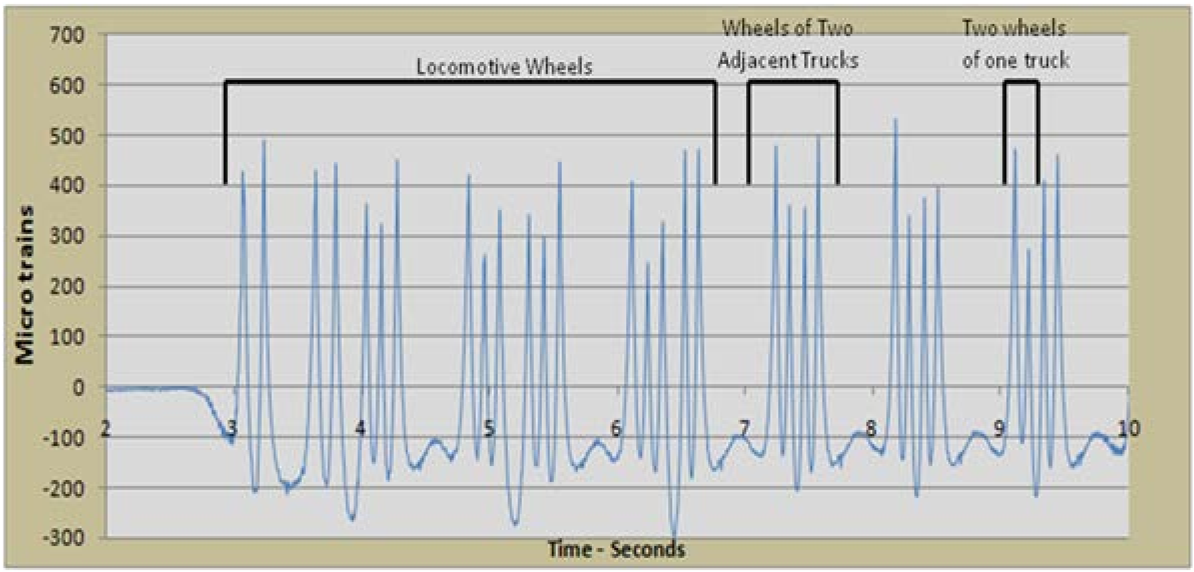


Figure 7. Typical Time History of Dynamic Bending Data

2.3 Thermal Stresses

Thermal stresses in rails and joint bars were measured in revenue service at an eastern and a western railroad using solar-powered data loggers (Figures 8 and 9). These data loggers recorded temperatures and strains at every 30 minutes for future download. On the eastern railroad, one pair of IJs 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 were three to five ties apart on adjacent rails. Standard joints were installed because they are typically installed in revenue service track with the middle two holes left blank. No pulling force was applied during installation of the joints. At the time of installation, the rail temperature was 62°F, which is also the neutral temperature of the joints. The IJs were initially bolted into the track but were welded into the rail at a later date.

One pair of standard and IJs was installed on tangent and 4-degree curve track on a western railroad. The tangent track has wood ties with cut spikes. The curved track has concrete ties with elastic fasteners. Both rail joints were welded on the day of installation. No pulling force was applied.

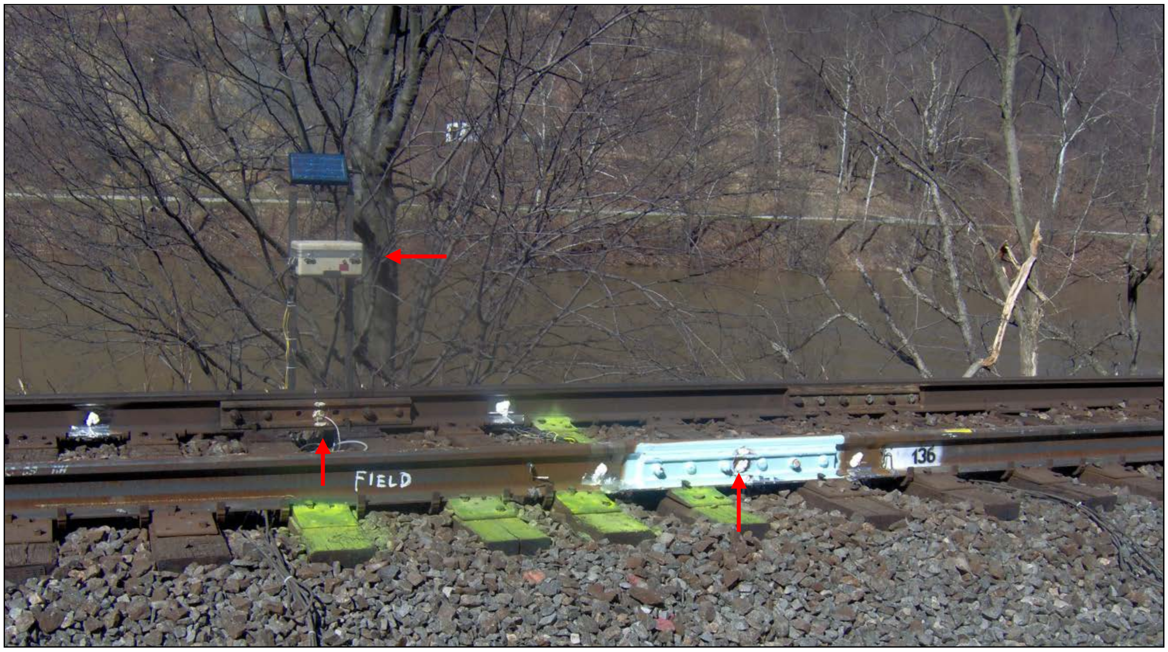


Figure 8. Data Logger, Bonded IJ and Standard Joint in Salina, PA

Figure 9. Thermal Stress – Temperature Data Collection on a Western Railroad, Colorado Springs, CO

2.4 Crack Propagation Rates

High cycle fatigue is the most common joint bar failure mode. Fatigue life is the sum of cycles to initiate a fatigue crack and cycles to propagate the crack. The number of cycles needed to initiate a crack is considerably higher than the number to propagate a crack. The former is considerably higher than the latter. After the crack has started, the rail joint becomes a safety concern. Many joint bars removed are found broken in service. It appears that once a crack began, a faster growth rate may break the joint bar before the next track inspection. After one joint bar breaks, the rail joint redistributes the load to the unbroken joint bar, which may break from yield or low cycle fatigue. An optimum track inspection period is desirable to locate and replace joint bars with cracks before they break. This requires a detailed study of crack growth rate of different design joint bars in varied environments and load conditions.

To estimate crack propagation rates, eight joint bars were notched on the bottom and top edges and installed on the GS of rail joints. Three joint bars were installed with notches on the top edge only. Notches were made using electrical discharge machining (EDM). During train operations, joint bars were inspected on a daily basis. All joint bar holes had bolts tightened to the manufacturer's recommended full torque. The notch sizes selected were based on the load environment measured during the current study. The selected notch location was in the longitudinal center of the joint bar. Figure 10 shows the shape, size, and location of notches on joint bars.

The notched joint bars were installed when rail temperature was between 80 and 90°F. These are the prevailing rail temperatures when the test train at FAST normally operates during spring and fall. These joint bars were subjected to variations in rail temperature, which can be more than 40°F on a daily basis. This temperature corresponds to a thermal force of approximately 100,000 lb on tangent track. A lesser thermal force may be assumed in curved track, where the track can "breathe" to relieve longitudinal stress attributable to the rail temperature variation.

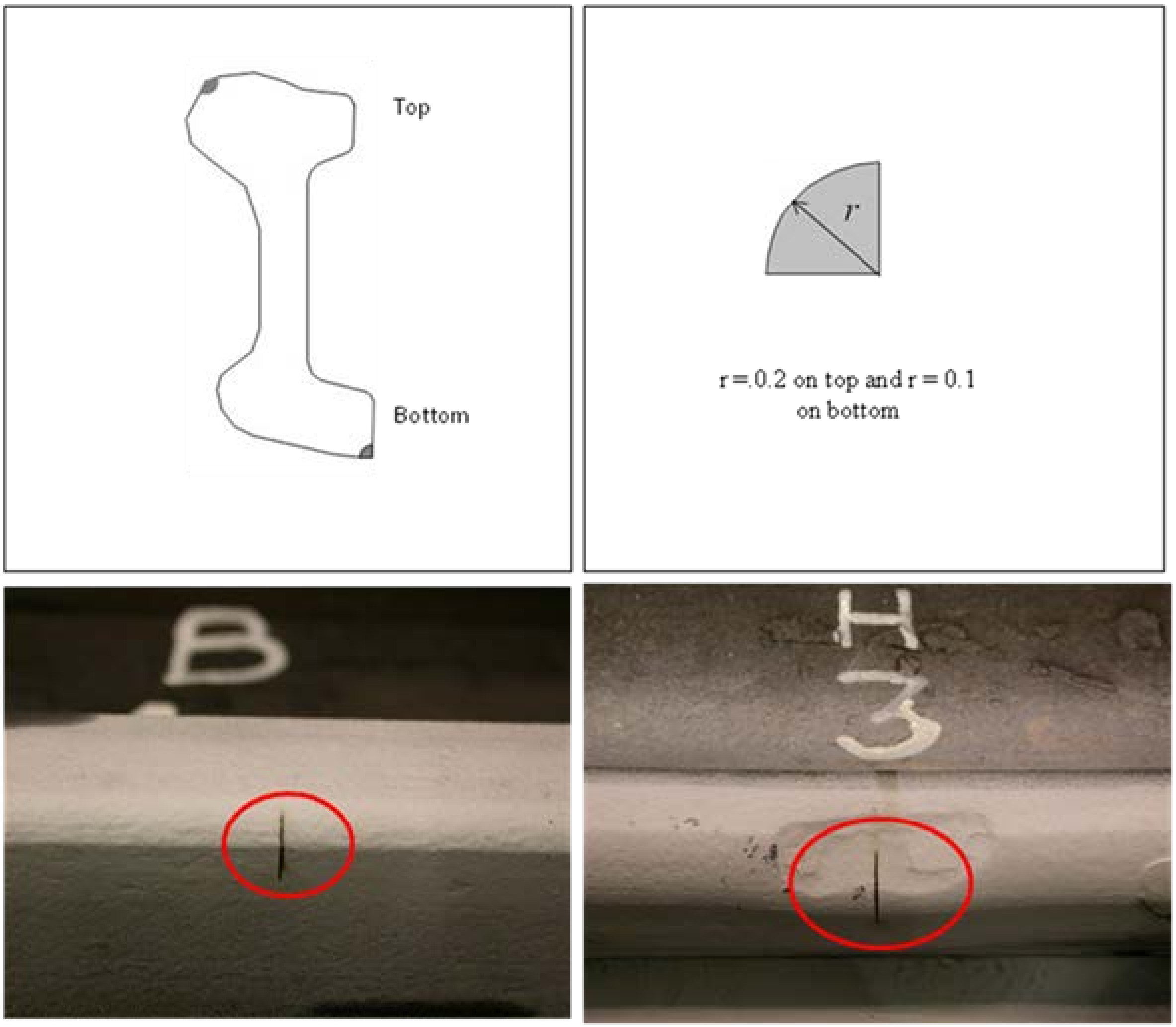


Figure 10. (Clockwise from top left corner) EDM Notch Locations, Approximate Notch Shape and Size, Notch on the Top and Notch on the Bottom

3. Discussion

3.1 Static Bending Stress – Deflection Relationship

Three track deflections and resulting bending tensile strains in the bottom of joint bars were recorded for each joint. Stresses were calculated from measured bending strains. Figure 11 shows the stress-deflection plot of 48 measurements from 16 joints installed at FAST. The envelope encompasses the lowest and the highest deflection-stress relationship of most common rail joints on moderate to poor foundations.

Joint bar stresses ranged from 8 to 25 ksi (1,000 lb per square inch) when the track was undisturbed. Track was then disturbed to simulate degraded foundations. As a result, the bending stress range increased from 15 to 60 ksi.

The overall relationship was initially linear but tended to flatten at higher deflections. Stresses of joints on tangent track were on the higher side of the envelope as compared to stresses on curved track, which were toward the lower side of the envelope. On curved track, unequal and nonsymmetrical wheel loading may cause torsion in the joint bars, reducing bending stress.

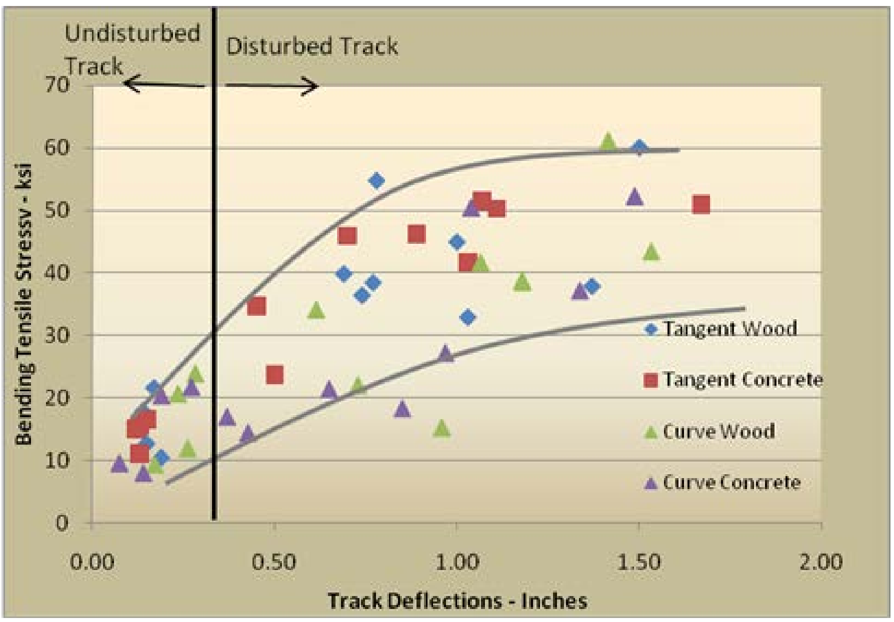


Figure 11. Static Stress-Deflection Relationship

3.2 Dynamic Bending Stresses – Facility for Accelerated Service Testing

Tables 4 through 7 show the data collected during 100 MGT of 315,000-pound traffic with the test train at FAST operating at 40–45 mph. Bending tensile stress is located on the bottom, and bending compressive stress is located on the top of the joint bars. Maximum stress is the maximum spike from one train traveling over a particular joint. Average is the average of stress on the GS and FS. Deflections are the net track deflection under empty and loaded coal cars (wheel load of 8,340 and 39,710 lb, respectively). Ninety-ninth percentile filters out 1 percent of measured stress spiking from flat wheels or other sources.

Figures 12 and 13 are a graphical representation of some of the data in these tables.

Table 4. Bending Tensile Stress History in the Bottom of Joint Bars 1/2

Accumulated Tonnage (MGT)			8 MGT				42 MGT				60 MGT				108 MGT			
Rail Joint Locations and Description			Vertical Deflec-tions (in.)	Stress - ksi: 99th Percentile	Stress - ksi: Avg.	Stress - ksi: Max.	Vertical Deflec-tions (in.)	Stress - ksi: 99th Percentile	Stress - ksi: Avg.	Stress - ksi: Max.	Vertical Deflec-tions (in.)	Stress - ksi: 99th Percentile	Stress - ksi: Avg.	Stress - ksi: Max.	Vertical Deflec-tions (in.)	Stress - ksi: 99th Percentile	Stress - ksi: Avg.	Stress - ksi: Max.
Tangent Wood Tie Track	8-hole IJ	FS	0.13	13.9	12.7	20.9	0.17	13.9	12.6	20.9	0.15	13.5	12.7	21.6	0.18	13.9	13.6	22.0
		GS		11.4		17.1		11.3		17.2		11.9		18.0		13.3		20.1
	6-hole IJ	FS	0.13	13.3	15.8	20.6	0.16	13.1	12.1	20.3	0.17	16.9	14.9	25.6	0.17	17.1	21.3	23.8
		GS		18.2		26.7		11.1		21.7		13.0		19.2		25.5		30.0
	8-hole std	FS	0.28	19.9	18.7	27.7	0.36	20.0	18.6	28.1	0.37	17.9	19.3	24.2	0.39	20.6	19.6	29.8
		GS		17.4		25.3		17.3		24.5		20.6		29.8		18.6		26.8
	6-hole std	FS	0.28	26.6	26.6	36.2	0.31	26.5	21.8	35.7	0.34	24.7	25.2	32.3	0.32	0.0	13.2	0.0
		GS		26.7		37.9		17.0		24.3		25.7		32.2		26.3		33.3
Tangent Concrete Tie Track	8-hole IJ	FS	0.08	20.5	16.7	31.0	0.09	23.5	18.1	39.5	0.10	27.4	21.1	59.4	0.10	22.2	18.2	30.0
		GS		12.8		19.0		12.8		18.9		14.8		20.5		14.1		19.9
	6-hole IJ	FS	0.09	13.0	15.3	19.3	0.08	12.5	14.9	18.4	0.08	17.8	15.8	25.1	0.09	14.3	12.9	27.2
		GS		17.5		35.9		17.2		36.6		13.8		19.1		11.5		17.9
	8-hole std.	FS	0.06	13.3	15.7	18.8	0.12	14.0	16.1	19.6	0.11	17.3	17.1	28.3	0.13	15.4	17.2	22.8
		GS		18.1		25.8		18.2		26.2		17.0		24.5		18.9		30.6
	6-hole std	FS	0.12	17.1	19.6	23.7	0.16	18.7	20.6	25.8	0.18	26.7	24.5	39.2	0.16	23.6	22.8	34.1
		GS		22.2		31.9		22.6		32.8		22.3		28.3		22.1		29.9

Table 5. Bending Compressive Stress History in the Bottom of Joint Bars 2/2

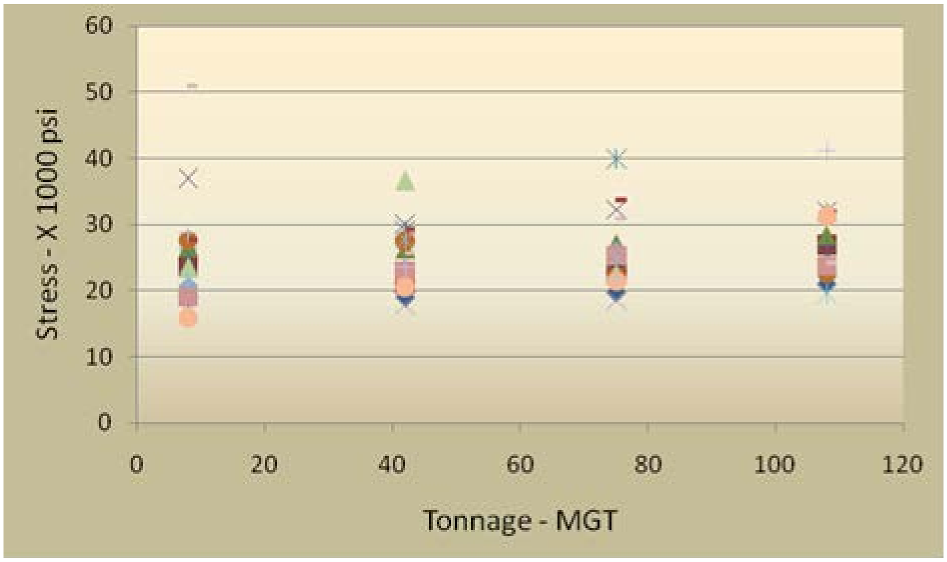
Accumulated Tonnage (MGT)			**8 MGT**				**42 MGT**				**60 MGT**				**108 MGT**			
Rail Joint Locations and Description			Vertical Deflec-tions (in.)	Stress - ksi			Vertical Deflec-tions (in.)	Stress - ksi			Vertical Deflec-tions (in.)	Stress - ksi			Vertical Deflec-tions (in.)	Stress - ksi		
				99th Percentile	Avg.	Max.		99th Percentile	Avg.	Max.		99th Percentile	Avg.	Max.		99th Percentile	Avg.	Max.
Tangent Wood Tie Track	8-hole IJ	FS	0.13	-11.9	-13.6	-16.9	0.17	-11.7	-13.4	-15.9	0.15	-13.1	-14.5	-27.7	0.18	-11.5	-12.8	-15.4
		GS		-15.3		-23.0		-15.1		-21.8		-15.8		-23.3		-14.1		-19.8
	6-hole IJ	FS	0.13	-14.4	-15.5	-20.0	0.16	-13.9	-13.3	-19.6	0.17	-14.9	-14.9	-19.1	0.17	-11.1	-13.2	-15.9
		GS		-16.6		-24.1		-12.7		-17.6		-14.8		-19.3		-15.2		-18.4
	8-hole std	FS	0.28	-17.2	-14.6	-23.9	0.36	-11.5	-13.7	-16.4	0.37	-15.9	-13.9	-22.7	0.39	-21.3	-19.3	-29.4
		GS		-12.0		-18.2		-16.0		-21.5		-11.9		-19.5		-17.3		-25.6
	6-hole std	FS	0.28	-10.7	-10.3	-19.1	0.31	-13.9	-14.6	-18.0	0.34	0.0	-8.4	0.0	0.32	-17.3	-18.2	-22.9
		GS		-9.8		-17.3		-15.3		-21.0		-16.8		-22.5		-19.1		-27.5
Tangent Concrete Tie Track	8-hole IJ	FS	0.08	-13.5	-15.2	-18.8	0.09	-14.6	-15.0	-20.4	0.10	-16.8	-17.6	-31.9	0.10	-15.5	-7.7	-24.4
		GS		-16.9		-26.0		-15.5		-24.3		-18.4		-27.0		0.0		0.0
	6-hole IJ	FS	0.09	-16.0	-15.0	-27.3	0.08	-13.8	-14.8	-18.2	0.08	-12.8	-14.5	-17.7	0.09	-16.4	-14.5	-22.6
		GS		-14.1		-19.1		-15.8		-25.2		-16.3		-24.0		-12.7		-17.1
	8-hole std.	FS	0.06	-12.0	-13.4	-8.5	0.12	-17.9	-17.8	-24.7	0.11	-19.4	-20.0	-30.5	0.13	-17.4	-14.5	-21.6
		GS		-14.8		-22.9		-17.7		-26.3		-20.5		-30.7		-11.5		-15.5
	6-hole std	FS	0.12	-11.8	-10.5	-22.4	0.16	-11.1	-13.9	-14.8	0.18	-25.2	-12.6	-30.1	0.16	-12.1	-13.4	-17.3
		GS		-9.2		-14.2		-16.7		-22.9						-14.6		-21.7

Table 6. Bending Tensile Stress History on Top of Joint Bars 1/2

Accumulated Tonnage (MGT)			**8 MGT**				**36 MGT**				**73 MGT**				**102 MGT**			
Rail Joint Location and Description			Vertical Deflec-tions (in.)	Stress - ksi			Vertical Deflec-tions (in.)	Stress - ksi			Vertical Deflec-tions (in.)	Stress - ksi			Vertical Deflec-tions (in.)	Stress - ksi		
				99th percentile	Avg.	Max.		99th percentil e	Avg.	Max.		99th percentile	Avg.	Max.		99th percentile	Avg.	Max.
Curved Wood Tie Track	8-hole IJ	FS	0.24	15.5	13.6	23.1	0.28	17.6	14.6	27.6	0.22	18.0	15.5	26.7	0.23	18.5	16.3	26.9
		GS		11.8		18.2		11.6		19.0		13.0		25.3		14.1		20.4
	6-hole IJ	FS	0.27	17.4	14.4	23.4	0.32	17.9	14.3	25.8	0.43	20.8	17.1	30.6	0.41	18.5	16.5	27.2
		GS		11.5		14.8		10.8		20.0		13.3		19.9		14.4		20.2
	8-hole std	FS	0.20	17.5	15.8	24.4	0.32	30.4	26.6	41.8	0.23	13.2	14.1	19.0	0.26	22.7	21.9	32.5
		GS		14.0		22.7		22.8		31.3		14.9		26.0		21.0		31.5
	6-hole std	FS	0.21	8.4	10.2	15.9	0.24	5.4	9.2	14.6	0.26	13.3	12.0	20.4	0.28	14.4	17.1	24.2
		GS		12.0		17.7		13.0		20.9		10.7		16.8		19.9		62.6
Curved Concre te Tie Track	8-hole IJ	FS	0.08	17.4	13.5	27.2	0.10	13.4	19.1	19.8	0.11	16.8	15.4	26.8	0.08	13.6	12.6	18.6
		GS		9.6		16.1		24.9		35.6		14.1		22.7		11.6		20.6
	6-hole IJ	FS	0.15	11.2	8.3	19.0	0.19	18.0	11.4	34.6	0.23	14.5	13.4	25.0	0.21	26.7	22.9	38.3
		GS		5.4		12.8		4.8		6.5		12.3		17.9		19.0		24.2
	8-hole std	FS	0.26	22.8	20.3	31.4	0.08	7.7	12.8	15.5	0.17	27.8	27.1	43.9	0.21	27.0	26.9	42.1
		GS		17.8		26.2		18.0		31.6		26.4		0.0		26.7		40.1
	6-hole std	FS	0.45	30.5	35.1	46.4	0.38	17.6	17.6	24.5	0.45	18.0	22.4	27.2	0.28	18.8	17.6	24.1
		GS		39.7		55.3		17.5		26.8		26.7		34.6		16.4		24.3

Table 7. Bending Compressive Stress History in the Top of the Joint Bars 2/2

Accumulated Tonnage (MGT)			**8 MGT**				**36 MGT**				**73 MGT**				**102 MGT**			
Rail Joint Location and Description			Vertical Deflec-tions (in.)	Stress - ksi			Vertical Deflec-tions (in.)	Stress - ksi			Vertical Deflec-tions (in.)	Stress - ksi			Vertical Deflec-tion (in.)	Stress - ksi		
				99th percentile	Avg.	Max.		99th percentile	Avg.	Max.		99th percentile	Avg.	Max.		99th percentile	Avg.	Max.
Curved Wood Tie Track	8-hole IJ	FS	0.24	-16.3	-15.4	-22.4	0.28	-18.7	-18.6	-26.1	0.22	-23.9	-20.3	-40.0	0.23	0.0	0.0	0.0
		GS		-14.6		-19.0		-18.4		-25.0		-16.7		-24.1		0.0		0.0
	6-hole IJ	FS	0.27	-15.9	-18.8	-20.5	0.32	-13.4	-17.2	-18.5	0.43	-9.6	-14.5	-13.8	0.41	-12.8	-16.8	-16.5
		GS		-21.8		-27.3		-21.0		-27.7		-19.3		-26.8		-20.9		-27.7
	8-hole std	FS	0.20	-14.5	-19.5	-21.6	0.32	-33.9	-29.5	-44.2	0.23	-6.0	-5.8	-7.6	0.26	-0.0	-8.3	0.0
		GS		-24.5		-33.8		-25.1		-33.0		-5.5		-9.6		-16.6		-23.1
	6-hole std	FS	0.21	-10.2	-8.1	-15.7	0.24	-11.2	-8.7	-17.0	0.26	5.0	-6.3	8.2	0.28	-5.1	-7.6	-9.2
		GS		-6.0		-9.8		-6.1		-10.2		-7.7		-12.1		-10.1		-22.5
Curved Concrete Tie Track	8-hole IJ	FS	0.08	-12.6	-13.7	-17.7	0.10	-18.3	-16.0	-25.4	0.11	-13.4	-13.5	-18.9	0.08	-11.1	-12.9	-16.1
		GS		-14.8		-20.4		-13.7		-19.3		-13.6		-20.3		14.8		-20.4
	6-hole IJ	FS	0.15	-7.9	-11.1	-13.1	0.19	-13.9	-15.4	-19.0	0.23	-9.7	-10.1	-14.2	0.21	-12.5	-14.2	-21.0
		GS		-14.3		-20.5		-17.0		-23.5		-10.4		-16.6		-15.8		-19.0
	8-hole std.	FS	0.26	-25.4	-19.4	-34.9	0.08	-9.4	-10.7	-15.5	0.17	-22.1	-19.0	-32.4	0.21	0.0	-8.4	0.0
		GS		-13.4		-20.5		-12.0		-18.9		-15.8		-21.1		-16.7		-23.1
	6-hole std	FS	0.45	-22.5	-19.6	-31.2	0.38	-15.0	-15.3	-23.3	0.45	0.0	-12.0	0.0	0.28	-11.4	-11.6	-16.0
		GS		-16.8		-24.6		-15.5		-20.9		-24.0		-32.0		-11.8		-15.6



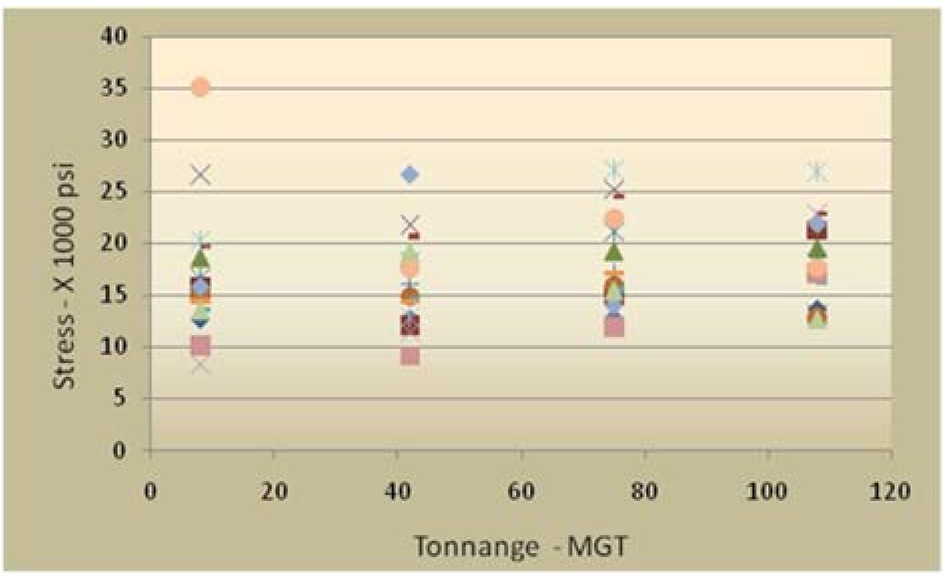


Figure 12. Tensile Bending Stress History of All 16 Test Joints at FAST (top) Maximum, (bottom) 99th Percentile

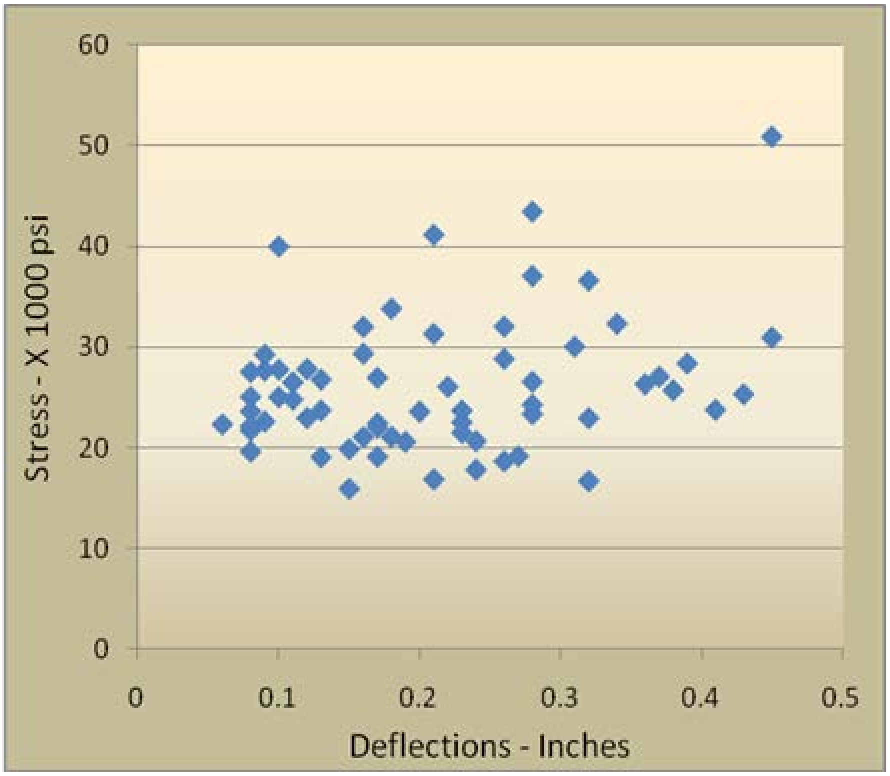


Figure 13. Dynamic Tensile, 99th Percentile, Bending Stress and Deflection Relationship of Test Joints during 100 MGT Service Life

3.2.1 Rail Joints Maintenance History

Normally rail joints require three major types of maintenance during service life:

- Surfacing as a result of ballast degradation
- Grinding as a result of 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 curved wood tie track required some maintenance, and joints on tangent concrete and wood tie track did not require any maintenance. Two joint bars and one bolt broke in curved concrete tie track, and one joint bar broke on curved wood tie track during 102 MGT (Figure 14). Tangent track did not need any maintenance during 108 MGT.

In general, concrete tie track provides higher lateral track strength than wood tie track. When the train moves from wood tie track to concrete tie track or vice versa, lateral deflections and ballast degradation under concrete tie track at the transition are likely to be higher. Among the four joints on curved concrete tie track, standard joints required more track surfacing, which is expected due to gap size. The gap between rails ends increases when the rail is in tension. Larger gaps generate higher impacts, which in turn accelerate track surface degradation. Degraded ballast increased vertical deflections of joints, which in turn overstressed and fractured joint bars.

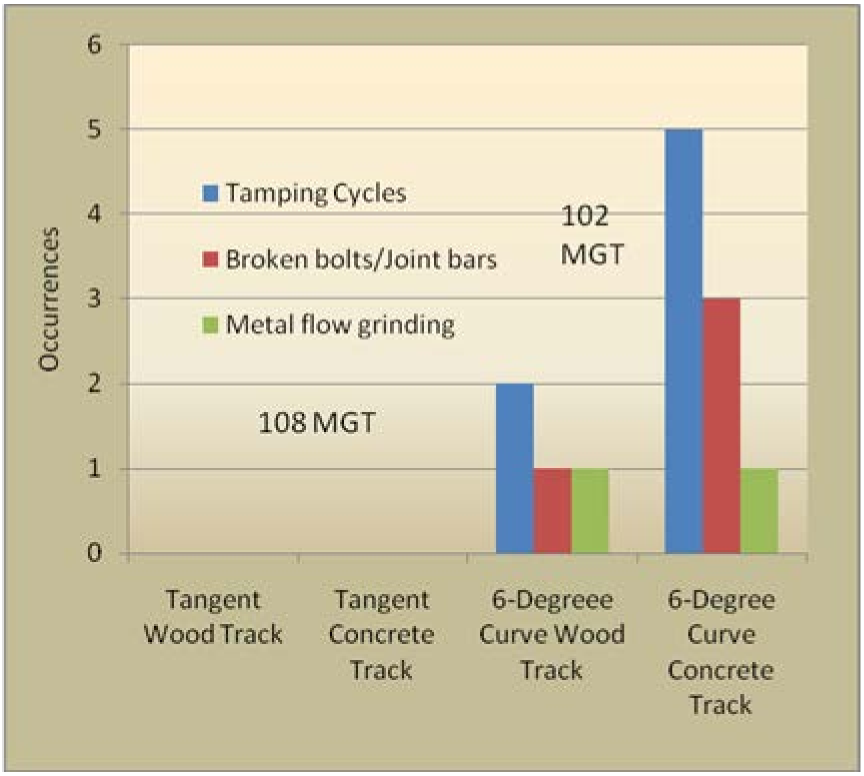


Figure 14. Maintenance History of Test Joints at FAST

3.2.2 Effects of Standard Joint Bar Lengths

Within the standard joints group, eight-hole joint bars have a lower bottom section modulus than six-hole joint bars. Under same load and foundation conditions, eight-hole joint bars should have higher stresses than six-hole joint bars. Yet bending tensile stresses at the bottom of the joint bars in the latter appear to be up to 25 percent higher than the former (Figure 15). Both joints had 1-inch-diameter bolts and torque applied was 600 ft-lb. No measureable stress level was observed in different lengths of IJ bars.

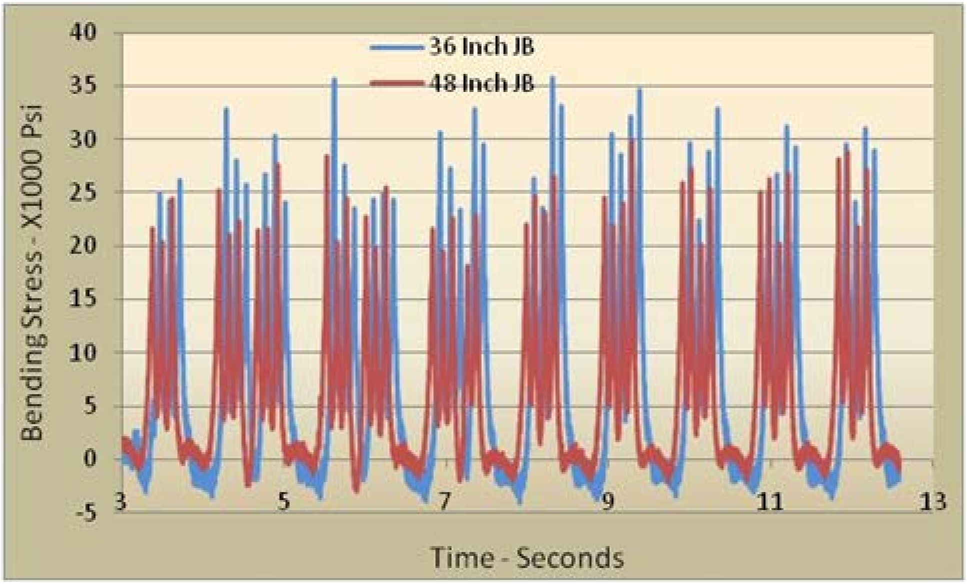


Figure 15. Bending Tensile Stress in the Joint Bar Bottom

3.2.3 Effects of Track Type and Geometry

In general, there is no consistent difference in stress levels induced in joint bars on tangent track for either wood or concrete ties. However, some instances of higher stresses in joint bars on curved concrete track in comparison to tangent concrete track were observed. Figure 16 shows the 99th percentile of bending stresses measured during 100 MGT service at four intervals.

Elastic fasteners on concrete tie track has better resistance to track gage widening and rail roll over than wood tie track with cut spikes. This higher resistance is likely to develop higher stresses on joint bars on curved concrete tie track. As described in Subsection 3.2.1, another reason for higher stress spikes during the service life is higher deflection because of accelerated ballast degradation. Two out of eight standard joint bars joint bars broke in this test section.

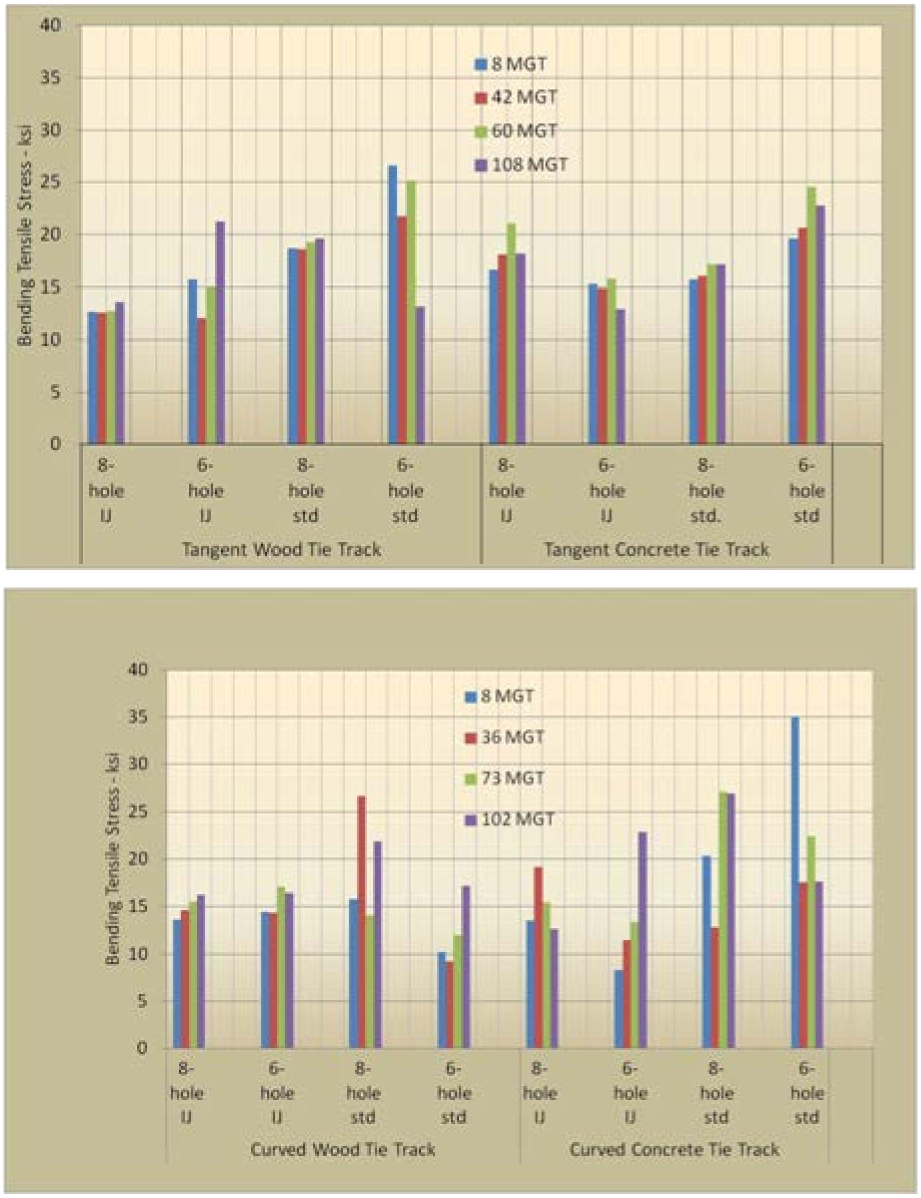


Figure 16. Bending Tensile Stress History of Joint Bars, 99th Percentile

3.2.4 Effects of Negative Bending

When a wheel is on top of the joint bar, it creates bending tensile stress at the bottom and compressive stress on the top of the joint bar. However, when the wheel is approaching the joint bar or moving away, it reverses the bending stresses (i.e., when tension is at the top and compression is at the bottom of the joint bar, it is normally referred to as negative bending).

On concrete tie track, tensile bending stresses on the top edge of the joint bar from negative bending in IJs were approximately 3,000 lb per square inch (psi). In wood tie track, tension on the top of IJ bars was up to12,000 psi. Lower negative tension bending stresses in rail on concrete track are likely attributable to better hold-down capability of elastic fasteners and higher stiffness of the concrete tie (see Figure 17).

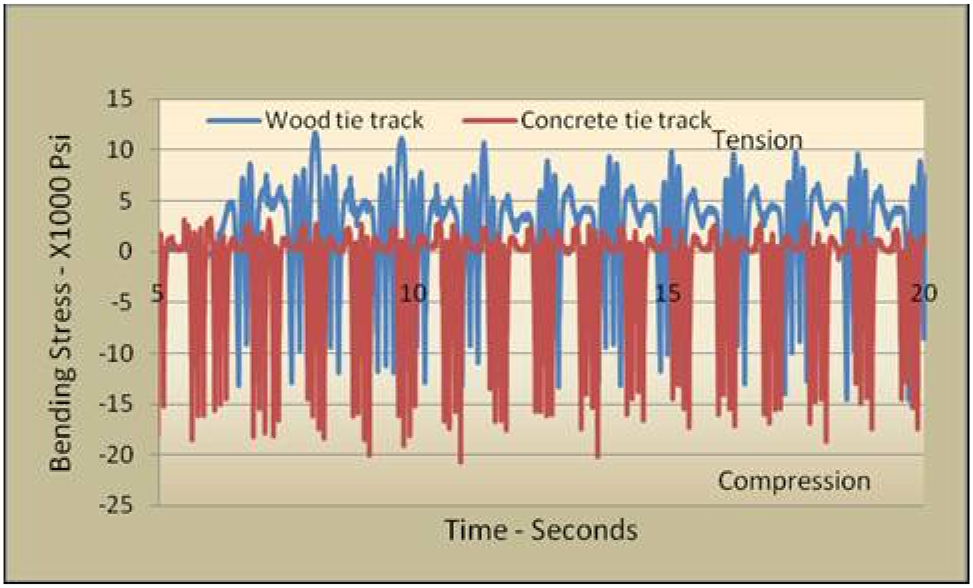


Figure 17. Partial Bending Stress History on Top of IJ Bars

3.2.5 Effects of Joint Bar location – Field versus Gage Side

Theoretically, FS and GS joint bars should experience similar levels of bending stresses. Data shows that most of the time this is not the case. Figure 18 shows the 99th percentile of FS joint bar stresses normalized to the GS joint bar stresses. On average, stresses in FS bars were between +20 to -20 percent of GS bars. However, differences up to 80 percent were observed.

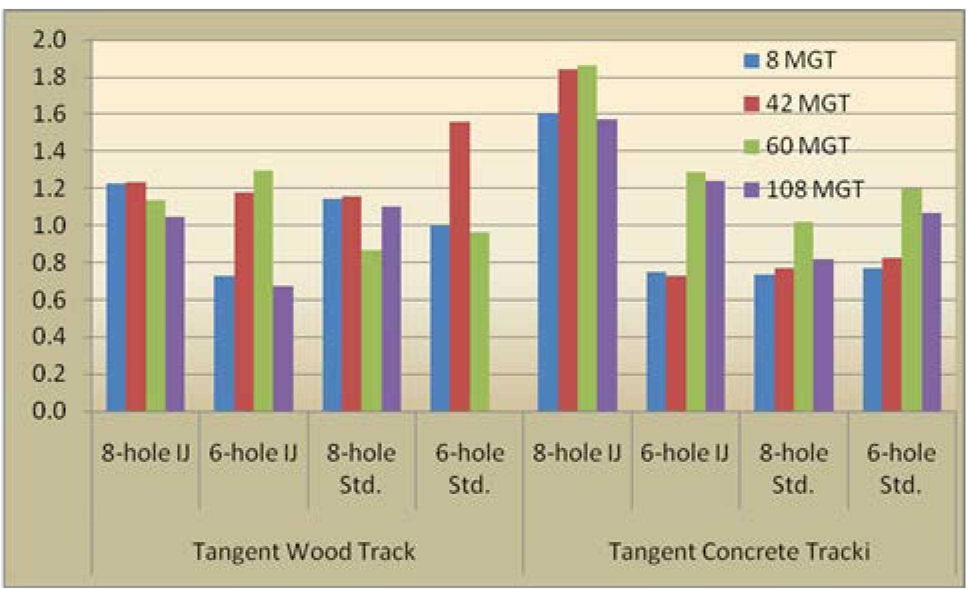


Figure 18. Stresses in FS Joint Bars Normalized to GS

3.3 Dynamic Bending Stresses – Revenue Service

Bending stress data was also collected from track in revenue service. Track conditions and traffic were different from that at FAST. Traffic ranged from empty and loaded coal cars to mixed freight.

3.3.1 Effect of Track Type

The time history in Figure 19 shows that maximum bending stresses on the bottom of joint bars on concrete tie track were approximately 2.5 times higher than in joint bars on wood track under some loading conditions. Stress ranges (difference of minimum and maximum stresses) were similar for both tracks. Concrete track has elastic fasteners, and wood track has cut spikes. Both track sections are maintained to FRA Class 4 standards.

When the wheel is approaching or moving away from the joint, uplift occurs in the track causing compression at the bottom of the joint bars. As soon as the wheel is over the joint bar, tension develops at the bottom. The track uplift appears to be much higher in wood track than in concrete tie track. This uplift tends to reduce the maximum stresses in wood tie track.

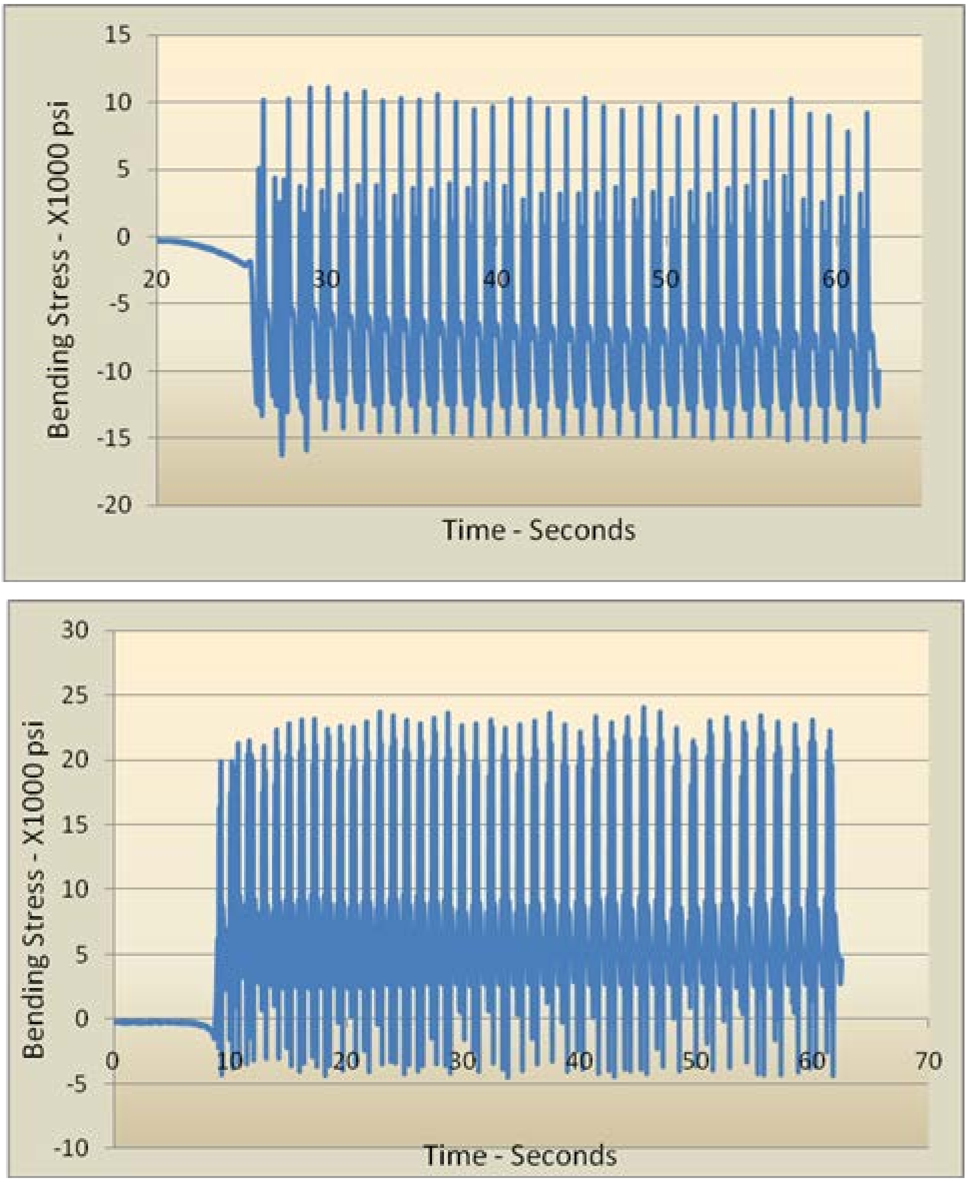


Figure 19. Bending Stress History on the Bottom of the Joint Bar (top) Wood Tie Track, (bottom) Concrete Tie Track

3.3.2 Empty and Loaded Coal Cars

Maximum measured bending stresses in joint bars under empty cars were less than 10,000 psi as compared with more than 25,000 psi of joint bars under loaded cars (Figure 20). Stresses caused by empty cars were lower than the threshold for fatigue failure. Thus, fatigue failure may not be an issue on tracks with mostly empty cars.

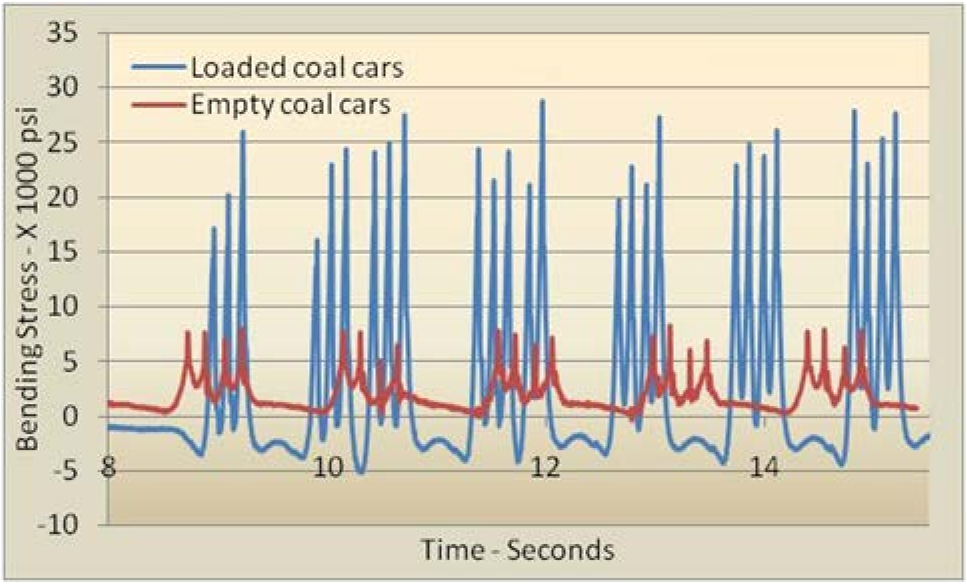


Figure 20. Bending Stresses in Bottom of Joint Bars under Empty and Loaded Coal Cars

3.4 Thermal Stresses

3.4.1 Effects of Joint Type – Standard versus IJs

As expected, stresses induced in standard and IJ bars were proportional to temperature change. However, stress induced per degree change in temperature was 40 percent lower in standard joint bars than in IJ bars. Figure 21 shows the temperature and thermal stress history for both joints collected over a period of approximately 1 year.

The standard joint bar broke during the test; therefore, a smaller temperature range is available. The two joints were installed across from each other and at the same neutral temperature.

As compared with IJ bars, which are rigidly bonded to the rail, standard joint bars have tolerances in bolts and holes. Slight rail movement due to this tolerance likely relaxes stresses in joint bars, causing lower stresses than IJ bars.

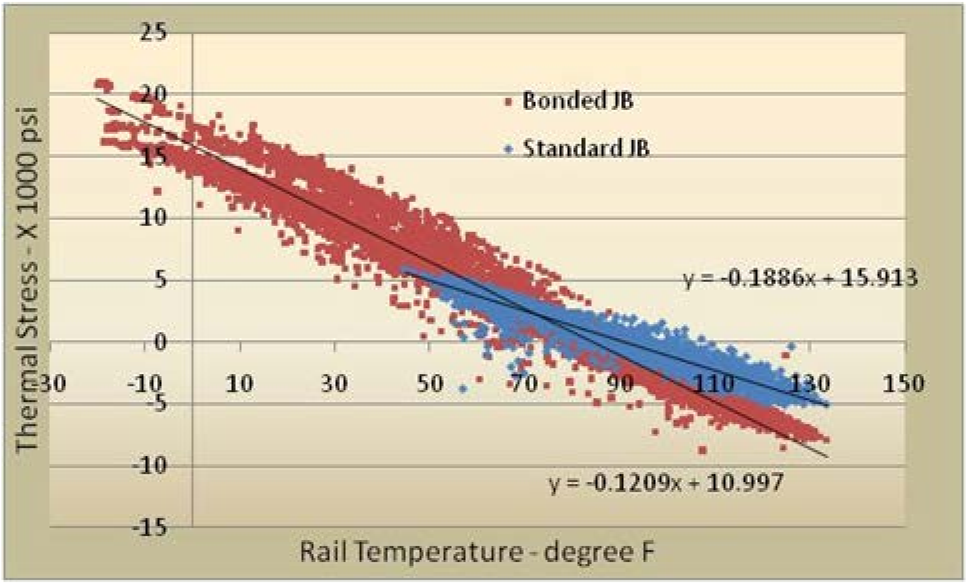


Figure 21. Temperature/Stress Relationship of Standard and Bonded Joint Bars on Tangent CWR Track in Pueblo, CO

3.4.2 Effect of One Broken Joint Bar on Unbroken Joint Bar

As stated in Subsection 3.4.1, one of the two joint bars in the standard joint broke during the test. As Figure 22 shows, after one joint bar broke, stresses in the other joint bar increased significantly. However, over time, stress in the joint bar reduced and settled to a new slope. Before the joint bar cracked, both joint bars had similar stress/temperature slope. This incidence of joint bar breaking and stress data explains why sometimes both joint bars are found broken during inspections. When one joint bars breaks, all the force in the rail is shifted to the other joint bar. This higher loading may cause yielding or low cycle fatigue failure.

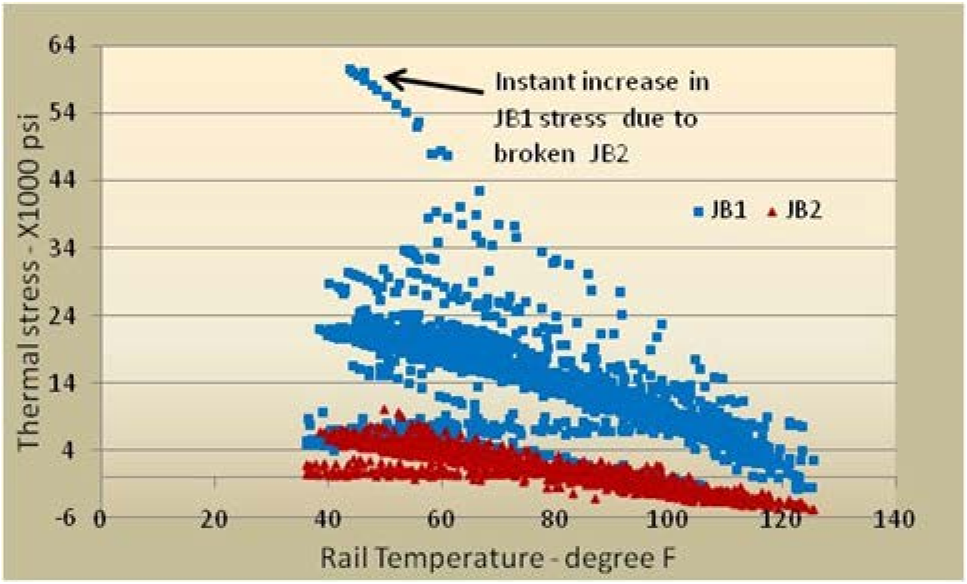


Figure 22. Stress History of Joint Bar before and after Crack Initiated

3.4.3 Effects of Track Geometry

The stress response of joints on a 7-degree curve was linear for rail temperature ranges from 0 to 20°F. Beyond that, the relationship is nonlinear, possibly because of curve breathing.

A shift in the data was also observed. During this time, track undercutting was conducted at this location. Neutral temperature and stress significantly increased because of track surfacing (Figure 23).

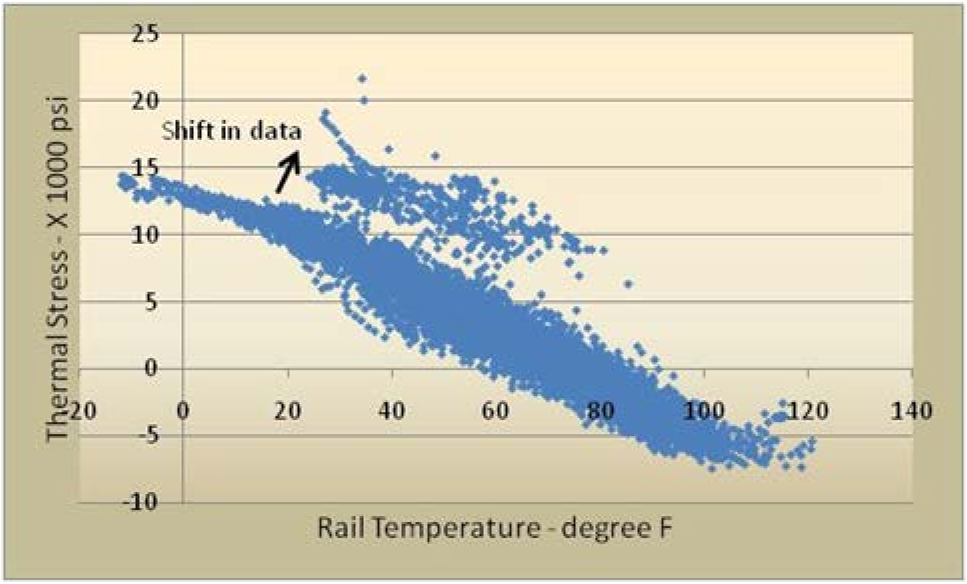


Figure 23. Thermal Stress History of Joint Bar in 7-Degree Curved CWR Track in Colorado Springs, CO

3.4.4 Maximum Thermal Stresses

Figure 24 shows the trend lines for temperature/stress relationship from the data collected from IJs at all four locations in revenue service. Data collected from Leechberg, PA, was collected only with rail temperatures of up to 20°F. Data above 20°F was extrapolated to cover the range of temperatures for the areas.

As Figure 24 shows, neutral temperature ranged from 80 to 90°F. Stress rise per degree rise in temperature was between 150 and 190 psi.

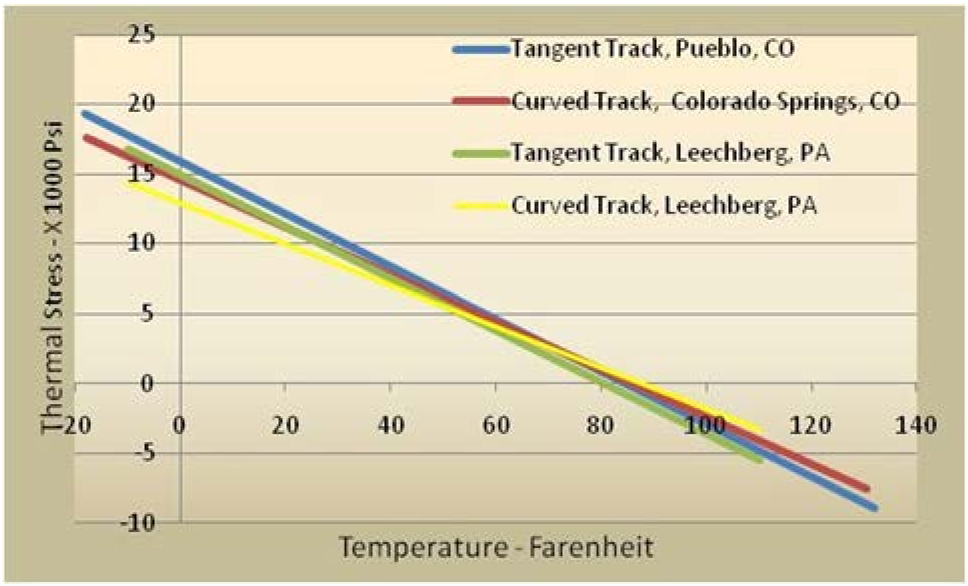


Figure 24. Temperature/Stress Relationship Trend

3.4.5 Statistical Analysis of Thermal Stresses

Maximum stresses help to understand the load environment but may not be adequate to design the joint bar. Joint bar design on the basis of maximum stresses may not be feasible. It is both practical and economical to design joint bars, based on most occurrences of stresses, such as 95th or 99th percentile of stresses. Therefore, a histogram was prepared on the basis of temperature/stress relationship of a typical joint. Figure 25 shows the percentage of occurrences for various levels of thermal stresses. For example, 95 percent of the time, during which data was collected, thermal stresses remained less than 14,000 psi.

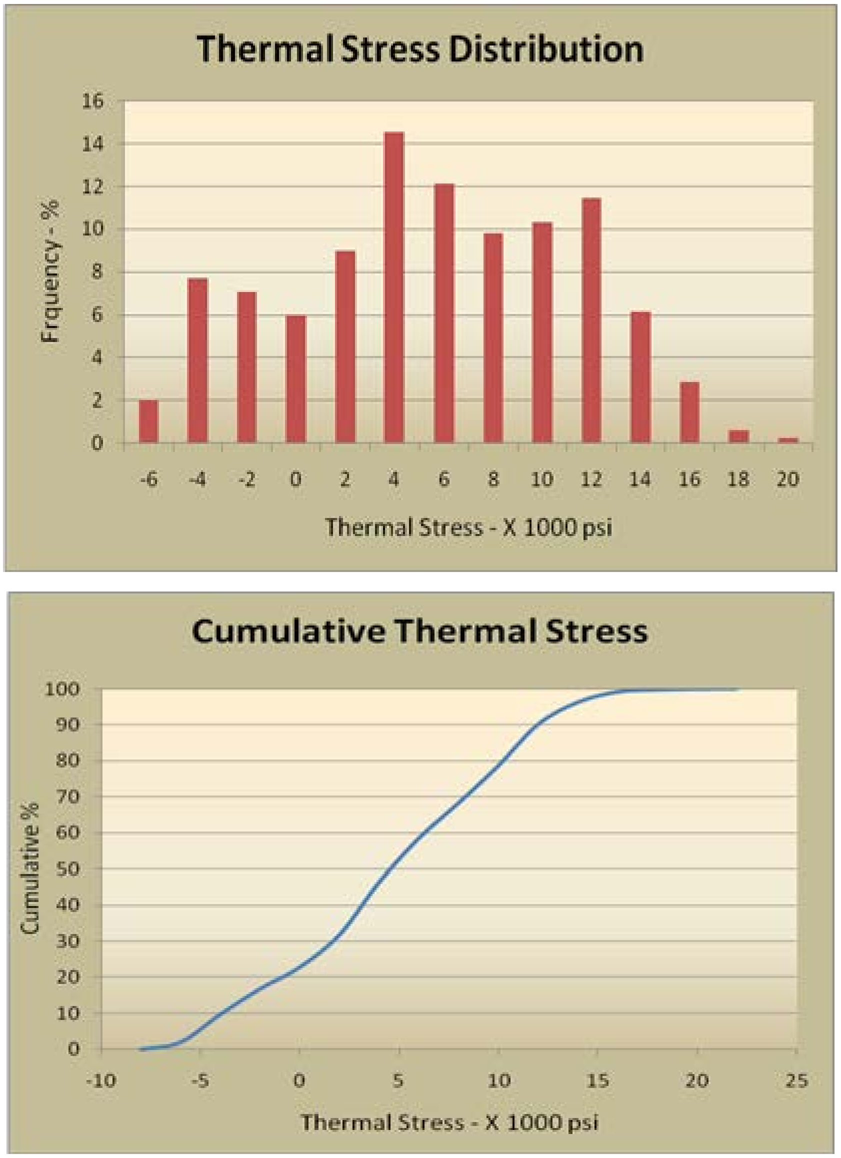


Figure 25. Statistical Distribution of Thermal Stresses

3.5 Joint Bar Residual Stress Measurements

The joint bar manufacturing process starts with cutting long pieces of rolled sections into 36- or 48-inch long bars. Holes are punched after heating to desired temperature and before water or oil quenching. After quenching, joint bars are then straightened. Residual stresses are likely to develop during this process. Another possibility for residual stress development is during quenching. When dropped in the quench tank, joint bars have the potential to bend in the direction of least resistance. Residual stresses up to 20 ksi, tensile at the bottom and compressive on top, have been measured in joint bars (Figure 26). Most of the information collection in this section was carried out under the Association of American Railroads' (AAR) Strategic Research Initiative on Heavy-Axle Load Effects on Rail Joints (5).

Because the residual stresses are of the same order of magnitude as the live load stresses, AAR is working on methods to reduce the residual stresses in new joint bars.

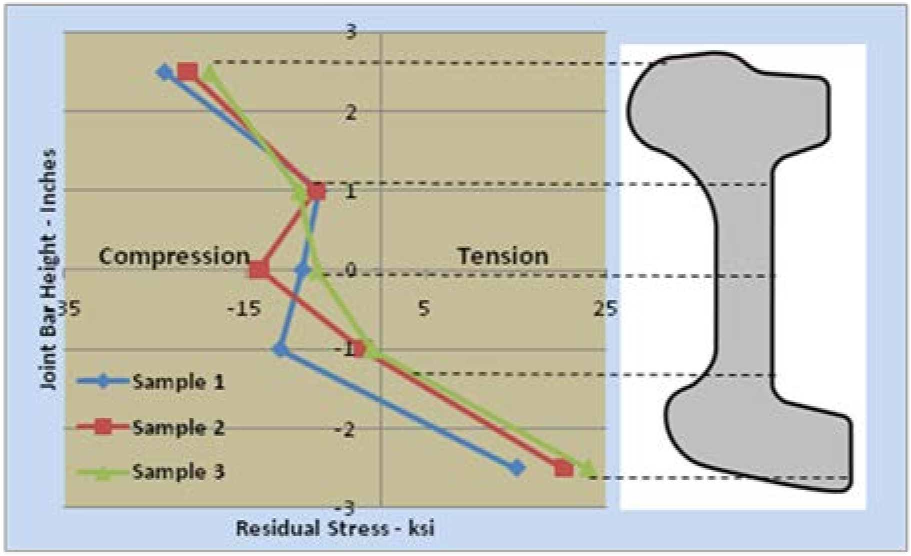


Figure 26. Residual Stresses along Cross Section in Production Joint Bars (5)

3.6 Crack Growth

3.6.1 Crack Growth Monitoring

Crack growth of joint bars with EDM notches was monitored on a daily basis. As Figure 27 shows, out of the eight joint bars with notches on top and bottom, two broke at 25 and 37 MGT under 40 mph, 39,000-pound wheel load traffic. One joint bar developed crack growth from the notch on top but then became dormant (not shown in the graph). No crack growth was observed in the remaining joint bars.

None of the three joint bars with notches only on top of the bar showed crack growth up to 40 MGT of traffic.

The local foundation and load conditions are likely be responsible for such a large scatter in crack propagation data. Maximum bending stress up to 60,000 psi was measured (see Subsection 3.2). Thus, locations where stresses were in the higher range had crack growth propagation, whereas the lower stress locations did not.

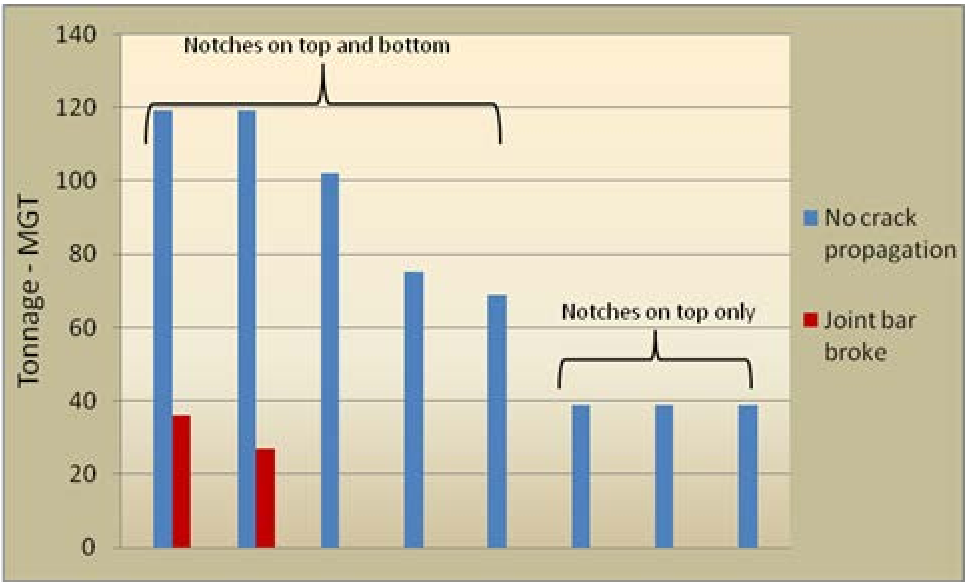


Figure 27. Status of Joint Bar Crack Propagation Monitoring

3.6.2 Inspection of Cracked or Broken Joint Bars

Three joint bars without EDM notches broke during testing at FAST. Both joint bars in each joint did not have notches. One test joint bar broke in revenue service. Three nontest joint bars were also found cracked or broken at FAST during the test period. All of these bars broke from cracks that were initiated from the bottom. Inspection of these joint bars and some more joint bars found from other sources suggest the following failure modes:

- Yield Failure

  This type of failure occurs when stresses in joint bars have exceeded the yield limit of joint bar material. The cracked surface is generally rough, with no obvious growth rings, as Figure 28 (left) shows.

- Fatigue Failure

  Fatigue cracks are evident from smooth surface and quarter circles. They are likely to start at locations where stresses due to live loads are the highest, as Figure 28 (middle) shows. Fatigue cracks may also start when a flaw or defect is present in the metal. This type of crack may or may not start at locations where stresses attributable to live loads are the highest, as Figure 28 (right) shows.

Figure 28. (left) Yield Failure (brittle failure), (middle) Fatigue Crack, (right) Crack Started at Fault

4. Conclusions and Recommendations

From the test results of the current study and the research conducted under AAR's program, the following conclusions and recommendations are made to reduce failures and increase service life of joint bars.

- Thermal forces due to temperature changes can induce stresses up to 15,000 psi. Residual stresses, which are induced during manufacturing processes, can be more than 20,000 psi. Bending stresses in joint bars on normal foundations may exceed 40,000 psi. The current recommended yield strength for joint bar steel is 75,000 psi. That means the sum of all measured stresses, such as bending, thermal, and residual stress, may reach or exceed the yield strength of material in service.
  - American Railway Engineering and Maintenance-of-Way Association (AREMA) recommended yield strength for joint bars is less than the yield strength of some rails, which can be as high as 140,000 psi. Furthermore, as Table 2 shows, the bottom section modulus of 136RE rail is approximately two times higher than a pair of standard joint bars combined. Thus, certain wheel loads may generate approximately two times higher stresses in the joint bars than the rail. Thus, by design, the joint is a weak point in track.
- The 99th percentile of measured bending stresses from this research ranges from 8,000 to 35,000 psi. Maximum stress ranges from 14,000 to 60,000 psi. Joint bar material has fatigue threshold of approximately 25,000 psi (6). Joint bars have finite fatigue life because stresses in most joint bars exceed the fatigue threshold life.
  - As stated above, bending stress levels from live loads are able to cause fatigue damage to current designs of joint bar. Because joint bars are reused and joint bar service history is unknown, they are only removed from service when found cracked or broken.
- Rail ends make contact with the top of the joint bars creating notches and causing metal flow. On good foundations, negative bending of rail is too low to initiate a crack at this location. However, tensile stresses of up to 15,000 psi were measured in revenue service on relatively poor track. This level of stress is likely to propagate the crack from the notch on top of the joint bar. AREMA recommends a relief at this location to reduce the risk of notch and crack initiation (4). A strict quality control is required for correct size, shape, and location of relief.
- Joint bars have high residual stresses induced during the manufacturing processes. Controlling residual stresses can be useful in extending service life. Improvement can be made in two steps: 1) reducing residual stresses to near zero throughout the bars and 2) adding residual stresses to counteract the live load stresses. In the second step, 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).
- The most undesirable design feature of standard joint bars for CWR track is its ability to allow longitudinal movement of the rails. Gaps of up to 1 inch were observed in test

joints in the winter. Such wide gaps cause bolts to bend and break and the material in the railhead 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 needed.

- Data shows that joints installed on similar foundations can develop very different level of bending stresses. This variation can be two to three times. Other factors such as joint bar length and number of bolts do not show that type of variation. Thus, of all the factors that affect the joint bar stresses, the condition of the foundation has the biggest effect on joint bar stress levels and thus on service life (7).
- Currently, joint bar inspection systems focus on finding cracks that initiate and grow on the top of the joint bar. These systems are a major improvement over the previous visual inspections. However, systems must be developed to find cracks in the entire cross section of the joint bar. This includes flaws that originate in surfaces that cannot be seen with a visual inspection (8). This level of inspection capability will allow further reduction in joint bar service failure rates.

5. Future Work

Occurrences of maximum stresses are generally limited. Thus, designing a joint bar using maximum measured bending and thermal stresses is not an economical or a feasible way of designing joint bars. For example, joint bar cross-sectional area required to resist maximum stresses may not fit against the rail.

Statistical analysis of the data already collected and presented in this report should be performed, which will suggest the most appropriate stresses for designing joining based on occurrences.

To understand fatigue life of joint bars, two types of data are needed: 1) load environment and 2) material fatigue properties. Load environment is now well understood. Stress histories should be used to construct histograms. Fatigue properties of coupons extracted from existing joint bars should be evaluated in the laboratory. This information can be used to construct S-N curves. All of this information would be used for a complete fatigue analysis of existing joint bars.

Although a large amount of data has been collected from different test joints under the current study, many questions still need to be answered. For example:

- What are the effects of these forces on multidirectional stress state of joint bars?
- What are the contact stresses at the point where railhead ends make contact with the joint bars?
- What are the equivalent stresses (combined effect of stresses in the *x*-, *y*-, and *z*-plane) on the top and bottom of joint bars
- What are the stresses in bolt-hole edges? Are the stresses caused by lateral loads significant?
- Joint bars make line contact with the rail, which causes plastic flow. Is it possible to reduce this metal flow by changing the design of joint bars?

A finite element analysis model should be developed using the data collected. The data should then be analyzed to answer the above questions.

Under AAR's SRI program, limited samples of new joint bars were strain gaged and saw cut. Differences in strains before and after saw cut show that joint bars have tensile residual stresses in the bottom of joint bars. A magnitude of stresses is nearly equal to the bending stresses from live load. That means, such joint bars may have a higher probability of failure because of yield when in service.

It is recommended that samples of joints from different suppliers and from different batches be collected. Residual stresses will be measured and an evaluation should be made if the higher residual stresses are a major source of joint bar failures in revenue service.

Notching of joint bar tops from rail end edges is a well understood phenomena. These notches may cause crack propagation or joint bar breaking when track is lifted for tamping or surfacing. This theory should be evaluated by using strain-gaged joint bars with the track lifted to the same height as during surfacing operations. Joint bars without notches and with artificial notches should be used for this purpose. Instrumented joint bars left over from Phase I can be used for this task. Strains should be measured during lifting, and joint bars should be inspected after track lifting for any signs of crack propagation on joint bars with notches.

The data collected in Phase I of this study shows that joint bars having bolts with lower torque normally have higher stresses compared with those having bolts with higher torque. However, the torque does not remain constant during the service life. There are three major sources of torque loss: vibrations, bolt relaxation, and metal flow at joint bar contact locations. First and second sources can be easily taken care of by using vibration free fasteners and retightening the bolts. The third issue is difficult to manage because, when bolts are tightened, metal flow increases causing further relaxation in the bolts. Various techniques should be studied to reduce or eliminate metal flow.

Research could be conducted into a rigid bolted joint for use when temporary repairs are needed in CWR. The benefits of no gap in joints with larger diameter bolts and higher torques should be evaluated. Larger diameter bolts can help freeze the joints.

The industry has developed machine vision and ultrasonic inspection systems that can inspect joint bars in-track at walking or higher speed. These systems are capable of detecting large cracks or breaks in certain locations. An industry survey should be performed to study other inspection systems capable of detecting very small cracks or faults. These handheld systems should be used to inspect joint bars before installation and after removal. The objective is to keep flawed bars out of track.

6. References

1. Federal Railroad Administration, Office of Research and Safety, Department of Transportation, http://safetydata.fra.dot.gov/OfficeofSafety/default.aspx Washington, DC.
2. Akhtar, M. N., Davis, D. D., and Riehl, W. S., III. (2008). Performance evaluation of mechanical joint bars. *Railway Track and Structures*, *104*(7), 17–19.
3. Akhtar, M., Davis, D., Maal, L., Gordon, J., and Jeong, D. (2010 Oct.). Effects of track parameters on rail joint bar stresses and crack growth. In *Proceedings of the AREMA 2010 Annual Conference and Exposition*, Orlando, FL.
4. American Railway Engineering and Maintenance-of-Way Association (AREMA). Rail. In *Manual for railway engineering* (Vol. 1, Chp. 4, p. 4.1.14). Lanham, MD: AREMA.
5. Akhtar, M. N., and Davis, D. D. (2011 May). Residual stress management of rail joint bars. *Technology Digest* TD-11-016. Pueblo, CO: Association of American Railroads, Transportation Technology Center, Inc.
6. Akhtar, M. N. and Davis, D. D. (2010 Aug.). Fatigue and crack growth analysis of joint bars in heavy haul track. *Technology Digest* TD-10-024. Pueblo, CO: Association of American Railroads, Transportation Technology Center, Inc.
7. Davis, D. D., Collard, D., and Guillen, D. G. (2004 May). Bonded insulated joint performance in mainline track. *Technology Digest* TD-04-006. Pueblo, CO: Association of American Railroads, Transportation Technology Center, Inc.
8. Davis, D. D., Akhtar, M., and Garcia, G. (2008 Oct.). Evaluation of the feasibility of automated joint bar inspection. *Technology Digest* TD-08-040. Pueblo, CO: Association of American Railroads, Transportation Technology Center, Inc.

Abbreviations and Acronyms

AAR	Association of American Railroads
AREMA	American Railway Engineering and Maintenance-of-Way Association
CWR	continuously welded rail
EDM	electrical discharge machining
FAST	Facility for Accelerated Service Testing
FRA	Federal Railroad Administration
FS	field side
GS	gage side
HAL	heavy-axle load
HTL	High Tonnage Loop
IJ	insulated joint
ksi	thousand pounds per square inch
lb	pound
MGT	million gross ton
mph	miles per hour
psi	pounds per square inch
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)