Experimental Determination of Crack Growth in Rails Subjected to Long-Term Cyclic Fatigue Loading

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It is well known that one of the most significant causes of train derailments within the U.S. is due to rail fracture [FRA 2023]. Despite this fact, a reliable model for predicting fatigue fracture in rails has not yet been deployed within the U.S. We have recently been developing a multiscale computational algorithm for predicting crack evolution in ductile solids subjected to long-term cyclic loading [Souza et al., 2008, Souza et al., 2009, Souza and Allen, 2009, Souza and Allen, 2012, Allen et al., 2017a,b,c, Little et al., 2018]. In this UTCRS funded project, we performed intricate experiments on rails with internal cracks as a means of both obtaining material properties and validating an advanced computational model under development in our companion proposal entitled Computational Model for Predicting Fracture in Rails Subjected to Long-Term Cyclic Fatigue Loading. Furthermore, with funding provided by MxV Rail, we have recently completed cyclic crack growth experiments on seven bi-axially loaded rails with internal cracks that had previously been in service [Whetstone et al, 2023]. We are, therefore, in this research developing the ability to: a) characterize fracture parameters for deploying our advanced fracture mechanics model; b) utilize these parameters to predict crack growth due to cyclic fatigue in rails; and c) utilize our experimental results obtained over the previous decade of testing to validate our computational predictive methodology. Should this model development prove to be useful, it is our ultimate intention to utilize this new advanced technology as a tool for determining how long rails in which flaws have been detected can be safely retained in service.</td></tr>
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1. Research Overview

We are developing state-of-the art models for predicting failure of railway due to buckling and/or rail fracture, and these research efforts are detailed within one of our companion annual reports [1] for this year. The development of these models includes the necessity to provide experimentally determined material properties within our advanced fracture mechanics model.

Toward this end, Our team has undertaken the following activities: 1) obtain rail sections with internal cracks that were previously in service from MxV Rail (by previous agreement with MxV Rail); 2) cut specimens from the rails that can be tested under uniaxial cyclic loading conditions; 3) subject these specimens to uniaxial cyclic mechanical loads that are representative of the loads incurred on in-service track (cyclic loading previously supplied to us by MxV Rail); 4) utilize these results to determine the material properties necessary to characterize the fracture properties required to perform simulations using our advanced computational fracture model described in our companion proposal entitled *Computational Model for Predicting Fracture in Rails Subjected to Long-Term Cyclic Fatigue Loading;* and 5) utilize the fracture properties to predict the growth of cracks in rails subjected to actual in-service loading conditions.

2. Research Results Obtained to Date

We note here that over the previous decade we have performed a series of complex full-scale multiaxial cyclic loading experiments (with funding from MxV Rail) on five rail specimens. The experimental apparatus we have used for our previous full-scale rail testing is shown in *Figure **1***. The railhead is contained within the apparatus but can be observed at the bottom where there is yellow paint. The longitudinal constraints allowed for the application of axial loading, thereby accounting for temporally constant thermal loads in the field, and the transverse portion of the apparatus subjects the rail head to fatigue loading. Applying both of these loadings simultaneously while constraining the rail head against both lateral and axial displacements simulated the loads applied by train cars continuously running over the segment of the rail.

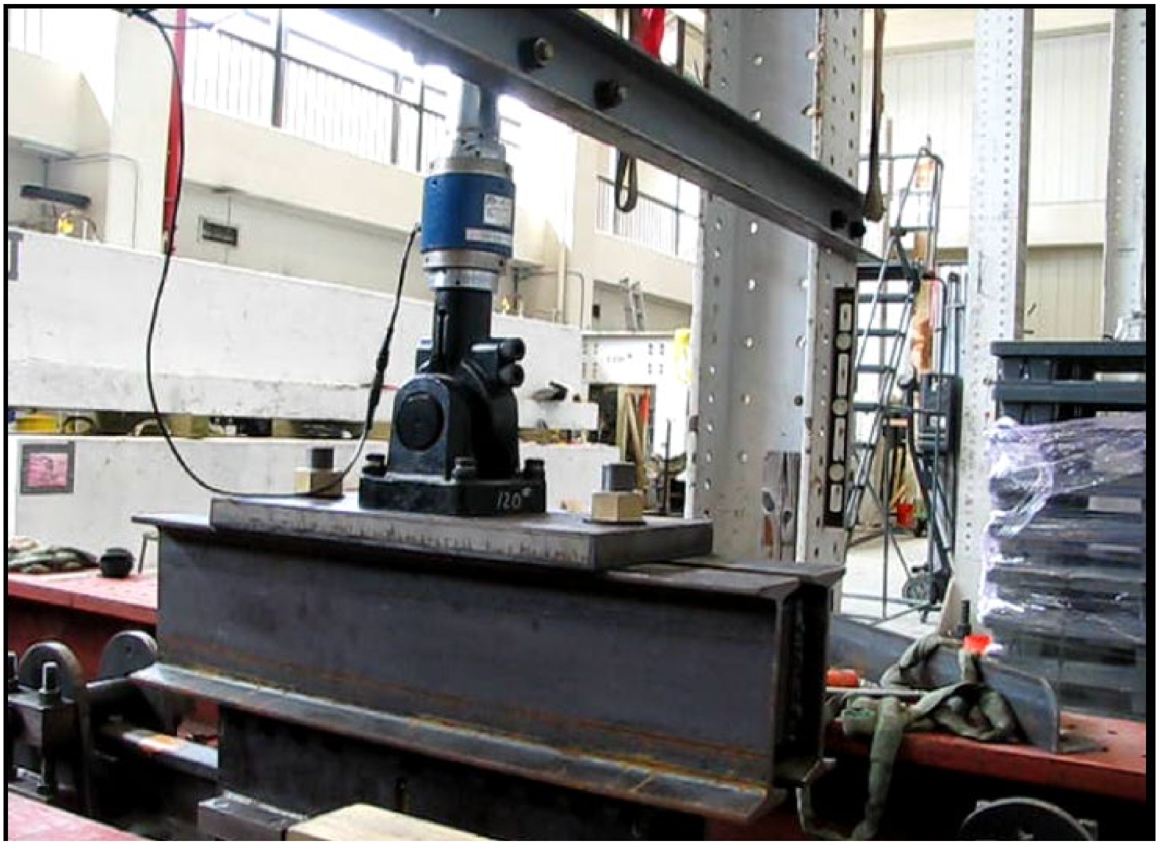

Figure 1: Rail Head in Experimental Apparatus

This apparatus was capable of exposing the segment to one-hundred thousand cycles per night, at which point the rail head was removed from the constraints and interrogated using a phased array. The acoustic emitter was run over the top of the rail head from the field side to the gauge side, during which the internal crack was observed using the phased array.

We have now been performing these tests for ten years, during which we have successfully tested five rails over several million cycles [2], thereby resulting in the crack evolution diagram shown in *Figure **2***.

The results shown in *Figure **2*** are utilized as a means of validating our advanced multiscale fracture mechanics model described in our companion report [1]. However, in order to deploy that model, it is first necessary to obtain the material properties required to deploy our fracture model from dramatically simplified (and less expensive!) experiments, to be described below.

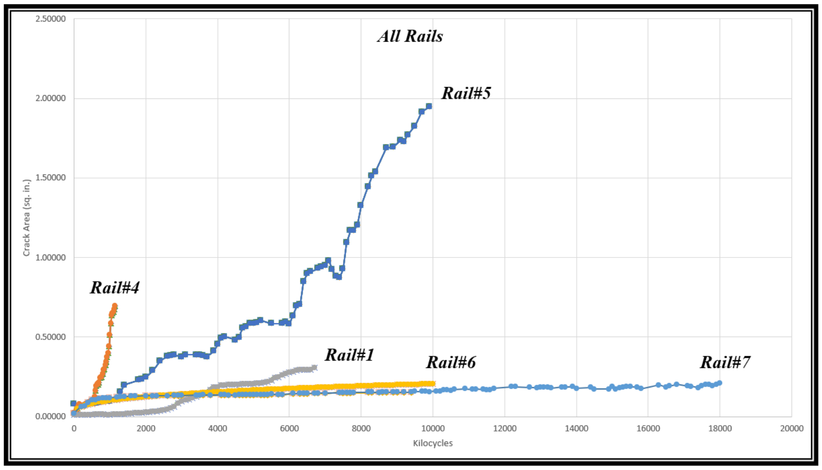

Figure 2: Comparison of Crack Progression in Each Rail Tested

As described in our companion annual report, we deploy a nonlinear cohesive zone model to account for internal crack growth within the rail head. This model requires the determination of accurate fracture-based material parameters in order to predict crack growth in in-service rail heads.

2.1 Obtain Rail Sections with Internal Cracks

In order to perform these material characterization experiments, it is necessary to obtain damaged rail specimens that have previously been in service, and toward this end, MxV Rail has provided us with pre-cracked rails (*Figure 3*) that we are currently testing in our own labs.

Figure 3: The Damaged Rail Sections Received from MxV Rail

2.2 Cut Specimens for Uniaxial Cyclic Testing

As depicted in *Figure **4*** and *Figure **5***, each specimen contains internal cracks. We determine where they are located within the railhead, and we cut test specimens (*Figure **6***), that we then test in our MTS Testing Machine.

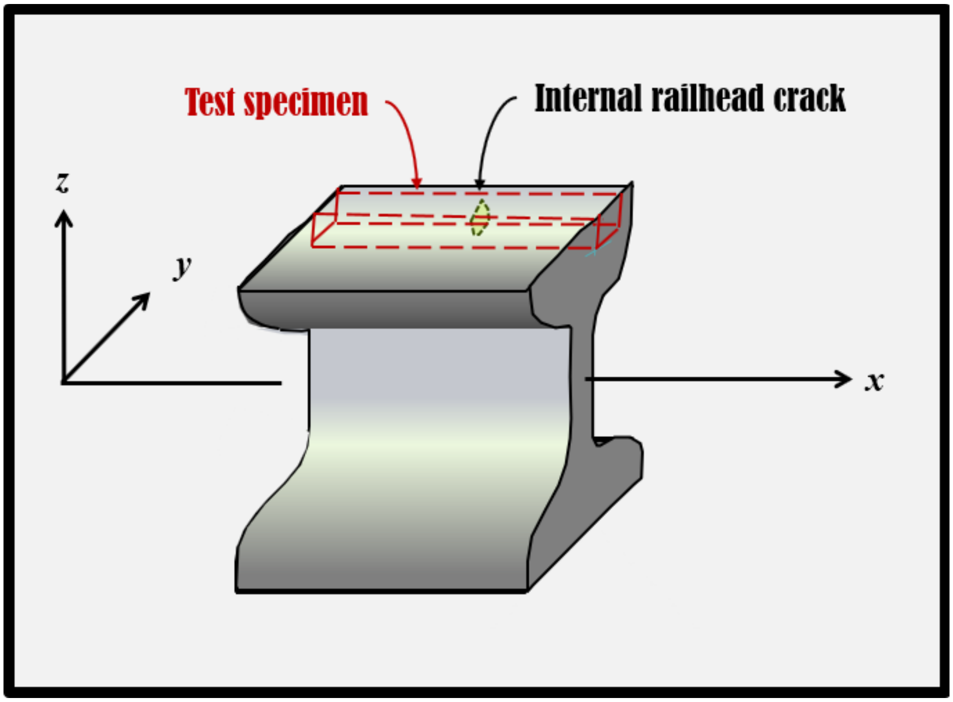

Figure 4: Depiction of Rail with Internal Crack Showing Test Specimen

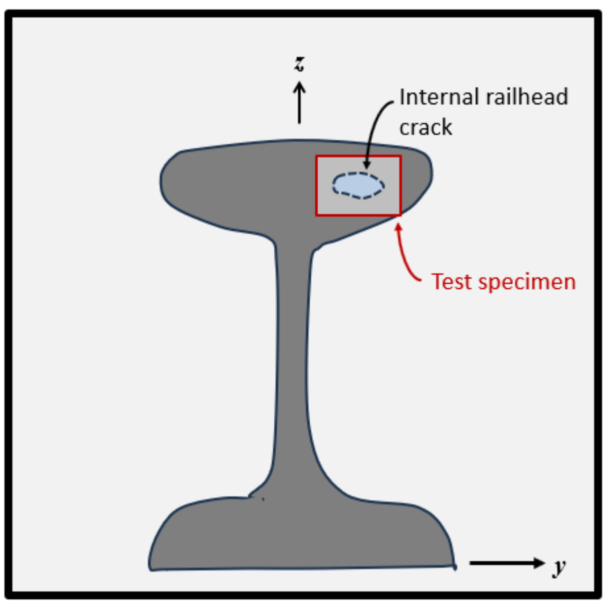

Figure 5: 2-D Cartoon of the Damaged Rail Showing the Cross-Section of the Test Specimen

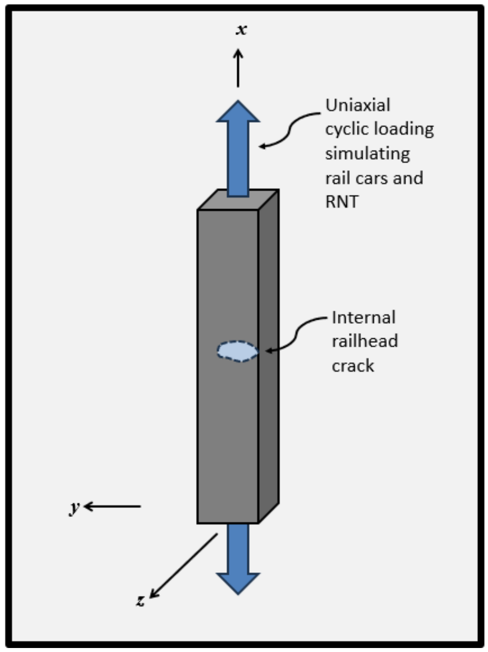

Figure 6: Cartoon Showing the Testing Configuration for Applied Cyclic Loading

2.3 Subject Specimens to Uniaxial Cyclic Loading

The specimens are then tested in our uniaxial MTS Testing Machine (*Figure 7*) and subjected to cyclic loading. Specimens are intermittently subjected to non-destructive evaluation (*Figure **8***) to evaluate the evolution of the internal crack geometry resulting from the uniaxial loading. A typical image from the output of the phased array is shown in *Figure **9***.

Figure 7: The 100 Kip MTS Machine Utilized for the Cyclic Fatigue Testing of the Railhead

Figure 8: Photograph of Test Specimen Periodically Interrogated with a Phased Array to Assess Internal Crack Growth Due to Cyclic Uniaxial Loading

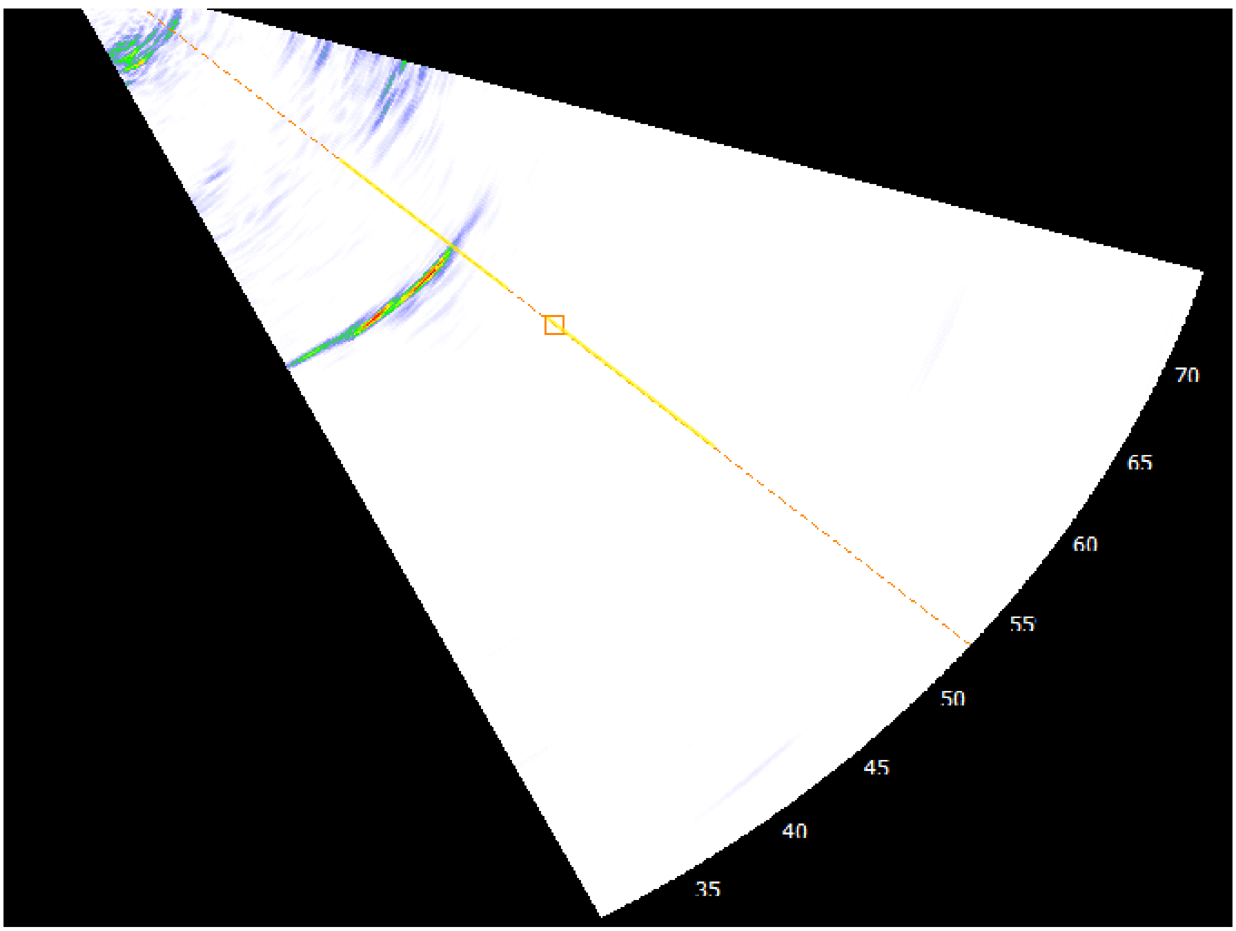

Figure 9: Phased Array Scan Showing Internal Crack in Railhead Shown in Figure 8

2.4 Utilize the Experimental Results to Calibrate Our Advanced Fracture Model

The results of the above experiment are utilized to calibrate our nonlinear cohesive zone model [3-7], given by

$$t_i\,(t) = \frac{u_i}{\delta_i}[1-\alpha(t)]\int_0^t D\;(t-\tau)\frac{\partial\lambda}{\partial\tau}d\tau \qquad (1)$$

where

- t_i are the components of the crack-opening traction vector
- u_i are the components of the crack opening displacement vector
- D(t) is the cohesive zone relaxation modulus
- α(t) is the current value of the interfacial damage parameter, which is modeled by a damage evolution law.
- λ(t) is the Euclidean norm of the cohesive zone interfacial displacement vector

2.5 Utilize the Experimentally Determined Fracture Properties to Predict the Response of In-Service Rails

The experimental results are used to determine the material parameters for deployment in our fracture model [8], and the above fracture model is deployed within our multiscale nonlinear finite element computational algorithm [9-13] to predict crack growth in rails subjected to complex long-term fatigue loading, and results to date are described in our companion annual report [1]. As an example, we show in *Figure 10* four comparisons of our predicted results to the experimental results we previously obtained in *Figure **2***. These results provide encouragement that our model is proceeding in the right direction.

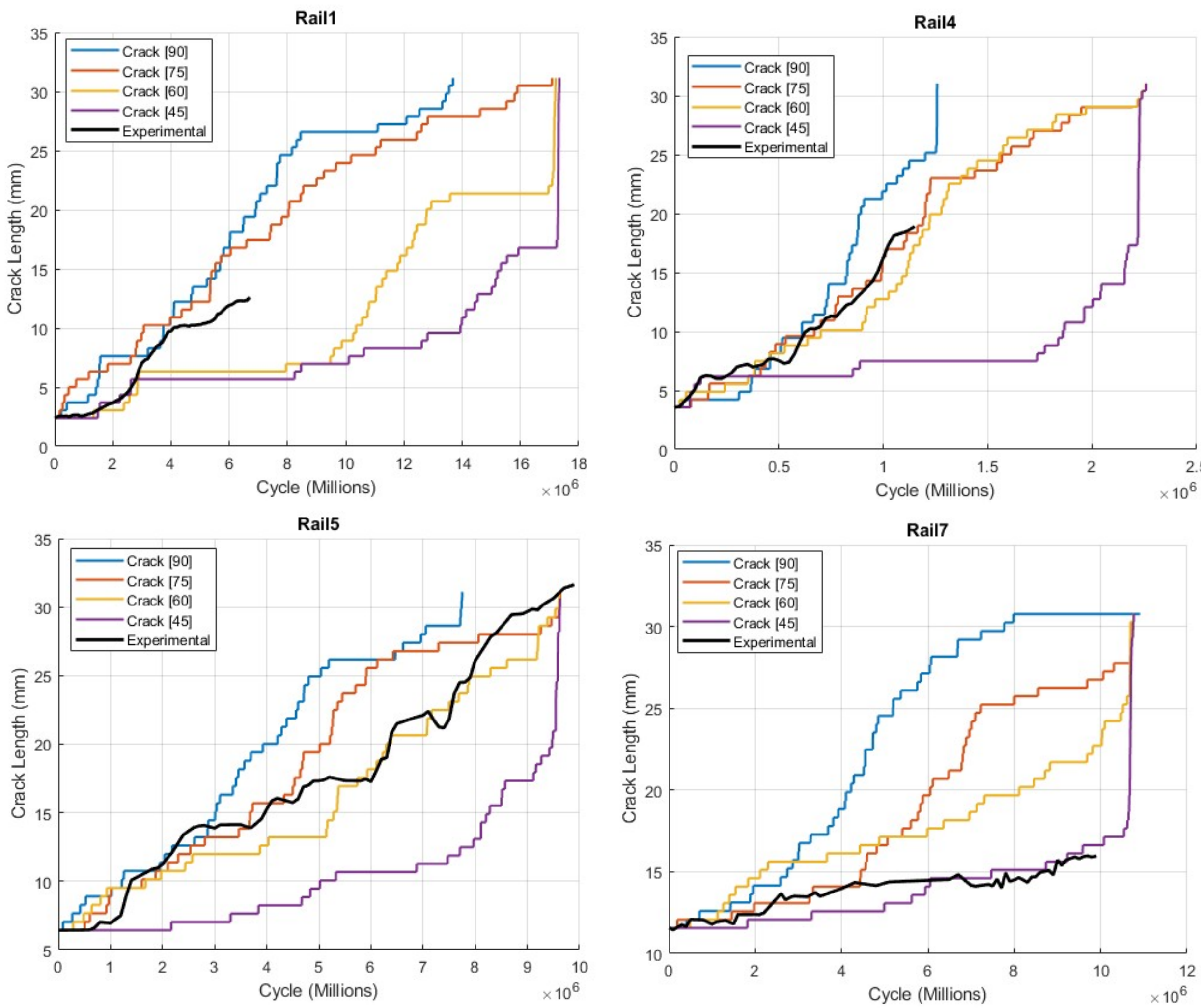

Figure 10: Comparisons of Numerical and Experimental Results

3. Conclusion

It is known that rail fracture causes nearly a hundred derailments every year within the United States [14]. Furthermore, previous efforts [8] to predict rail fracture have for the most part failed to be sufficiently accurate determining if/when internally damaged rails should be removed from service.

The purpose of the current research being to develop just such a model, if successful, would then be useful in developing an AREMA standard for the purpose of advising field engineers when rails with detected internal flaws should be removed from service. Based on the location, size and orientation of an internal crack within the railhead, engineers could therefore make informed decisions as to if/when rails with flaws need to be replaced. This ability would provide continued rail transport in certain circumstances, thereby saving the cost of immediately shutting down rail lines, while maintaining high-level safety standards.

4. Future Work

Our companion research project, entitled ***Computational Model for Predicting Fracture in Rails Subjected to Long-Term Cyclic Fatigue Loading*** is in the process of developing a high-fidelity multiscale computational algorithm that will be capable of predicting crack growth in railheads as functions of crack location, crack size, and crack orientation within the rail head. Since these three artifacts can be regularly detected remotely using a phased array, given these three pieces of information, when completed, our computational model will be capable of informing track engineers if/when track section with detected internal flaws will need to be removed and replaced.

Unfortunately, whereas our modeling effort is proving useful, it requires input information from the experimental research described within this report. As such, the experimental data to be acquired in this research project is necessary to prove the accuracy of the computational model that is under development in our companion project. The experimental results to be obtained in this project therefore represent a necessary component to that end – the development of a model for predicting crack growth rates in rails with previously detected internal flaws.

Our future work will then focus on utilizing the experimental results from this project as input to our rail fracture model so that the accuracy of our model can be established concisely. Should our predicted results prove to be accurate when compared to previously obtained multiaxial testing results [15, 16].

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