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Modeling of Low Rail & Wheel Rolling Contact Stresses

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SUMMARY

To increase the understanding of the root causes of rolling contact fatigue (RCF), Transportation Technology Center, Inc. (TTCI) has conducted a study of wheel and rail contact stresses. This study, conducted under the Association of American Railroads' Strategic Research Initiatives (SRI) Program, evaluated the leading axle of a non-steering truck under a 36-ton axle load on a non-lubricated track. The force environment measured via instrumented wheelsets (IWS) in field tests¹ served as inputs for linear elastic models in boundary element-based (CONTACT)² and finite element-based models.

Results are as follows:

- In an absence of tangential forces, maximum equivalent stress location is approximately 3/16 inch below the surface with 106 ksi magnitude. Cyclic application of these subsurface stresses is expected to result in subsurface cracks (delamination). This finding is consistent with results of the inspection of out-of-service wheelsets with shelling.³
- As tangential forces increase, maximum equivalent stress location moves to the wheel and rail surface, but equivalent subsurface stress magnitudes remain similar. This implies that a subsurface fatigue mechanism is always active under 36-ton axle load operation.
- Surface yielding occurs at low traction ratios ($T/N < 0.3$), which conventional Shakedown theory fails to predict. Preliminary results of tests on the new rolling contact fatigue simulator (RCFS) at the Transportation Technology Center (TTC) show that surface RCF was generated with AAR Class C wheels and intermediate strength rail (ISR) at 0.1 T/N and 0.2 T/N, which aligns with the model results so far.

High impact wheels (HIW) and rail spalling are attributed to RCF at the interface between wheel tread and top of rail.^{3,4} Wheelset removal, which is primarily driven by HIWs, consistently forms more than half of the rolling stock maintenance cost for Class I railroads.

A more accurate wheel and rail damage map to predict material flow, wear and combination will be provided after the validation of the contact stress model with the RCFS. Wheel and rail interface management can be applied on the basis of the damage map to prolong wheel and rail life. Future *Technology Digests* will present the results of surface initiated RCF test program.



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INTRODUCTION

The objective of the RCF research program is to provide effective wheel and rail interface management strategies to mitigate the safety and financial burden of RCF. Modeling of rolling contact stresses under a variety of vertical loading, wheel and rail profiles, friction coefficients and tangential forces is essential to understand wheel and rail damage mechanisms and associated conditions.

This *Technology Digest* (TD) and follow-on TDs investigate HIW and rail spalling resulting from RCF.

METHODOLOGY

Contact stresses between the rail head and wheel tread depend on contact geometry, friction and contact forces. The RCFS was used to imprint a contact patch between 36-inch diameter wheel tread and 136RE rail head under 36-ton axle load. An elliptical patch forms with approximately 1/2 inch width and 3/4 inch length under unworn profiles (Figure 1).

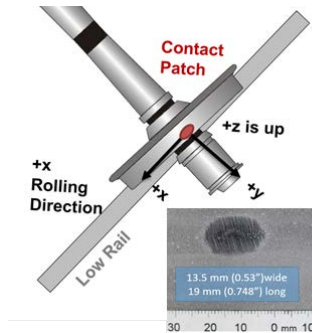


Figure 1. Coordinate System of the Low Rail Contact and Contact Patch Geometry from RCFS

The force input environment was determined from curving tests at TTC’s Wheel and Rail Mechanism (WRM) non-lubricated loop under 36-ton axle load and at balance speed.¹ Wheel and rail forces were measured via instrumented wheelsets (IWS). Figure 2 shows the lead axle low rail wheel traction ratio as a function of degree of curvature for a non-steering truck and 36-ton axle load.

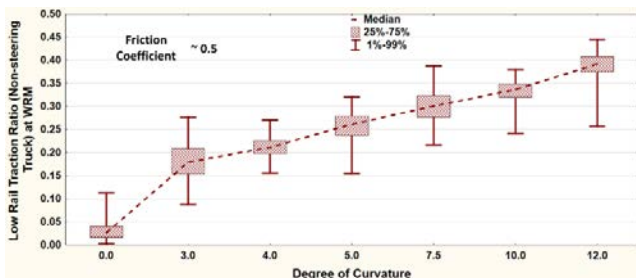


Figure 2. Low Rail Traction Ratio Characteristics of Non-Steering Truck as a Function of Degree of Curvature (286,000-pound Hopper, Non-lubricated Track, Balance Speed Curving)

Boxes show 25th and 75th percentiles, and whiskers show 5th and 95th percentiles. Median values are connected via lines from tangent to 10-degree curve. Lateral and longitudinal forces are shown in Figure 3 in a similar way. Median lateral forces increase between 3- and 10-degree curves with a linear relationship, while longitudinal forces stay similar between 3- and 10-degree curves. The median lateral and longitudinal forces in the bodies of 3-, 4-, 5-, 7.5-, 10- and 12-degree curves were used as inputs for the contact stress model. The RCFS test program was also established with the same force environment.

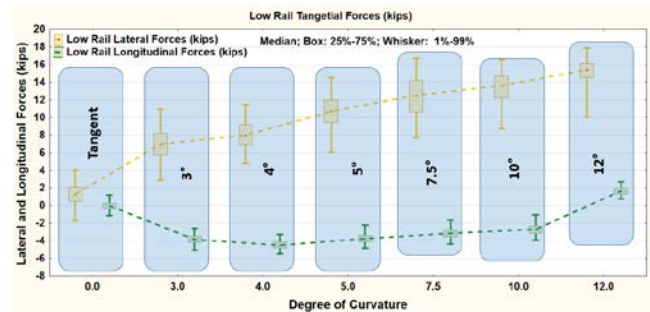


Figure 3. Lateral and Longitudinal Force Environment of a Non-Steering Truck as a Function of Degree of Curvature (286,000-pound Hopper, Non-lubricated Track, Balance Speed Curving)

The wheel and rail force environment is described in terms of the traction ratio (T/N), the ratio between tangential and normal contact forces.¹ It can be defined as the demand for adhesion and plays a major role in understanding wheel and rail damage as well as quantifying steering performance of trucks (Figure 4).

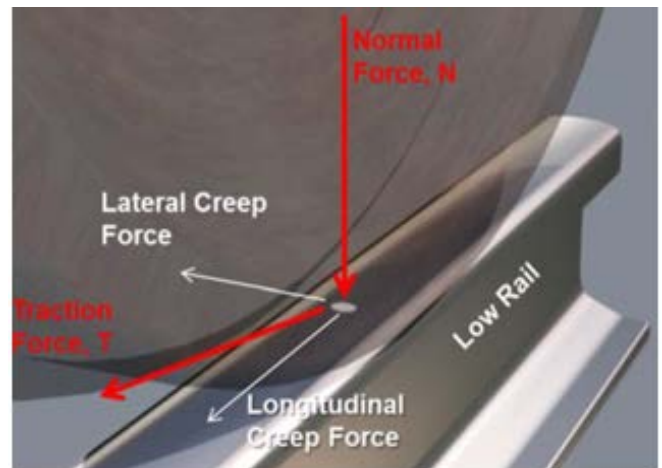


Figure 4. Definition of Traction Ratio

Traction ratio is calculated from measured wheel/rail forces using the following formula:

$$\frac{T}{N} = \frac{\sqrt{F_{long}^2 + (F_{lat} \cos \alpha - F_{vert} \sin \alpha)^2}}{F_{vert} \cos \alpha + F_{lat} \sin \alpha}$$

α contact angle
 $F_{long}, F_{lat}, F_{vert}$ longitudinal, lateral, and vertical wheel/rail forces
 N total force normal to the wheel surface
 T total tangential force

CONTACT STRESS MODEL

Crack initiation at the wheel and rail surfaces is attributed to the accumulation of plastic deformation (ratcheting).⁵ Thus, quantifying contact stresses under a varying load environment that results in plastic deformations is critical. In this study, von Mises (maximum energy of distortion) theory is used to predict plastic deformation. Operating within the elastic contact stress regime will not eliminate RCF, since fatigue strength is less than yield strength, but it is expected to prolong wheel and rail life. The complete fatigue life model of different wheel and rail metallurgies will be investigated in the future.

Modeling of lead axle, low rail contact showed that the stress distribution difference between CONTACT and finite element method is negligible (Figure 5, 6).

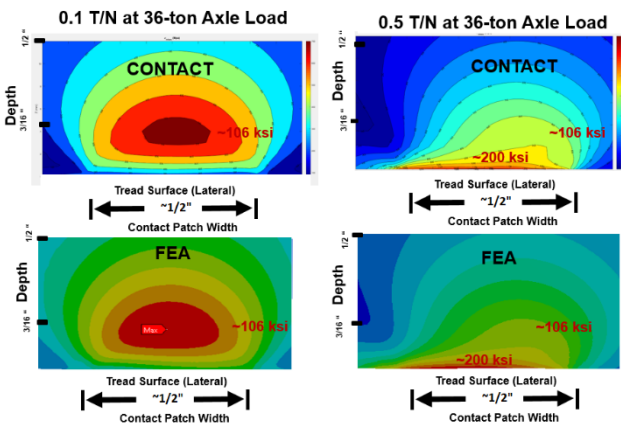


Figure 5. von Mises Stress Distribution along the Vertical Plane (-yz Plane at Figure 1) at the Center of Contact Patch at Low (0.1) and High (0.5) Traction Ratios

CONTACT uses Kalker’s three-dimensional rolling contact model, which is based on boundary element method, as opposed to finite element method. Surface and subsurface von Mises stresses were calculated with both techniques. Figure 5 shows the von Mises stresses along vertical plane where maximum surface stresses are generated, and Figure 6 shows surface von Mises

stresses in the contact patch plane. These findings are consistent with other studies.^{6,7}

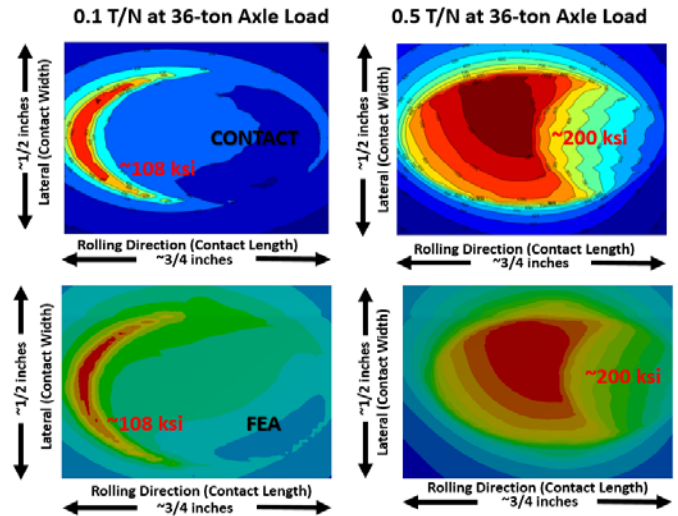


Figure 6. von Mises Stress Distribution along the Contact Surface (xy plane at Figure 1) at Low (0.1) and High (0.5) Traction Ratios

CONCLUSION

Contact stresses between an unworn, 36-inch wheel tread and 136RE rail under 36-ton axle load and non-lubricated conditions were modeled. The results have been consistent with the results of the RCFS test program so far. It should be noted that maximum contact pressure, pressure distribution and resultant surface traction distribution can change with worn wheel and rail profiles. The contact location and different combination of wheel and rail profiles will be investigated in the future.

Figure 7 shows the modeling results of maximum von Mises stresses on the surface and at 3/16 inch depth below surface as functions of traction ratio under 36-ton axle load. Maximum surface von Mises stress increases from 38 ksi to 186 ksi with increasing traction forces and von Mises stresses at 3/16 inch depth below surface slightly increase from 106 ksi to 114 ksi.

Based on the given conditions, the following is concluded:

- An average low rail tangential force environment for a lead axle of a non-steering truck on a non-lubricated track is sufficient to result in permanent surface deformations on surfaces of Class C wheels, Class D wheels, intermediate strength rail (ISR) in 2-degree and sharper curves, and in permanent deformation of high strength rail (HSR) in 3-degree curves and sharper.

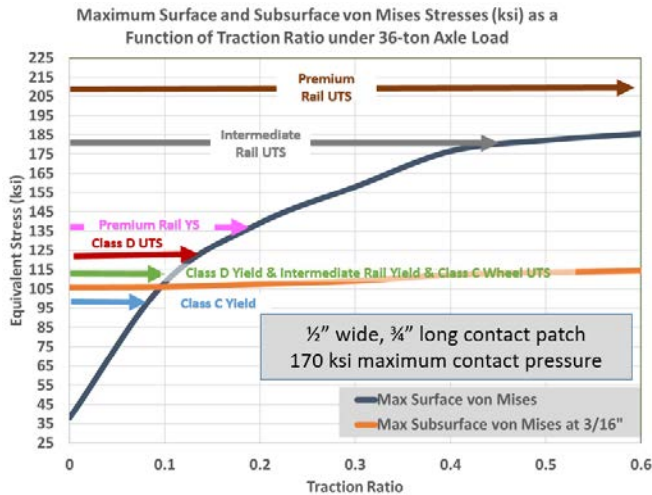


Figure 7. Maximum Surface and Subsurface von Mises Stresses under 36-ton Axle Load between Unworn Wheel Tread and Top-of-Rail (136RE) Profiles as a Function of Traction Ratio

- In an absence of tangential forces, the maximum subsurface equivalent stress location is approximately 3/16 inch below the surface and its magnitude is about 106 ksi.
- As tangential forces increase, maximum equivalent stress location moves to the wheel and rail surface, but equivalent stresses at 3/16 inch depth below the surface remain similar (between 106 ksi and 114 ksi). This implies that a subsurface fatigue mechanism is always active under 36-ton axle load operation.
- The magnitude of the maximum predicted subsurface equivalent stress (106 ksi) is above the yield strength of Class C wheel and below the yield strengths of Class D wheel, ISR and HSR (Figure 5 and 7).
- Surface yielding occurs at low traction ratios ($T/N < 0.3$), which conventional Shakedown theory fails to predict.

The primary limitations of this modeling study are wheel and rail geometry (single set of unworn profiles) and the use of linear elastic models in CONTACT as well as finite element software.

FUTURE WORK

A damage map (similar to Shakedown theory⁸) will be developed on the basis of modeling results supported with RCFS test results for non-lubricated and unworn wheel and rail profile conditions. Wheel and rail interface management can be developed on the basis of the damage map to prolong wheel and rail life.

Future modeling efforts will incorporate non-linear elastic-plastic model of material behavior.

Damaging contact stresses which result in RCF and wear will be investigated under combinations of vertical forces, wheel/rail friction coefficient values, and wheel and rail profiles.

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