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Fatigue and Crack Growth Analysis of Joint Bars in Heavy Haul Track

Muhammad N. Akhtar and David D. Davis

Summary

Fatigue resistance of rail joint bars is important for the safety and efficiency of railroad operations. The increased number of higher axle load cycles in heavy haul track in recent years poses a greater challenge to the fatigue performance of rail joint bars. Common joint bar failure modes are cracking on the bottom surface, cracking on the top surface, and cracking in the bolt holes. The first mode is related to load environment and is the subject of this analysis. Being in the tension zone, these cracks are likely to grow faster, reducing joint bar fatigue service life. The other two failure modes are usually related to manufacturing, installation, and maintenance practices.

There are three major sources of forces acting on joint bars: (1) stresses induced due to live load, (2) residual stresses induced during the manufacturing process, and (3) thermal stresses due to temperature changes. In continuous welded rail (CWR) territory and assuming good joint and track maintenance, the load environment that results has much larger tensile stresses at the bottom of the joint bar than at the top. The sum of these stresses may exceed American Railway Engineering and Maintenance of Way Association recommended yield stress for joint bars. In jointed rail territory, similar loads act on joint bars, with the exception of thermal forces which may be lower. The current analysis is applicable to CWR coal routes in particular. It can also be applied to jointed rail territory where joint bars are subjected to similar loads.

Because joint bar service history is generally unknown, an increase in fatigue strength is a desirable safety factor to inhibit fatigue failures. Fatigue life is the sum of crack initiation and crack propagation life. Analytically, the crack initiation life of current joint bars in CWR can be increased by three (with elimination of tensile residual stresses in the joint bar bottom) to five times (by inducing compressive stresses in the bottom of joint bars). Elimination of residual stresses (or reversal to compressive stresses) can increase the crack propagation life as well, which provides a longer window of opportunity to detect and replace joint bars before failure. The benefits of elimination or reversal of residual stresses in joint bars in jointed rail territory are slightly lower than in CWR.



INTRODUCTION

Fatigue cracks can initiate at bolt holes and on the top or bottom edges of the joint bar where it makes contact with the railhead or base ends. Cracks originating from bolt holes are mainly due to manufacturing, installation, and maintenance practices. Cracks on top are in a largely compressive stress field and are more of an issue with older designs of joint bars. American Railway Engineering and Maintenance of Way Association currently recommends an easement to reduce the possibility of rail end contact with a joint bar.

This *Technology Digest* (TD) addresses cracks that initiate in the bottom of joint bars. Being in the tension zone, these cracks are likely to grow faster, reducing joint bar fatigue service life.

Joint bar service life can be increased in two ways: increasing fatigue strength of material or reducing the loading environment. This TD analyzes the latter option. Fatigue analysis of joint bars subjected to various types of loadings suggests that service life can be increased by three times just by relieving residual stresses in the joint bars.

Crack growth modeling shows that, once initiated, cracks can grow and break the joint bar in as little as 20 million gross tons (MGT). The model was verified by artificially initiating cracks in six joint bars on wood tangent track at Facility for Accelerated Service Testing (FAST). Three out of six joint bars broke between 15 to 20 MGT of traffic, the fourth broke at 25 MGT, the fifth at 45 MGT, and the sixth at 60 MGT. Local foundation conditions and variable thermal force appeared to cause joint bar breakage at different tonnages.

Data also shows that the tops of joint bars are subjected to minimal tensile stress. Thus, cracks on the top of the bar appear to be design related, not load related. These cracks can be avoided by providing proper relief on the top of the joint bar where railhead corners tend to make notches on the joint bar.

FATIGUE ANALYSIS

Strain gaged joint bars were installed on a tangent wood tie track to collect bending compressive and tensile stresses on the top and bottom edges of joint bars, respectively. The test train at FAST consists of about 100 315,000-pound cars and four locomotives. Bad wheels and trucks are rare, and the track is fairly well maintained. Figure 1 shows a typical tensile bending stress spectrum for the train at FAST for a strain gage installed on the bottom of a joint bar.

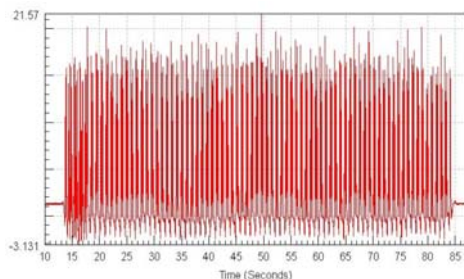


Figure 1. Bending Stress Spectrum of Train at FAST

At any given time, there are three types of forces acting on joint bars: (1) bending stresses due to live load, (2) residual stresses induced during manufacturing process, and (3) thermal stresses due to temperature changes. Bending stress is alternating stress, but the other two types of stress are not. Bending stress has nonzero mean value; and therefore, has an additional effect on fatigue life. Thermal and residual stresses increase the value of this mean, but do not affect the alternating stress.

Each wheel pass creates a cycle that has a maximum stress, α_{max} , and a minimum stress, α_{min} . Stress range, $\alpha_{max} - \alpha_{min}$, and mean stress, $(\alpha_{max} + \alpha_{min})/2$, were calculated for each wheel pass. Using rain flow analysis, effective stress for the full load spectrum was calculated. Each effective stress is the constant amplitude stress of the spectrum that will cause the same damage as the variable amplitude spectrum, as Figure 2 shows.

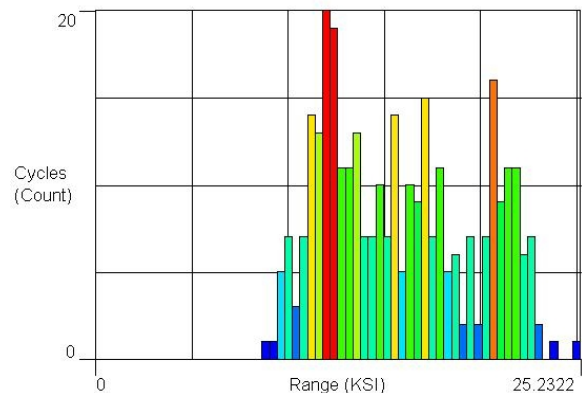


Figure 2. Histogram of Rain Flow Analysis

Mean effect has been taken into account using Goodman's equation:¹

$$\frac{\alpha_a}{S_e} + \frac{\sigma_m}{S_u} = 1$$

Where α_a is amplitude stress, s_e is modified stress due to mean, α_m is mean stress, and s_u is ultimate strength.

For all three loading cases, amplitude stress (from train loading) is the same, but the mean is different. The mean stress makes a considerable difference in the service life estimate. Residual stress is tensile on the bottom of the joint bar, and can be up to 23,000 pounds per square inch (psi).²

Similarly, thermal force on a tangent in revenue service can be as high as 270,000 pounds.³ For 136 pounds per yard rail, it corresponds to about 20,000 psi. However, thermal stress of 10,000-12,000 psi is more common. Residual and thermal stresses were added to mean stress, and modified alternating stress was calculated.

Table 1 shows fatigue life calculations.

Table 1. Fatigue Life Calculations

Load Case	Amplitude Stress psi	Mean Stress psi	Modified Amplitude Stress psi	Life in Cycles N	Life MGT	Normalized Fatigue Life
Bending	14,370	7,840	15,280	1.54E+07	600	5
Bending + Thermal	14,370	19,840	16,910	9.52E+06	370	3
Bending + Residual + Thermal	14,370	42,840	21,270	3.24E+06	125	1

Fatigue life is the number of cycles corresponding to the modified effective stress on a S-N curve. Figure 3 shows a generic S-N curve that was generated using the following mechanical properties of joint bar material.⁴

Ultimate Strength, $S_u = 132\text{ksi}$
 Endurance limit, $Se' = 0.5 S_u = 66\text{ksi}$
 $S_{1000} = 0.9 S_u = 118.8\text{ksi}$
 Modified Endurance limit, $Se = Se' C_{size} C_{load} C_{finish} C_{treatment} C_{temp} C_{environment}$
 $C_{size} = .748, C_{load} = 1, C_{finish} = 0.55, C_{treatment} = 1, C_{temp} = 1, C_{environment} = 1$
 $= 27\text{ksi}$

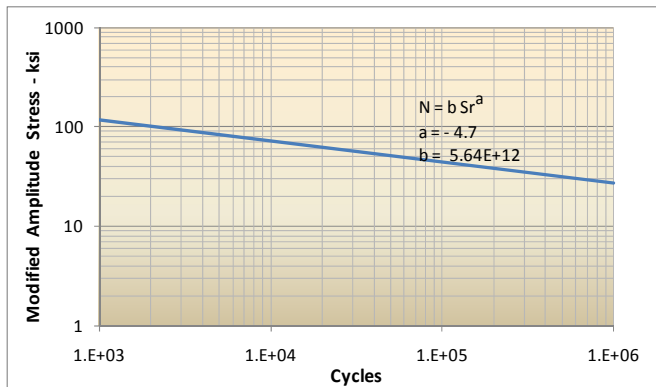


Figure 3. S-N Curve for Joint Bar Steel

By normalizing all three loading cases with the current load, a comparison of fatigue life is achieved. Figure 4 shows that by eliminating residual stresses, the fatigue life of the current joint bar design can be increased by three times.

By inducing compressive stresses in joint bars, fatigue life can be increased by up to five times. Compressive residual stress in joint bar is expected to reduce or eliminate tensile thermal stress. The only stress that can cause fatigue is bending stress. Fatigue life due to bending stress is five times more compared to current life.

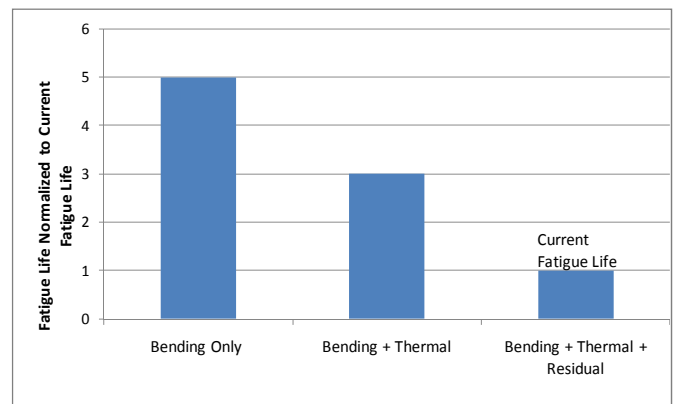


Figure 4. Comparison of Predicted Fatigue Life under Different Loading Conditions

CRACK GROWTH ANALYSIS

A crack growth model was developed to predict joint bar service life after a crack initiated. Knowledge of a crack growth period can help railroads to adjust automated inspection intervals so that a crack is intercepted before the joint bar breaks. AFGROW was used for crack propagation modeling.^{5,6} AFGROW is a workstation based, graphically interactive computer program for the simulation of fatigue crack growth in various structural geometries subject to spectral loading.

The model used a typical spectral load of the train at FAST going 40 miles per hour with residual and longitudinal stresses. AFGROW has a large material database. Material data with similar mechanical properties as joint bar material was used for crack propagation simulation. Residual stress of 23,000 psi and thermal stress of 12,000 psi were also considered. An initial crack size of 0.05 inch was assumed. The program predicted that under the assumed loading conditions, joint bars are likely to break within 20 MGT under the unit train at FAST.

In order to verify the model, cracks were artificially induced in the bottom of six new joint bars by making Electrical Discharge Machine notches. All joint bars were on wood tie tangent track with cut spikes. (The crack growth period is likely to be different for joint bars on other track types and geometry or subjected to different load environments.) Three out of six joint bars broke between 15 and 20 MGT, the fourth broke at 25 MGT, the fifth at 45 MGT, and the sixth at 60 MGT, as Figure 5 shows. Local foundation conditions appear to have caused joint bar breakage at different tonnages. Also, effects of thermal stress may have been significant.

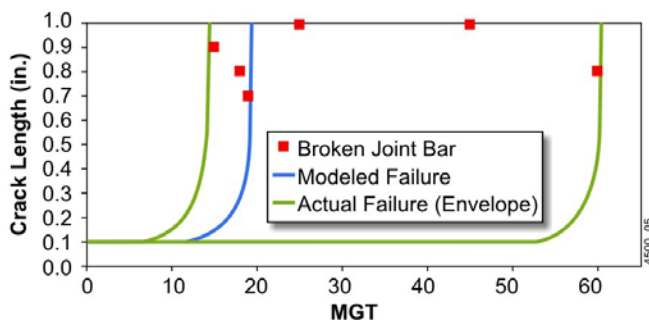


Figure 5. Crack Growth Model Prediction and Joint Bar Crack Growth History

CONCLUSIONS

Joint bar fatigue life can be improved by using better materials or reducing the load environment, the latter being more economical. Analytically, the fatigue life of the current joint bar design can be increased by three (with elimination of tensile residual stresses in the bars) to five times (by inducing compressive stresses in joint bars).

Dynamic data collected under the train at the FAST shows that tensile stresses on the bottom may exceed the endurance limit; and therefore, joint bars may develop a crack during service. Once initiated, cracks in the bottom grow at a relatively high rate and can break the joint bar before being detected.⁵ Crack growth rates may be slowed down by reducing or eliminating residual stresses in joint bars.

FUTURE WORK

Heat treatment and shot peening of joint bars is planned to relieve residual tensile stresses on the bottom of the joint bars. In order to induce compression in tensile stress areas, slight modifications in the joint bar cross sections can also be made.

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