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Evaluation of Reverse Detail Fracture Growth using a Fracture Mechanics Model

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Summary

Transportation Technology Center, Inc. (TTCI) used a fracture mechanics model named RailGrow to analyze the various parameters affecting the growth of reverse detail fractures (RDFs). RailGrow has been developed for simulating defects in rails and predicting the growth of defects as a function of accumulated traffic (million gross tons (MGT)). Thermal stress and effects of curvature have been found to be the factors most important for RDF growth. RDF is one of the defects simulated by RailGrow and this digest summarizes the effects of different parameters on the growth of an RDF. An actual RDF sample from revenue service was used as a case study to do a sensitivity analysis of the various factors affecting the growth of the defect. Apart from sensitivity analysis, the capabilities of RailGrow was also assessed by comparing with an earlier model developed in 1998.

The range of crack growth life of a 5 percent RDF due to various service conditions revealed track curvature and thermal stress to be the most significant parameters. Results showed that an RDF will have a shorter life on a 10-degree curve compared to a shallower curve, primarily due to increases in lateral forces with increasing curvature. Finite element analysis (FEA) indicates off-centered contact forces to be causing tensile stresses to form in the lower gage corner where RDFs initiate. Thermal stresses chosen for the sensitivity analysis were based on rail temperatures where the RDF sample was obtained. The temperature range (39°F to 90°F) tested affects RDF growth, and the results indicate any temperature above and below the range can further affect RDF growth. The results show why RDFs might not last as long in colder temperatures compared to hotter summer temperatures.

RailGrow uses principles of fracture mechanics and strength of materials to calculate stresses acting in the head of the rail, and it predicts the growth of the defect until it causes fracture. Effects of various parameters were analyzed to understand the capabilities of RailGrow and to compare with the earlier fracture mechanics model. The crack growth life (MGT) values were found to be comparable between models for most parameters. Both models showed the same trends in the results when the parameters were varied. However, RailGrow allows the user more flexibility by making more inputs user-selected and describing these input parameters in detail. The critical crack size measured as a percentage of head area was found to differ between the two models, although both models show crack growth to be initially slow and most of the fatigue life is spent before the RDF reaches approximately 20 percent of the head area.

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INTRODUCTION

A reverse detail fracture (RDF) is a type of transverse defect that forms at the lower gage corner of the rail, typically in the plastic flow that sometime develops at the bottom of a curve-worn high rail. The defect gets its name from its initiation point and the fact that the defect propagates upward (typical detail fractures (DF) initiate at the upper gage corner and propagate downward). As per the Federal Railroad Administration's *Track Inspector Rail Defect Reference Manual*, an RDF's origin is a stress riser associated with a notching condition on the cold rolled lip located at the bottom corner of the rail head, and it is associated with severely worn rail and high axle loadings.[1]

RailGrow is a Microsoft Excel based model developed under the AAR Strategic Research Initiatives Program. RailGrow uses the principles of fracture mechanics and strength of materials to predict crack growth rate in the rail head or rail base as a function of accumulated MGT. RailGrow has capabilities of modeling DFs, surface defects, and RDFs and provides final/critical crack size at fracture as a percentage of head area (HA). Figure 1 right side shows the illustration of an RDF in RailGrow, and the defect size can be defined by two parameters, a and b. The red arrows on the left side indicate the directions of the growth of a real RDF in the rail head.

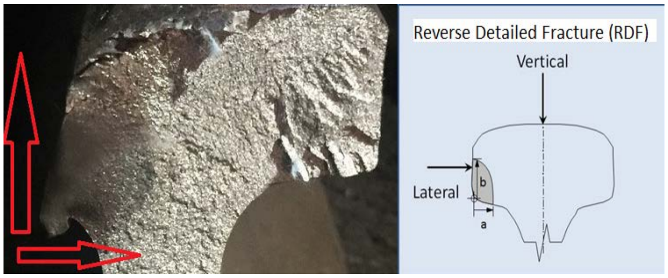

Figure 1. Illustration of an RDF in RailGrow model

Figure 2 shows the stress range in the rail head under the action of two axles of the trailing truck of one car and two axles of the leading truck of the next car. The rail is modeled as a beam on an elastic foundation for computing bending stresses. The tensile stresses in the rail head causing RDF growth are comprised of primarily three components: (1) thermal stresses due to deviation of the actual rail temperature from neutral temperature, (2) residual stresses from axle loads and rail rolling, and (3) bending stresses due to alternate tensile and compressive loading from axle loads. The highest tensile bending stress occurs underneath the coupler. The spikes of compressive stresses (<0 ksi) in the rail are due to the wheel loads, but compressive stresses do not contribute to defect growth.

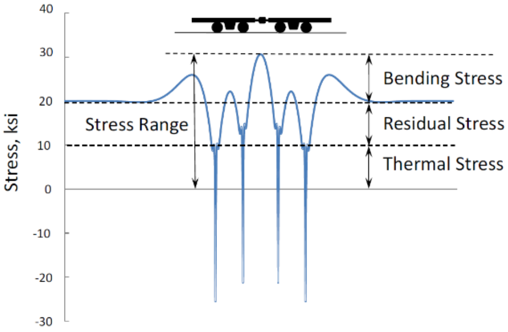

Figure 2. Stress range and stress components in rail head

COMPARISON WITH EXISTING MODEL

Jeong et al. developed a fracture mechanics model (referred here as FM98) two decades back and published a report in 1998 about the model's capabilities of predicting crack growth life of an RDF.[2] The results of their analyses indicated that the crack growth life of an RDF is about 20 percent shorter than that for an ordinary detail fracture (DF) under the same conditions. However, the report does not specify the exact location of the simulated DF. RailGrow provides options to the user for specifying location of a DF using coordinates and the crack growth life depends on where the DF is in the rail head. Under the same conditions, RailGrow predicts an RDF can have anywhere between 10 percent to 40 percent shorter life than a DF based on the location of the DF.

Benchmarking analysis of RailGrow was done as a first step to understand the model's similarity to Jeong et al.'s FM98 model. Similar conditions were used and the effects of individual factors are listed here: 35.75 kips of vertical (V) wheel load was used, which is the nominal wheel load averaged from data collected at wheel impact load detector (WILD) sites at various revenue service track locations.

1. Effects of Thermal stress – Temperature differences of 5, 10, and 25°F were tested, and FM98's predicted MGT values were less than RailGrow's MGT values by about 27 percent for 5°F difference, 19 percent for 10°F difference, and almost equal for 25°F difference.
2. Effects of Residual stress – FM98 used severity factors (SF) equal to stress values. These stress values were deduced from experiments where defects of various sizes were compared with residual stresses found in the rail heads containing these defects. SFs of 1 (3ksi), 2 (6ksi), and 3 (9ksi) were tested, and results at SF=1 were almost the same for both models. At higher values of SF, FM98 predicted shorter crack growth life than RailGrow predicted.
3. Effects of foundation stiffness – Unlike FM98, which allows only vertical modulus as an input parameter for foundation stiffness, RailGrow allows the user to use

both vertical and lateral track moduli. Four values were used (1, 2, 3, and 5 ksi), and both models showed comparable results, with RailGrow showing more variation.

4. Effects of track curvature – Values of L/V= 0.05 representing tangent track, 0.4 representing an 8-degree "sharp" curve, and 0.3 representing a 5-degree "mild" curve were used. The difference between the two models in predicting the RDF's growth was more than 30 percent for tangent track and less than 10 percent for curves.
5. Effects of rail size and head height loss – RDF growth for various rail sections and various amounts of head wear were also computed, with RailGrow showing larger variation than FM98.

The results of the benchmarking analysis of both models showing the influences of various parameters on crack growth life (MGT) is shown in Figure 3.

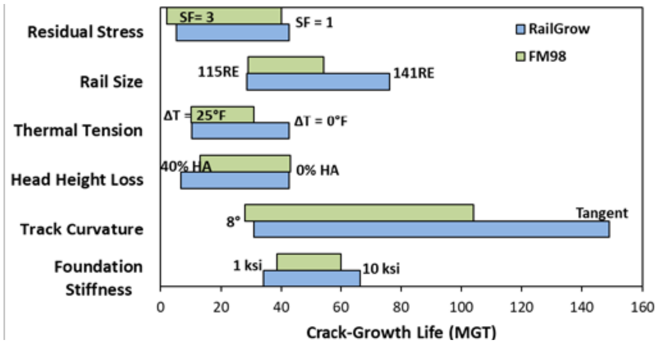

Figure 3. Influence of various parameters on crack growth life (MGT) of an RDF

For all parameters analyzed in this study, a difference in critical crack sizes calculated by FM98 and RailGrow was observed. In all cases of crack growth, both models showed that an RDF grows in a manner with almost all of the fatigue life being consumed before it reaches 20 percent. The transition from 20 percent to the critical crack size happened within a span of 10 to 20 MGT, as shown in the example in Figure 4. Modern rail flaw detection techniques can detect defects as small as 5 percent in size, and in the great majority of cases, a rail is removed from track during the window of inspection opportunity before the defect grows to fracture.

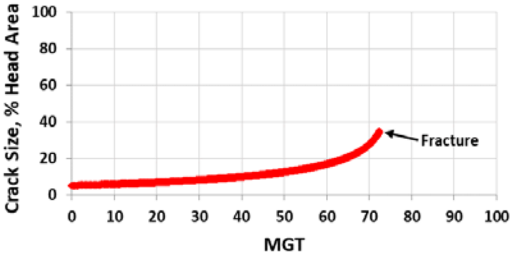

Figure 4. Example of increase in crack size with tonnage (MGT) in RailGrow

CASE STUDY AND SENSITIVITY ANALYSIS

Benchmarking analysis showed the capabilities of RailGrow, and the model was exercised for an actual RDF sample collected from a revenue service track. The sample was from a 132 RE rail installed in a 10-degree curve. The rail was severely worn as shown in left side of Figure 1, and the rail profile was measured. The worn head area was found to be 43 percent less than the head area of an unworn 132 RE rail section. Wheel-rail contact stresses were simulated by WRTOL® software using the worn rail profile of the RDF sample and wheels of various profiles for two different coefficients of friction conditions (0.35 and 0.50).

FEA modeling was done to simulate the magnitude of stress buildup in the bottom gage corner due to eccentric loading as shown in Figure 5. The FEA model simulated three conditions of wheel-rail contact: center of the rail, 0.4 inch offset, and 0.8 inch offset on an unworn rail section. The stress buildup at the bottom gage corner (red in Figure 5) was calculated for all three wheel-rail contact conditions. The results are used in RailGrow by a trilinear interpolation/extrapolation method to calculate vertical bending stresses. The method is built into the code for simulating RDFs, whereas for simulating DFs and other defects, wheel-rail contact is always assumed to be at the center of the rail. The wheel-rail contact patch is a compressive stress zone shown in blue in Figure 5. When the wheel-rail contact is at the center, the tensile stresses at the RDF initiation site are the lowest.

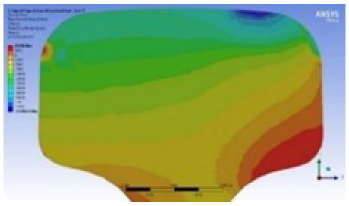

Figure 5. FEA analysis of stresses due to off-centered wheel-rail contact on an unworn rail head

For sensitivity analysis, thermal stresses are calculated using the equation $\sigma_{thermal} = E\ \alpha\ (T_o - T) = 0.195(T_o - T)$ where α is the coefficient of thermal expansion, E is Young's modulus, T_o is the track neutral temperature. For most rail steels, $E\alpha$ is close to 0.195 ksi/°F. For this RDF sample, a neutral temperature of 85°F was selected based on the track information obtained. Using T_o = 85°F, a range of thermal stresses were used from -1ksi to 9ksi, where -1ksi equates to 90°F and 9ksi equates to 39°F. RailGrow provides options of using either thermal stress data or stresses computed from a table of monthly temperature data in ¼ day increments. In addition to this, the MGT per month can be specified, as it is directly related to the number of axles per month and is evenly divided between the four time periods.

Results of the sensitivity analysis for two different rails are shown in Figure 6. Rail wear conditions, rail sizes, foundation stiffness, effects of high impact wheels, coefficient of friction and L/V ratio were the other factors.

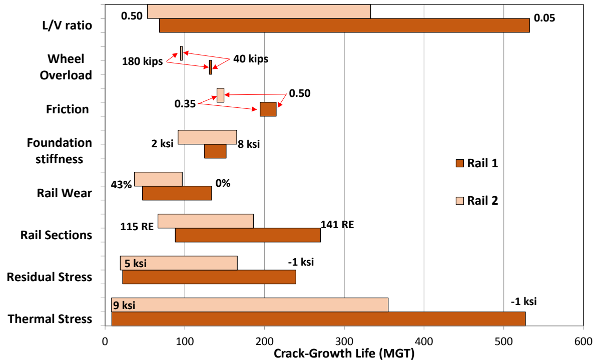

Figure 6. Sensitivity analysis of factors influencing RDF

Mechanical properties of a standard strength rail (Rail 1) and an intermediate strength rail (Rail 2) were used in RailGrow for this sensitivity analysis. Effects of different friction levels and wheels do not seem to have much influence on RDF growth. Effects of high impact wheels are referred in Figure 6 as wheel overload. Defects in wheels can cause a sudden impact load on the rail, but the chance of this high impact occurring on an existing RDF in the rail is rare. As per Figure 6, the effects of different wheel overload conditions are not substantial enough to influence the RDF growth. Rail sections make some significant impact on RDF growth due to the differences in mass of the rail head between 141 lb/yd and 115 lb/yd sections. Most RDFs have been observed in rails having considerable wear and metal flow at the bottom gage corner. While RailGrow is unable to simulate a rail head with metal flow at the RDF location, the model predicts the effects of wear on RDF growth, which are opposite to the effects of rail sections because of the decreasing mass in the rail head due to wear. Rail with high wear also has high residual stresses. Residual stresses ranged from -1ksi of compressive stress in the rail head to 5ksi tensile stress for the sensitivity study. A variation of 20 MGT to 200 MGT caused by residual stress variation is substantial, but still small in comparison to the effects of thermal stresses.

L/V ratio and thermal stress seem to be the most influential factors exhibiting the largest variation of crack growth life. In addition to L/V ratios of 0.05, 0.3, and 0.4 used in benchmarking, L/V= 0.5 was assumed for a 10-degree curve. The sensitivity analysis showed a 5 percent RDF in a 10-degree curve is predicted to last for 50 to 60 MGT, whereas the same crack will last more than 300 MGT on a tangent track depending on other factors and rail type. This is primarily due to higher lateral forces observed in sharp curves compared to shallower curves and tangent tracks, even if the degree of off-centered loading is assumed to be constant. Thermal stress influences in the sensitivity analysis showed why RDFs are so detrimental in cold winter conditions compared to summer. In the model, thermal stress of 9ksi (39°F for a track with T_o = 85°F) caused a 5 percent RDF to grow and fracture within 20 MGT. The temperature effects can become even more critical as temperature differences increase between actual rail temperature and rail neutral temperature. Tracks in colder areas are known to have lower target neutral temperatures to allow for less tension in rails, because differences between actual rail temperature and rail laying temperature increase in winter.

CONCLUSIONS

TTCI used RailGrow, a fracture mechanics model, to analyze the various parameters affecting the growth of RDFs. RailGrow predicted comparable results for the crack growth life of RDFs for similar service conditions studied in the FM98 model. Unlike FM98, RailGrow provided more flexibility by allowing the user to define thermal stresses, residual stresses, wheel loads, material properties, and other track information in details.

Various parameters were analyzed using RailGrow to understand the major contributors for RDF growth. Track curvature and thermal stresses present in the rail head were found to be the most influential contributors to the crack growth life of a 5 percent RDF.

ACKNOWLEDGMENTS

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