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Development of Fatigue Loading Test Rig of Rails

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Summary

Transportation Technology Center, Inc. (TTCI) tasked Texas A&M University (TAMU) to build a rail fatigue test rig and to test service-worn rails with pre-existing head defects to fracture. This work is funded under the Association of American Railroads' (AAR) Strategic Research Initiative (SRI) program.

The intention is to test future rail samples to fracture and compare actual crack growth with simulated outputs from *RailGrow*, a fatigue crack growth model developed by TTCI. This could lead to an improved understanding of crack growth behavior and possible refinement of *RailGrow* for better predictive capabilities.

In the rig, rail is loaded to simulate conditions of passing coupled cars. The loading includes the following: 1) vertical bending to simulate wheel load cycles, and 2) axial tension to simulate thermal stresses. The first rail was subjected to 1,277,000 cycles of loading over a four-month period, during which an evolving crack within the rail was interrogated using a phased array instrument approximately every 25,000 cycles of loading. During the test, the crack in the rail was observed to grow from an initial measured area of approximately 0.02 in.^{2} to 0.70 in.^{2} without fracture. As a part of the work, all rail that is unbroken after a specified number of cycles will be broken open and the final crack size, along with growth rings observed at fracture in the test rails, will be compared with simulated crack shapes predicted by *RailGrow*.

In addition to load and thermal cycles, *RailGrow* simulates the influence of residual stresses due to a combination of roller-straightening stresses from the rail manufacturing process and rolling contact in service. TTCI intends to measure residual stresses after fracture to more accurately model crack growth.

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INTRODUCTION

TTCI tasked TAMU to build a test rig to simulate the fatigue loading of rail. This rig will be used to validate crack growth rates of pre-existing defects in the railhead modeled by *RailGrow,* a TTCI-developed fracture mechanics program. The rig also could be used in the future to fatigue a rail subject to other defects, or to fatigue welds.

Background

RailGrow is a Microsoft® Excel-based fracture mechanics model developed under the AAR SRI Program. *RailGrow* uses the principles of fracture mechanics and strength of materials to predict the growth of pre-existing transverse defects in the rail head or surface cracks from the rail base as a function of accumulated MGT. Fatigue crack growth rates are obtained from standard laboratory tests of rail samples as per ASTM E647. A simultaneous study was done to generate fatigue crack growth rate parameters and other mechanical properties of different types of rail steels using samples machined from the head of rails.

Figure 1 shows the bending moments 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. There are four bending moments created by direct loading of the wheels and five reverse bending moments underneath the coupler, in between wheels and in front and behind the trucks. The highest tensile bending stress in the head of the rail occurs underneath the coupler under “reverse bending.”[1] The highest tensile stress occurs in the rail base directly under the passing wheel load, and is termed “direct bending.”

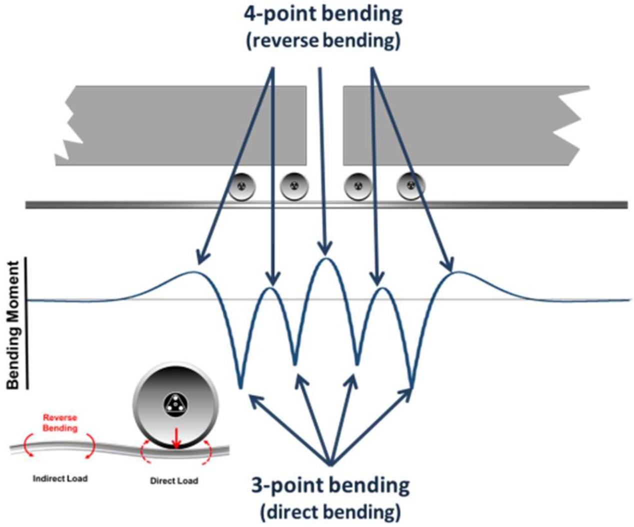

Figure 1. Bending moments applied to the rail

The tensile stresses in the rail head causing crack growth are comprised of primarily three components: bending stresses due to wheel loads, thermal stresses due to deviation of the actual rail temperature from neutral temperature, and residual stresses from wheel/rail contact and rail straightening after rolling. Among the three different contributing stresses, residual stresses are unknown while thermal stresses can be computed as mentioned in a previous *Technology Digest.*[1] Crack growth predicted by the model also is a function of material properties including fracture toughness, yield strength, ultimate tensile strength, elastic modulus and fatigue parameters calculated from fracture mechanics.

Experimental procedure

RailGrow had been exercised using a variety of parameters including wheel loads. The schematic test rig and the actual rig are shown in Figure 2.

1. *Wheel load stresses:* Stresses in the head of the rail due to wheel loads were calculated from *RailGrow* simulations for loads due to empty and loaded cars as shown in Table 1.

Table 1. Stresses for cyclic fatigue loading on rails

Load Condition	Location	Loaded Wheel Load (35.75 kips)	Empty Wheel Load (8.33 kips)
		Stress (ksi)	Stress (ksi)
Direct 3-point bending	Under inner wheels of car	-11.64	-2.71
	Under outer wheels of car	-8.54	-1.99
Indirect 4-point reverse bending	Under coupler	5.53	1.28
	Between the two wheels of the truck	1.62	0.38
	In advance and behind the trucks	3.73	0.87

The cyclic loading conditions shown in Figure 1 are being simulated in the test rig from the stresses mentioned in Table 1. The bending moments in the rail under the action of wheel loads are recreated in this experiment using a 3-point direct bending (red) and a 4-point reverse bending (blue) on the test rail as shown in Figure 3.

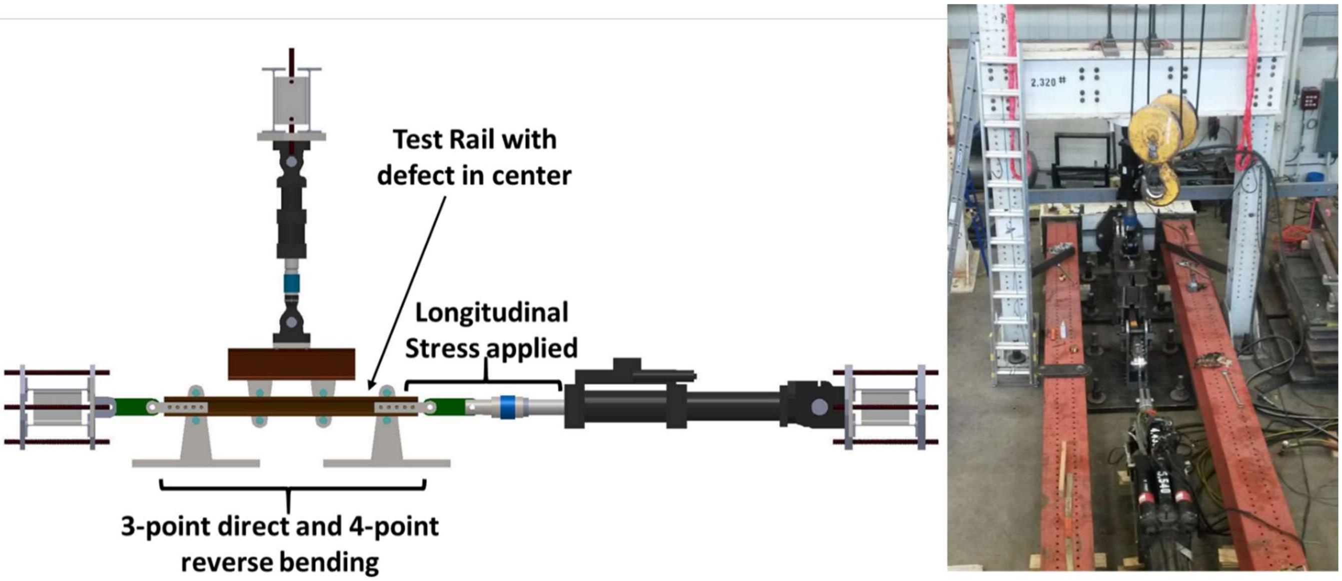

Figure 2. Schematic test rig (left) and the actual rig (right) for fatigue testing of rails at TAMU

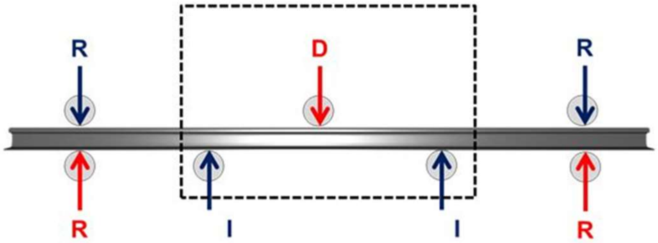

Figure 3. 3-point direct bending and 4-point reverse bending loading on rail (D=Direct Wheel Load, I=Indirect Load and R=Reaction from test setup supports)

2. *Thermal stresses*- A constant longitudinal stress was also applied to the rail to simulate thermal stress conditions. A thermal stress of 5 ksi was applied in the first test equivalent to a temperature of approximately 25°F below the rail neutral temperature as per 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.[1]

Phased array crack growth

The internal crack size was measured periodically during the test using a phased array ultrasonic device. With the current test apparatus, it is necessary to remove the transverse load housing to deploy the phased array ultrasonic detector. Accordingly, the rail was subjected to approximately 25,000 continuous loading cycles approximately every 18 hours. The rig was disassembled, and the phased array was used to make both a longitudinal and a transverse pass over the railhead, as shown in Figure 4.

Figure 4. Photograph of the phased array deployed on the railhead

The output from the phased array was then utilized to calculate the vertical and horizontal dimensions of the crack (approximated by assuming that the crack is elliptical in shape). For example, the estimated crack shape is shown at three different numbers of load cycles in Figure 5.

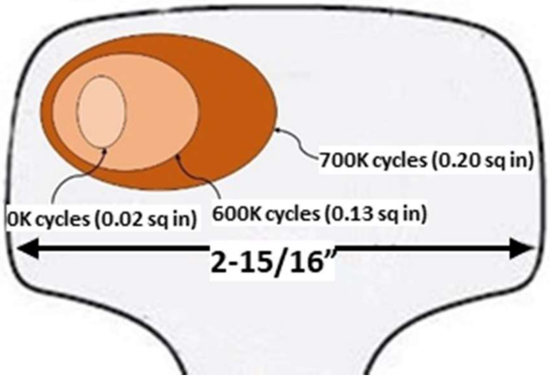

Figure 5. Estimated crack size and shape at three different numbers of fatigue cycles

Experimental results

The initial rail was tested for a total of 1,277,000 cycles of loading over a time span of approximately four months, with results obtained from the phased array output shown in Figure 6. The rail will be broken-open and critical crack size at failure measured by phased array will be compared with actual crack dimensions visible at the fractured surface.

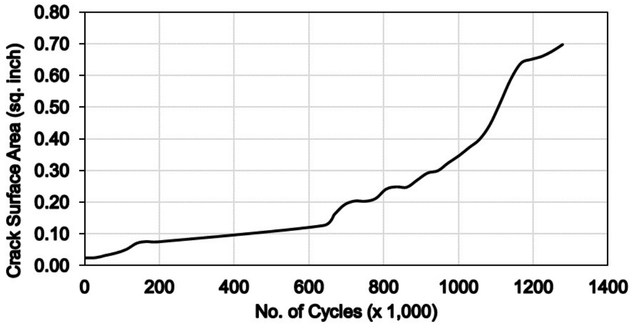

Figure 6. Graphical depiction of crack size vs. number of fatigue cycles applied to the rail

Conclusions

An experimental approach to validating *RailGrow* has been developed by testing rails with internal defects in the head by a combination of direct and indirect bending. Initial results suggest that applied service loads can be replicated in this test rig in support of this validation.

Future work

Additional rails are scheduled to be tested in the near future. However, as a means of improving the accuracy of the experimental data, the phased array is first being equipped with an encoder that is capable of measuring the transverse coordinate location of the phased array on the railhead to a high degree of accuracy. It is anticipated that this improvement will render the experimental results more precisely than was possible in this, the first of a series of experiments that are intended to capture the actual load history applied to in-service rails more accurately than has been heretofore possible.

At the completion of testing of all rails, results will be compared with *RailGrow’s* simulation outputs under similar conditions of wheel loads and thermal stresses. The life of the crack as measured by accumulated MGT in *RailGrow* will be compared with the number of cycles of loading recorded by the test rig’s software. *RailGrow’s* output includes a shape of the final defect with growth rings as calculated by fracture mechanics and the shape and direction of defect growth is mostly controlled by the pattern of residual stresses existing in the cross-sectional plane of the head of the rail. This shape of the defect will be compared with the defect growth observed in the tested rails. Differences between simulated defect shape and actual defect shapes will probably lead to further understanding of crack growth behavior and refinement of *RailGrow* for better predictive capabilities. It is also expected that the differences in results between *RailGrow* and this experimental study will provide insight about the influence of residual stresses in rails.

ACKNOWLEDGMENTS

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References

1. Banerjee A, William Zdinak, and David D. Davis, “Evaluation of Reverse Detail Fracture Growth using a Fracture Mechanics Model,” *Technology Digest* TD-17-030, November 2017, AAR/TTCI, Pueblo, CO.