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Fatigue Crack Growth Rate Properties of Rail Steels and Their Influence on Rail Life

Ananyo Banerjee, Kenny Morrison

Key Findings:

- Modern high strength (HS), standard strength (SS) and intermediate strength (IS) rails have lower ΔK_{TH} values than 1980s rails, but linear region of crack growth dictated by Paris' law indicate slower crack growth rates than 1980s rails, which have steeper slopes of the linear region and higher crack growth rates.
- As a direct influence of higher ΔK_{TH}, rail life in tonnage predicted by RailGrow during crack growth phase of a 5 percent transverse defect is higher for 1980s rails than modern HS, SS and IS rails. Modern rails are less susceptible to defect initiation than 1980s rails (due to cleaner steel manufacturing processes) and have longer rail life in terms of tonnage. The results show the importance of assumptions in the theory of fracture mechanics, which does not consider metallurgical discontinuities and is applicable to crack growth behavior only when defects have already initiated.

Transportation Technology Center, Inc. (TTCI) conducted a two-year test to determine the importance of fatigue crack growth rate (FCGR) properties of five modern rail steels and one 1980s-era rail steel. Results were compared with FCGR properties of other 1980s rail steels. These properties were used in a fracture mechanics model named RailGrow — a Microsoft® Excel-based model developed by TTCI in collaboration with the University of Illinois Urbana-Champaign (UIUC) under the Association of American Railroads' Strategic Research Initiative program — to analyze the influence of FCGR properties on growth of transverse defects that form in the head of a rail. All FCGR testing was conducted using middle tension specimens that were subjected to alternate tensile and compressive stresses of the same magnitude similar to stress conditions experienced by rails in revenue service. FCGR properties including threshold stress intensity (ΔK_{TH}) and Paris' law constants (C, m) which dictate the linear region of fatigue crack growth were determined for five samples of each rail steel.

Along with those listed in key findings, the study showed that fatigue growth curves of HS, IS and SS rails are similar in shape, along with similar ΔK_{TH} values, which resulted in similar predictions in rail life using RailGrow under identical simulated conditions of crack growth. This explains why crack growth in modern HS or SS or IS rails are usually of similar nature once a defect has initiated, although there are differences in wear rates among the rail types due to variation in yield strength, tensile strength and hardness.

A recent analysis on the growth of reverse detail fractures (RDF) was conducted by TTCI using RailGrow and additional details about the model have been provided in an earlier *Technology Digest*.[1] RailGrow utilizes different parameters, including material properties of the rail, to estimate the stresses that typically cause the propagation of a crack. The FCGR properties of the rail steel are important inputs for RailGrow. In this work, three modern HS rail steels, along with one modern SS rail steel and one IS rail steel, were tested for FCGR estimation and to determine the crack growth rate as a function of stress intensity factor range. For comparison, a relatively unworn 1981 standard grade rail was collected from revenue service and tested.

FCGR TESTING

Defects in rails are considered as cracks whose growth can be quantified by fracture mechanics. The crack growth in a metal follows three stages during its growth from initiation to fracture as shown in Figure 1. **Delta (Δ) K** is the range of the stress intensity factor (K_{max}-K_{min}) and is composed of three factors as shown in Equation 1:

$$\Delta K = \Delta\sigma\sqrt{\pi a}\ F\ (a, W,...)$$

where **Δσ** is the stress range and **a** is the size of the defect. The **F** is a geometry function where **F** (a, W,…) accounts for the defect shape, geometry of the object (head of rail) containing the defect, orientation of the defect, and stress gradients. The first stage of the sigmoidal curve of the fatigue crack growth is bound by a “threshold” (TH) value ΔK_{TH} below which there is no observable fatigue crack growth. At stresses below ΔK_{TH} cracks behave as non-propagating cracks. Region II is the longest and stable region of crack growth and represents a linear relationship as defined by Equation 2:

$$\frac{da}{dN} = C(\Delta K)^m$$

where **C** is the intercept of the logarithmic plot and **m** is the slope of the linear Region II. Equation 2 is also known as Paris’ law and the constants C and m are material parameters known as Paris constants. Figure 2 shows actual FCGR curves of five samples of one HS rail head tested in this study. Region II of all samples are almost similar indicating Paris law behavior is a material property. Region III is the last region of crack growth where the crack grows faster in a non-linear manner causing fracture. Stress intensity (K_{max}) at fracture is a size-independent material property known as fracture toughness (KC).

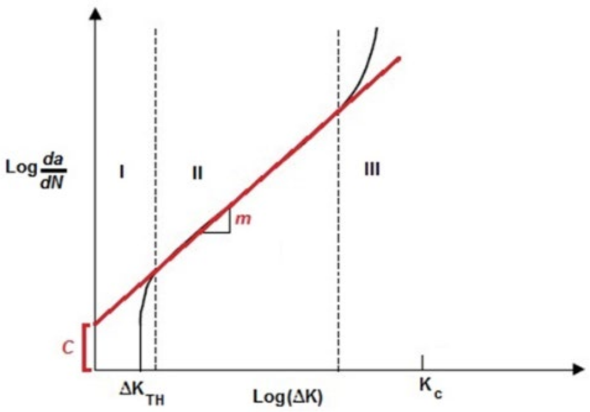

Figure 1. Typical FCGR curve in metals showing Paris constants (C, m) and three stages of crack growth

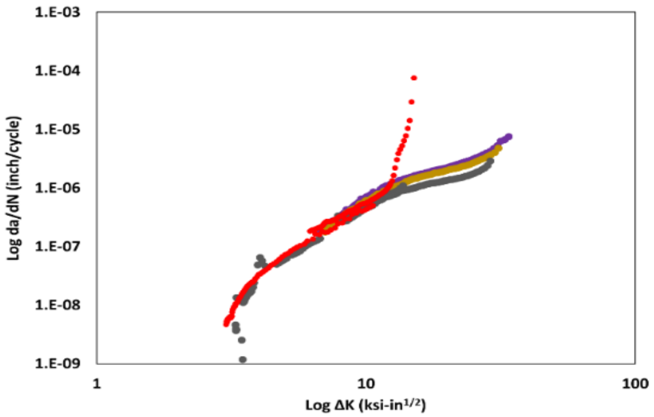

Figure 2. Actual FCGR curves of four different samples from the head of one HS rail tested in this study

All FCGR testing was done as per ASTM E647 standard which calls for two types of specimens: 1) compact tension (CT) and 2) middle tension (MT). Compact tension specimens are more common as the fatigue tests are conducted only in tension. They are smaller than MT specimens and easier to machine thereby reducing machining and material costs. The MT specimen is a center crack specimen that can be loaded in tension and compression. As rails are subjected to alternate tensile and compressive stresses from the bending loads of the wheels, all fatigue tests were done at a stress ratio of R= -1, which means an alternating cycle of tensile and compressive stresses of the same magnitude. Most FCGR tests on rail steels found in literature have been conducted using CT specimens under tensile loading only and disregarded the compressive stresses. Figure 3 shows designs of MT and CT specimens.

Comparison of FCGR properties

FCGR properties of three different HS rails, one SS and one IS rail, all manufactured after 2015, showed similar FCGR curves, lower ΔK_{TH} and similar slopes in Region II as shown in Figure 4. Comparison with FCGR curves of rails manufactured in the 1980s show that most FCGR curves of older rails have higher ΔK_{TH} values and steeper slopes in Region II. This means the 1980s rails have higher thresholds of stress intensity, and cracks will start growing at higher stress levels compared to cracks of the same size and shape present in modern rails. Once the threshold stress intensities are reached, the steeper slopes of Region II in the 1980s rails would lead to faster crack growth compared to modern rails having gentler slopes in Region II. Modern rail steels having gentler slopes in Region II cause cracks to grow at slower rates than 1980s rails thereby allowing a chance for the track inspection crew to monitor the crack growth for some time and replace the rail accordingly before it fractures.

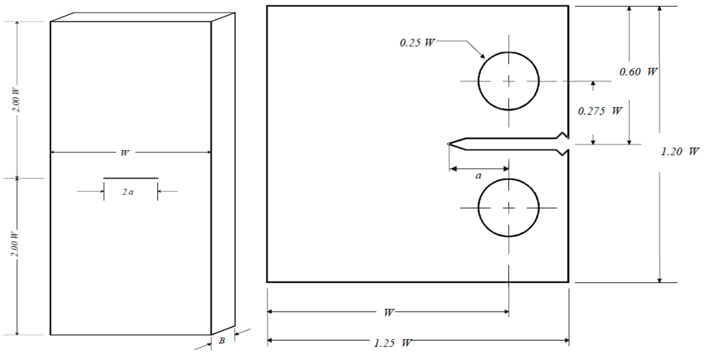

Figure 3. Schematic drawings of MT (left) and CT (right) specimens where W (width)=2.8 inches; width of a 136RE rail head and tolerance on thickness B is W/8 < B < W/4

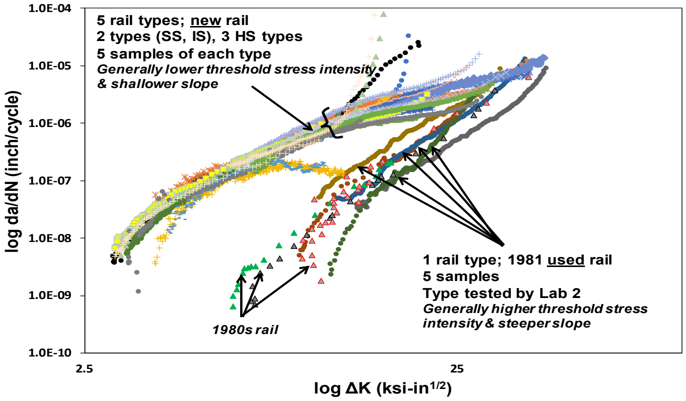

Figure 4. Comparison of FCGR curves of rails

The ΔK_{TH} values and Paris constants calculated from the slopes of Region II were used in RailGrow along with other parameters held constant for a simulated crack representing a transverse defect of size 5 percent of the head area of a 136 pound per yard (lbs./yd.) rail and located towards the gage side of the head as shown inset of the plot in Figure 5. The median of the predicted rail tonnage (MGT) during crack growth until fracture was almost seven times higher for the 1980s rails having higher ΔK_{TH} values than modern rails with lower ΔK_{TH} values. It needs to be noted that the results of the 1980s rails includes the tested rail's FCGR properties as well as FCGR properties obtained from literature 2,3 and the data is scattered from 66 MGT to 347 MGT with outliers at 47 MGT and 462 MGT. Also, the box plot of HS rails includes 15 samples of three HS rail types while the SS and IS data has five samples each.

Although Figure 5 shows 1980s rails having longer lives than modern rails with crack growth starting from the same defect size, crack growth is dependent on various factors other than FCGR properties and can be shorter for any rail of any age. Rather modern rails have reduced chances of defect formation than 1980s rails because of reduced amounts of voids and inclusions compared to 1980s rails due to cleaner steel manufacturing processes like continuous casting and degassing. Voids, inclusions and metallurgical contaminants act as stress risers for defect formations and modern steel making practices address this issue by making cleaner steels.

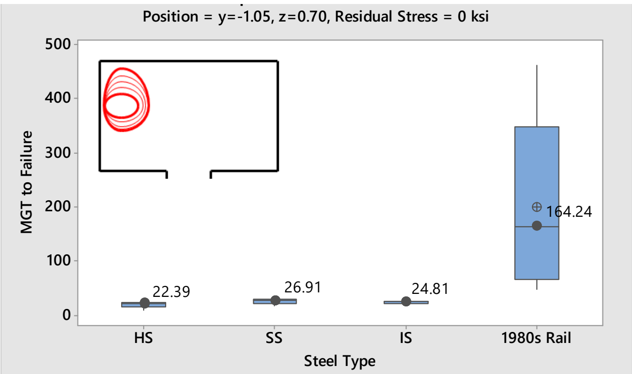

Figure 5. Comparison of MGT to failure for modern HS, IS, SS and 1980s rails

Fracture mechanics equations only apply to rails with defects already formed and cannot answer questions on what factors can form defects. Fracture mechanics does not consider metallurgical differences like grain size, absence/presence of inclusions or variation in interlamellar spacings in pearlite grains. The relationship between FCGR properties and metallurgical properties of modern rail steels was beyond the scope of this study but has been addressed to some extent in previous studies.[2,4]

Similarities of FCGR properties in modern rails

Residual stresses are formed during hot rolling processes during final steps of rail manufacturing as a rail gets its final shape from a cylindrical or rectangular cross-section. Rails that accumulate sufficient tonnage develop more complex residual stress patterns in the heads due to the multiple bending cycles under wheel loads. RailGrow allows the user to select one single value of residual stress or to choose different stress values in different locations as shown in Figure 6. The second option helps in generating a residual stress pattern that affects the crack growth depending on where the crack is located and how the stress pattern affects the growth. For example, a compressive stress of -15ksi will hinder crack growth as the crack's boundary enters the zones of the running and gage surfaces leading to longer life of the crack. As the crack grows into the residual stress field the magnitude of the residual stresses reduces to maintain equilibrium. RailGrow assumes the head as a rectangle and provides a simple way of generating a complex residual stress pattern as shown in Figure 6. The data generated in Figure 5 was under zero residual stress conditions while results shown in Figure 7 are for different residual stress conditions.

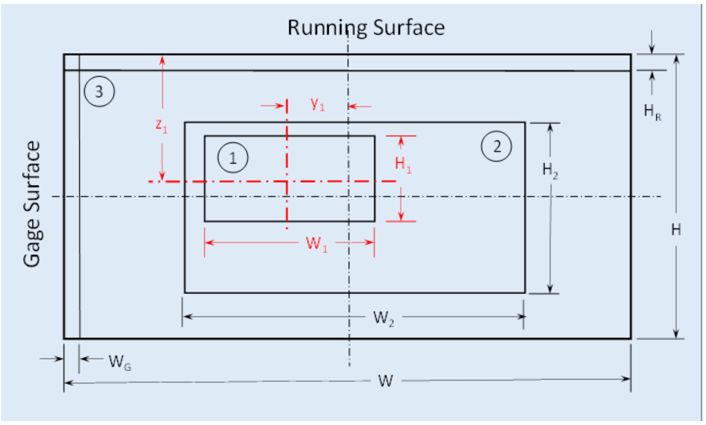

Figure 6. Residual stress pattern module in RailGrow

Keeping other parameters constant, three different conditions of residual stresses were tried. Those included a residual pattern as shown in Figure 6, 10 ksi uniform residual stress and zero residual stress. Figure 7 shows the boxplots of predicted rail tonnage (MGT) during crack growth up to fracture for modern HS, SS and IS rails under three different residual stress conditions. It is evident that the median values of rail life in tonnage for HS, SS and IS rails are varying over a range of 2 MGT for 10 ksi residual stress, 8 MGT for a complex residual pattern and 5 MGT for zero residual stress conditions.

In revenue service, HS rails tend to last longer than IS and SS rails due to decreased wear rates but rate of growth of a transverse defect in the head of the rail is quite unpredictable for any rail type. Differences in wear rates are affected by hardness, tensile strength and yield strength. Figures 4 and 7 are related because similarities in FCGR curves of HS, IS and SS mean similar FCGR properties and hence closely related tonnages of defect growth predicted by RailGrow. Figure 7 also shows the importance of having periodic rail inspections by non-destructive techniques on all rails to detect defects before they grow up to fracture. The values shown here can be high or lower based on where the defect is in the rail head, wheel loads, thermal stresses and other track inputs mentioned in RailGrow.

CONCLUSIONS

TTCI conducted fatigue testing of modern rail steels and one 1980s-era rail to obtain FCGR properties and use them in a fracture mechanics model named RailGrow to understand the influence of FCGR properties on crack growth. Results showed 1980s rails to have higher ΔK_{TH} values and steeper slopes in Region II of the FCGR curves than modern rails. FCGR curves of modern rails were found to be similar for HS, IS and SS rail types with similar prediction of tonnage accumulation in rails during simulated growth of a transverse defect under identical conditions.

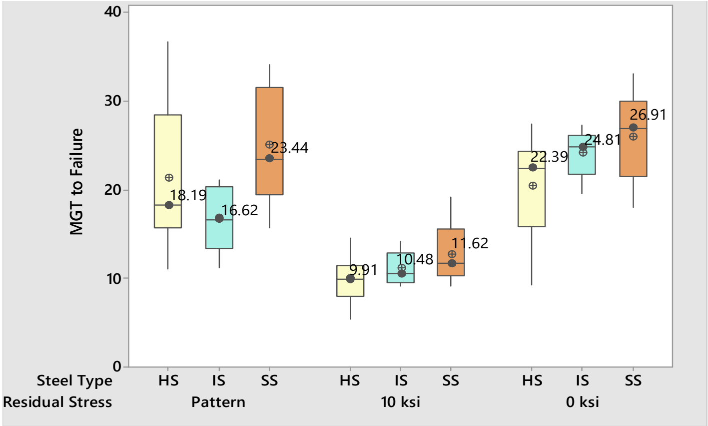

Figure 7. Comparison of MGT to failure for modern HS, IS and SS rails under different residual stress conditions

References

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For comments or questions about this publication, contact Ananyo_Banerjee@aar.com