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# Preliminary Study of the Subsurface Rolling Contact Fatigue of Railway Wheels

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## Summary

A three-dimensional finite element model (FEM) was constructed to simulate the stress and strain fields that take place under the rolling-contact of railway wheels on rails. This FEM constitutes a realistic replica of a railway wheel that is rolled on a rail segment using a "hard contact" over-closure relationship and an elasto-plastic material model with isotropic and kinematic hardening. This material model permits the consideration of the wheel's stabilized structural (steady-state) response in the Fatemi-Socie multiaxial critical-plane fatigue model.[1]

The steady-state stress and strain response of the wheel is post-processed with the Fatemi-Socie fatigue criterion in an attempt to obtain improved analytical predictions of the subsurface fatigue initiation and subsequent life in railway wheels. This fatigue criterion is appropriate for use in rolling-contact fatigue predictions, because it takes into account the nonproportional and out-of-phase nature of the multi-axial state of stress that occurs when a railway wheel rolls on a rail. It predicts fatigue initiation at a depth of approximately 0.12 inch beneath the wheel surface, which is consistent with the findings of previous research.[2-6]

Based on the current results, the following conclusions can be drawn:

- The fatigue criteria used are able to predict the fatigue life as well as the orientation of the cracks.
- The models used in this work can account for nonproportional loading, which is characteristic during rolling contact and also the effects of the material's plastic behavior.
- The fatigue life predicted by the Fatemi-Socie fatigue model is about 220,000 cycles, which is comparable to that predicted in previous studies.[2-6]
- This similarity in the results may be due in part to the limited amount of plastic deformation in the region of contact. Although the elastic limit of the material is passed in an important region beneath the wheel, the predicted stress field did not reach values that were significantly greater than the material's yield stress, so that an overall state of elastic shakedown may be presumed.

The procedure developed herein of using the Fatemi-Socie fatigue model is also in agreement with previous research[2-6] in the prediction of the critical crack plane orientation and exact location of the estimated fatigue initiation spot (x = 0.84 inch, y = 0.15 inch, φ = 80 degrees, and θ = 300 degrees). The value of y = 0.15 inch corresponds to a fatigue-crack initiation depth of about 0.12 inch, which, as stated above, is consistent with the findings of previous research.[2-6] The critical plane orientation corresponds to a circumferential configuration, which also agrees with previous research results.[2-6]

## INTRODUCTION

Technological advancements in the railway industry have resulted in longer wear lives of wheels. Simultaneously, current economical and logistical needs demand increased train speeds and load capacities. These demands have resulted in larger contact forces acting on rails and wheels. Longer wear lives, higher speeds, and larger loads have made fatigue failure the primary cause of railway wheel replacement and re-engineering.[2]

Analysis of industry data on wheel replacements shows that 67 percent of railroad wheel failures are caused by fractured rims, a form of subsurface initiated rolling-contact fatigue (RCF) failure. This suggests a need for methods that can effectively predict the occurrence of RCF. Effective predictions require computational tools and mathematical models that can more accurately simulate material behavior and structural interactions like the contact between railway wheels and rails that takes place as the wheels roll.

### Description of RCF in Railway Wheels

The roots of the RCF problem in wheels have previously been identified together with the mechanisms that cause the evolution of an initial or initiated crack into a structural failure of a wheel. Three different regions where fatigue can initiate have been identified. The differences in these regions stem, apart from their locations, from the causes that trigger the development of the fatigue processes. The three regions are (1) the tread surface, (2) a subsurface region that ranges from approximately 0.12 inch to 0.4 inch deep, and (3) a tertiary region located mostly between 0.4 inch and 1.18 inches below the wheel's surface. It should also be noted that in wheel steels made to modern metallurgical cleanliness standards, crack initiation below the surface tends to take place at approximately 0.4 inch to 1.18 inches below the wheel rolling surface.[4]

### Engineering Assessment of Subsurface Fatigue

Microscopy of RCF defects have shown that fatigue damage may initiate from microscopic defects at depths of 0.12 to 0.16 inch below the tread surface (Figure 1), a zone where plasticity and wear represent competing damaging mechanisms.

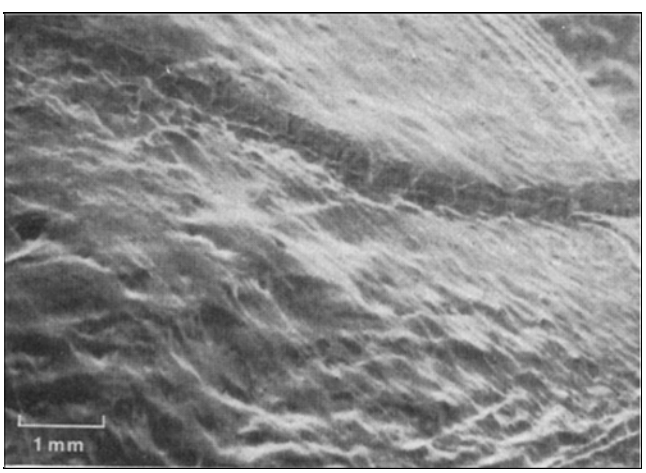


**Figure 1. RCF Initiation in AAR Class C Wheel Material**

Metallographic examinations like these suggest that shear cracking is responsible for RCF initiation once it exceeds fatigue-crack growth thresholds under the combined influence of normal and tangential forces.[5] In the subsurface region, crack initiation is the rate controlling step in RCF.

This study comprises two analytical procedures to provide an adequate numerical assessment of the subsurface RCF environment in railway wheels:

- Developing a three-dimensional FEM to predict stresses due to wheel-rail rolling contact.
- Using the results of the stress analysis to identify "hot spots" for fatigue initiation based on the Fatemi-Socie fatigue model.

## FINITE ELEMENT MODEL

In the FEM snapshot given in Figure 2, the FEM nodes denoted in white are subjected to the following boundary conditions. Due to symmetry, the displacements along the longitudinal axis of the axle are restrained at the end of the tributary axle corresponding to the middle of the actual axle; the rail is restrained at its ends on its longitudinal axis to also account for symmetry and continuity with the rest of the "infinite" rail. Portions of the bottom of the rail are fixed at the locations where the rail segment is assumed to make contact with the ties. Although, in reality, this latter is a contact boundary condition and, fixing the nodes is justified because the effects of the fixities of these nodes on the stress response of the wheel are minimal (due to St. Venant's principle).

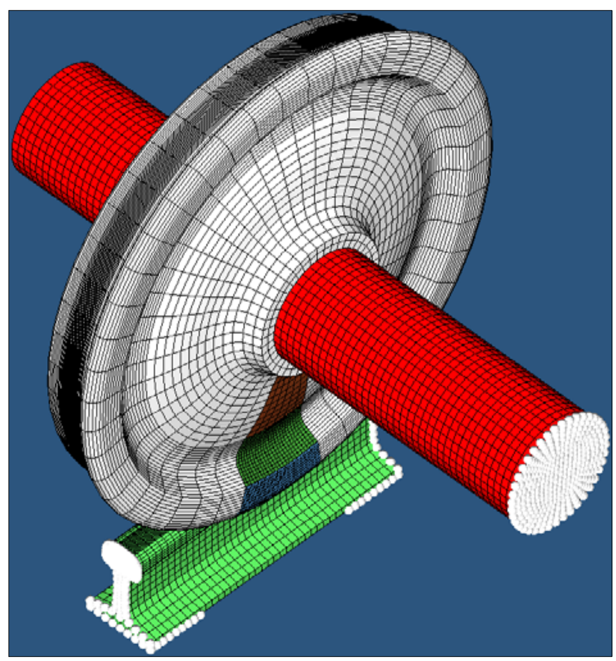

**Figure 2. Boundary Conditions of the FEM**

The stress-strain relationship for all the components in the FEM is defined using a plasticity model with both isotropic and kinematic hardening. The inclusion of both types of hardening in the plasticity model accounts for the phenomena of ratcheting, elastic shakedown, plastic shakedown, and the

Bauschinger effect. The yield criterion in the model uses the von Mises equivalent stress concept, in which a material point is considered to reach its yielding point when the second invariant of the deviatoric stress tensor at that point equals the square of the yield stress of the material.

The material properties and hardening parameters for pearlitic rail-wheel steel used in this analysis are:

- Modulus of elasticity, $E$ = 30,000 ksi,
- Poisson's ratio, $v$ = 0.29,
- Initial yield stress, $\sigma|_0$ = 60 ksi,
- Initial kinematic hardening modulus, $C_k$ = 1900 ksi,
- Kinematic hardening modulus decreasing rate, $\gamma_k$ = 3.12,
- Maximum change in the size of the yield surface, $Q_\infty$ = 22 ksi, and
- Yield surface development rate, $b$ = 3.97.

The friction coefficient specified for surface interaction is 0.3 and the tributary weight applied on the wheel is equal to 36 kips.

Figure 3 illustrates the nodes in wheel section that are being monitored during RCF analysis.

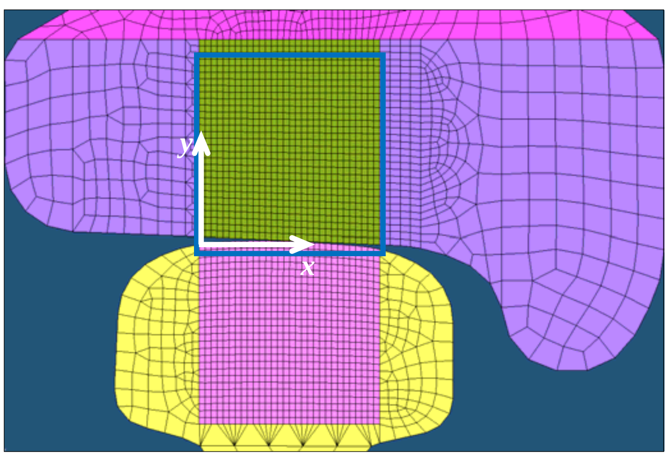


**Figure 3. Wheel Nodes that are Monitored for Fatigue Index Evaluation Enclosed in a Blue Box**

## FATIGUE ANALYSIS USING FATEMI-SOCIE FATIGUE MODEL

The basis of the Fatemi-Socie model is that the irregular shapes of crack surfaces produce friction forces that oppose shear deformations along the crack's plane.[1] This mechanism limits crack growth, thereby increasing the fatigue life of the material. If tensile stresses normal to the plane of the crack are present, they reduce the normal forces on the crack surfaces, thereby reducing the friction forces acting on the crack faces. If this reduction in the friction forces takes place, the crack tips must carry a greater fraction of the shear forces, which is assumed to favor the growth of the crack (Figure 4).

The Fatemi-Socie model accounts for the interaction between cyclic shear strain amplitude and normal stress at a particular material point on a particular plane during a cycle of load. The normal stress across a plane accounts for the influence of friction.

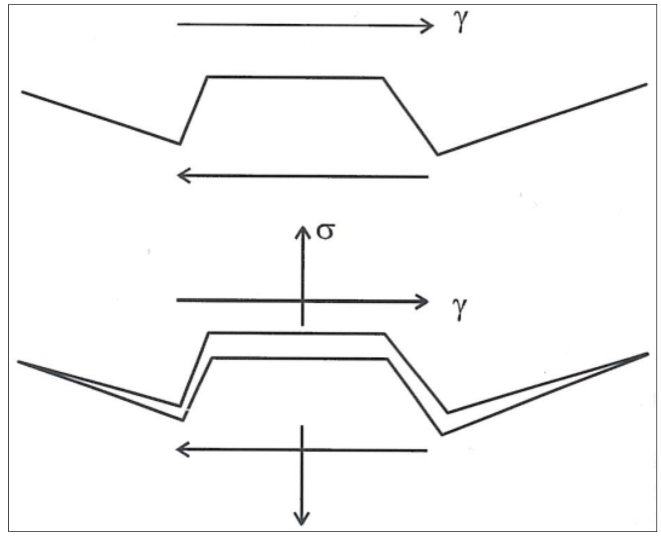


**Figure 4. Physical Basis of the Fatemi-Socie Fatigue Model**

The coefficient term used to include the influence of normal stress on Fatemi-Socie fatigue criterion is called the normal coefficient (η) in this study. It is material dependent and, for pearlitic rail/wheel steel, it is determined by a regression analysis of a set of fatigue life data from previous studies.[2-5]

The chosen value of η is the one that gives the best linear fitting of a log-log plot between the Fatemi-Socie fatigue index and fatigue life (Figure 5).[6]

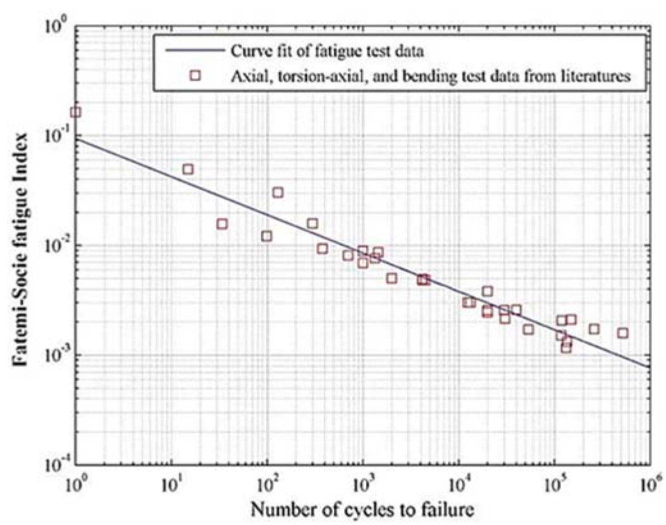


**Figure 5. Fatemi-Socie Fatigue Index Correlation with the Number of Cycles to Failure for a Pearlitic Rail Steel (η = 1)**

## RESULTS

For each node in the green box of Figure 3, the Fatemi-Socie fatigue index is calculated from a stress and strain tensor history for all selected planes. Among those planes, contours of the largest fatigue indices for different normal coefficients (η) are illustrated in Figures 6–8.

For pearlitic rail-wheel steel (η=1), the value of y = 0.15 inch corresponds to a fatigue-crack initiation depth of about 0.12 inch, which is consistent with the findings of previous research.[2-6]

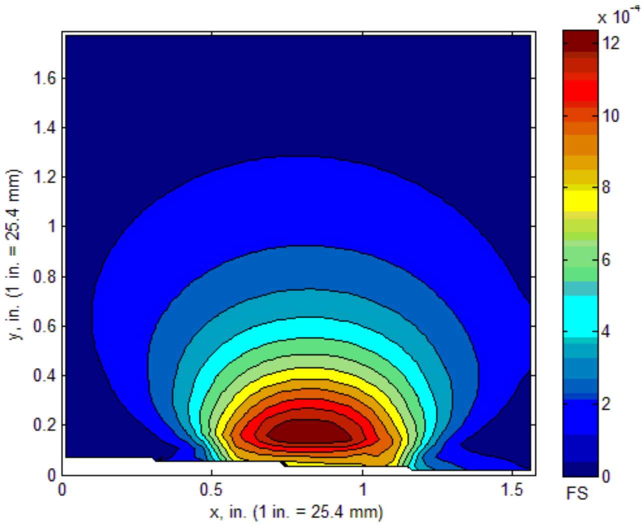


**Figure 6. Maximum Fatemi-Socie Fatigue Index Contour for η = 0**

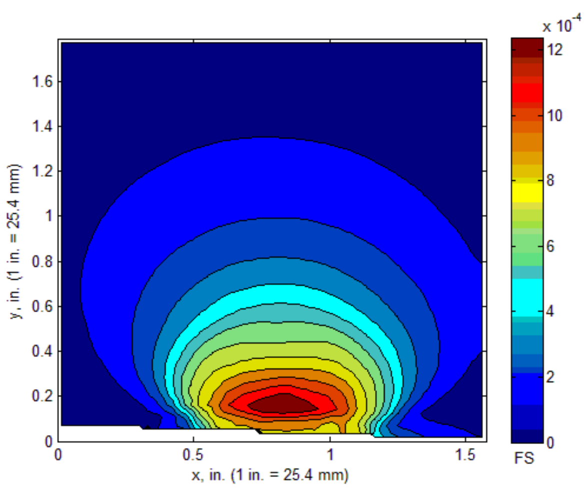


**Figure 7. Maximum Fatemi-Socie Fatigue Index Contour for η = 1**

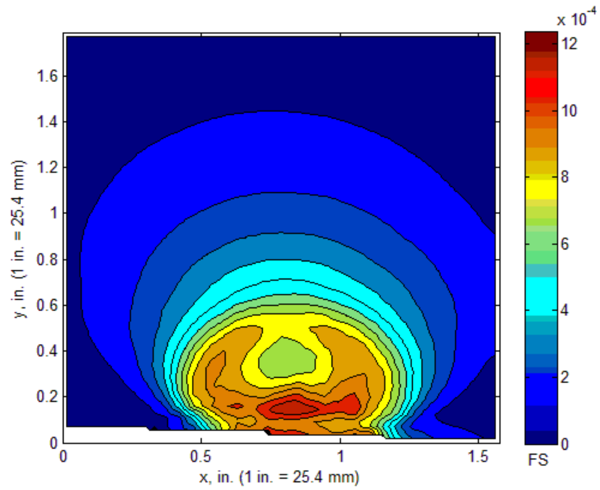


**Figure 8. Maximum Fatemi-Socie Fatigue Index Contour for η = 3**

## Future Work

The model was developed to analyze subsurface fatigue of wheels. It is being used to develop improved performance wheel designs and materials under the Association of American Railroads' Strategic Research Initiatives Program. The model also has the capabilities to evaluate railhead fatigue.

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