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Modeling of Shattered Rim Wheel Failure Mode

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Summary

Cracks in wheel rims were analyzed using computer simulation and fracture mechanics to quantify the circumstances necessary for the development of the shattered rim wheel failure mode. The work was conducted as part of the Association of American Railroads' (AAR) Strategic Research Initiatives Program to prevent wheel failures. The methodology developed in this study can help to predict whether a given set of parameters, such as wheel load, rim thickness, crack size, crack depth, and residual stress state can lead to a shattered rim failure.

The findings of the study show the combination of AAR requirements for ultrasonic testing of wheels and wheel condemning limits for rim thickness and impact loads are set at appropriate levels to minimize the number of shattered rim wheel defects. Large wheel loads, a thin rim, and a relatively large defect are necessary to initiate the cracking that results in a shattered rim. In general, the as manufactured residual stress is beneficial and service-induced residual stresses are detrimental.

Multiple values of wheel rim thickness, residual stress state, load magnitude, crack size, and crack radial depth were parametrically modeled to evaluate likely scenarios for the initiation and growth of shattered rim cracks. Fatigue crack growth rate testing funded by a cooperative Federal Railroad Administration research program enabled the results of the modeling to be applied to the measured performance of wheel steel. A total of 2,016 parametric computer simulations were conducted while varying the following inputs:

- Rim thickness from 1.5 inch to 0.6875 inch
- Vertical wheel load from 50,000 pounds to 200,000 pounds
- Crack size from 0.039 inch to 0.125 inch
- Crack depth from 0.125 inch to 1 inch below the tread surface
- Residual stress state
    - No residual stress
    - As-manufactured residual stress
    - Residual stresses developed due to both the manufacturing process and the on-tread braking for 60 minutes with a thermal load of 45 horsepower as the initial stress

Shattered rim failures are the result of large subsurface fatigue cracks that propagate roughly parallel to the wheel tread surface. These cracks generally initiate from voids or inclusions under a very high wheel load, such as an impact load, and can propagate under regular service loading.

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INTRODUCTION

The authors of this *Technology Digest* (TD) used computer simulation and fracture mechanics to quantify the circumstances necessary for the development of shattered rim cracks in wheels. This work was conducted as part of the AAR's Strategic Research Initiatives Program to prevent wheel failures. Multiple values of wheel rim thickness, residual stress state, load magnitude, crack size, and crack radial depth were parametrically modeled to evaluate likely scenarios for the initiation and growth of shattered rim cracks.

BACKGROUND

Shattered rim failures are the result of large subsurface fatigue cracks that propagate roughly parallel to the wheel tread surface.[1,2] These cracks generally initiate from voids or inclusions under a very high wheel load, such as an impact load, and can propagate under regular service loading.[3]

Residual stress in wheel rims is one of the important factors that can significantly affect the crack growth rate, and thereby affect the wheel failure life. Residual stress develops in wheel rims during both the manufacturing process and on-tread braking under service conditions. Beneficial compressive residual hoop stress develops in the wheel rim during the manufacturing process. This compressive stress inhibits crack growth and increases the wheel failure life.[4,5,6] Detrimental tensile residual hoop stress can develop during on-tread braking. This tensile stress increases crack growth rate and decreases the wheel life.[7] The final residual stress distribution in the wheel rims is the complex combination of these two types of residual stresses.

MODEL

The shattered rim cracking in railroad wheel rims is modeled using elastic-plastic finite element analysis and fracture mechanics. The analysis is performed in two steps: full model analysis and sub model analysis. In the full model analysis, the stress response in the wheel rim under a mechanical load on the tread surface along the taping line is estimated using an elastic-plastic finite element analysis. The residual stress distribution is included as the initial stress for the full model analysis. Detailed explanation of the development of the residual stress distribution can be found in a previous report.[8]

The full model analyses provide the required boundary conditions to the sub model analyses. The sub model consists of a half inch cubic block with an embedded circular mathematically sharp crack. This block is considered as the shattered rim crack initiation site. Shattered rim cracking can be simulated by applying the full model stress results at any location within the rim as the inputs to the sub model. This sub model analysis calculates the equivalent stress intensity factor ranges along the crack front. Figure 1 shows the full model and Figure 2 shows the finite element details of the sub model.

In order to prevent crack propagation, the stress intensity factor range at the crack tip should be less than the threshold stress intensity factor range. In this analysis, it is assumed that the shattered rim crack will not propagate when the equivalent stress intensity factor range (ΔK_{eq}) at the crack tip is less than the mode I threshold stress intensity factor range. Early simulation results found that a crack orientation of 20 degrees to the tread surface is critical. This finding is in good agreement with the values reported in the literature,[9] and therefore, cracks oriented at an angle of 20 degrees to the tread surface are considered in this study.

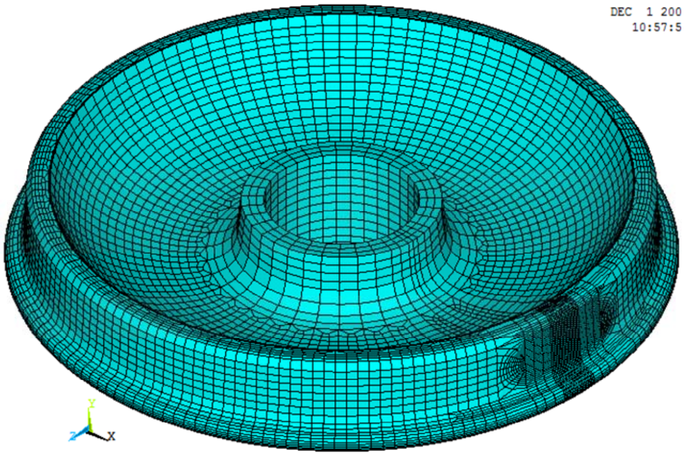

Figure 1. Full Model

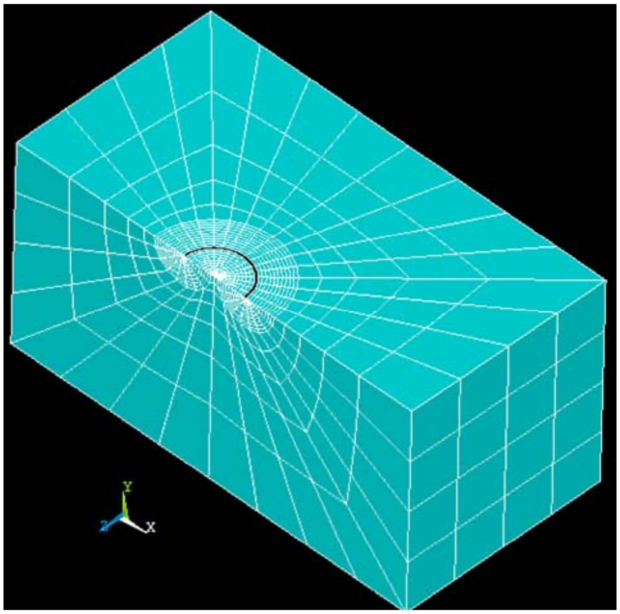

Figure 2. One quarter of the sub model showing the details of the mesh close to the embedded circular crack (X – axial direction of the wheel, Y – radial direction of the wheel, Z – along the rail)

The mechanical loads on the tread surface are applied over a Hertzian contact area centered along the taping line, and shattered rim cracks are considered directly below the load location. The contact area parameters depend on the wheel geometry and load magnitude.

The stress intensity factor values of the sub model under remote mode I, mode II, and mode III loading conditions were calculated using the finite element model and compared to those of the stress intensity factor handbook values available in the literature to verify the sub model.

The stress intensity factor values at a circular crack tip subjected to remote loading conditions under different modes are given by Equations 1-3.[10]

$$K_I = \frac{2}{\pi}\sigma\sqrt{\pi a} \qquad (1)$$

$$K_{II} = \frac{4}{\pi(2-\nu)}\sigma\sqrt{\pi a} \qquad (2)$$

$$K_{III} = \frac{4(1-\nu)}{\pi(2-\nu)}\sigma\sqrt{\pi a} \qquad (3)$$

where K_I, K_{II}, and K_{III} are mode I, mode II, and mode III stress intensity factor values, σ is the applied remote stress, ν is the Poisson's ratio, and *a* is the half-crack size (radius, in this case). The finite element sub model analysis was performed assuming the following parameters: $\sigma = 10$ ksi, $\nu = 0.3$, and $a = 0.04$ inch.

The finite element analysis estimated the K_I, K_{II}, and K_{III} values as 2.28 ksi√in, 2.66 ksi√in, and 1.83 ksi√in, respectively. The corresponding values calculated using Equations 1-3 are 2.26 ksi√in, 2.65 ksi√in, and 1.86 ksi√in, respectively. Because the estimated stress intensity factor values almost equal the literature values, the finite element sub model was considered verified.

PARAMETERS

Railroad freight car wheels with a nominal 36-inch diameter are considered in this study. The full model analysis is performed on a new, single-wear wheel with a rim thickness of 1.5 inch and thinner rim wheels with rim thicknesses of 0.875 inch and 0.6875 inch. Because the rim thicknesses 0.875 inch and 0.6875 inch correspond to the AAR and the Federal Railroad Administration (FRA) condemning rim thickness limits respectively, these values are considered in this paper.

Three different residual stress states were modeled: (1) no residual stress as the initial stress, (2) as-manufactured residual stress as the initial stress, and (3) residual stresses developed due to both the manufacturing process and the on-tread braking for 60 minutes with a thermal load of 45 horsepower as the initial stress. At the tread surface near the tapeline, residual hoop stress was 0 ksi for the no residual stress case, -34 ksi for the as-manufactured residual stress case, and 32 ksi for the on-tread braking case.

This TD considers wheel loads ranging from 50,000 pounds to 200,000 pounds with an increment of 25,000 pounds. Nominal wheel load for a 36-inch diameter wheel is 35,750 pounds. Wheels are condemnable under AAR rules at 90,000 pounds impact load and are required to be removed from service at 140,000 pounds impact load, but larger impact loads have been recorded. Additionally, gaps in the rail running surface such as crossing diamonds can produce large impact loads in wheels.

Embedded cracks of sizes 0.039 inch, 0.063 inch, 0.088 inch, and 0.125 inch were modeled. The rationale in selecting these crack sizes is because 0.039 inch is the current practical limit of ultrasonic testing equipment, 0.063 inch represents the current AAR maximum allowable defect limit, and 0.088 inch and 0.125 inch represent historical AAR maximum allowable defect sizes.

In this model, the shattered rim crack is always considered directly below the load location (over a Hertzian contact area centered along the taping line) at depths ranging from 0.125 inch to 1 inch below the tread surface with an incremental depth of 0.125 inch.

RESULTS

This study performed a total of 2,016 simulations. Figure 4 is an "effects plot" showing the overall relative effect of each parameter considered in this analysis. The data in this plot is generated by averaging the stress intensity factor results from all of the analyses in which one variable is held constant. For example, of the 2,016 total analyses conducted, 504 of these were conducted with a crack size of 0.039 inch. Averaging the stress intensity factor results from these 504 analyses gives a result of 1.08 ksi-√in. Likewise, the average stress intensity factor from the 504 analyses with a crack size of 0.063 inch gives a result of 1.35 ksi-√in. While this type of plot does not capture all of the interactions occurring between variables, it does give a broad view of the relative importance of each variable.

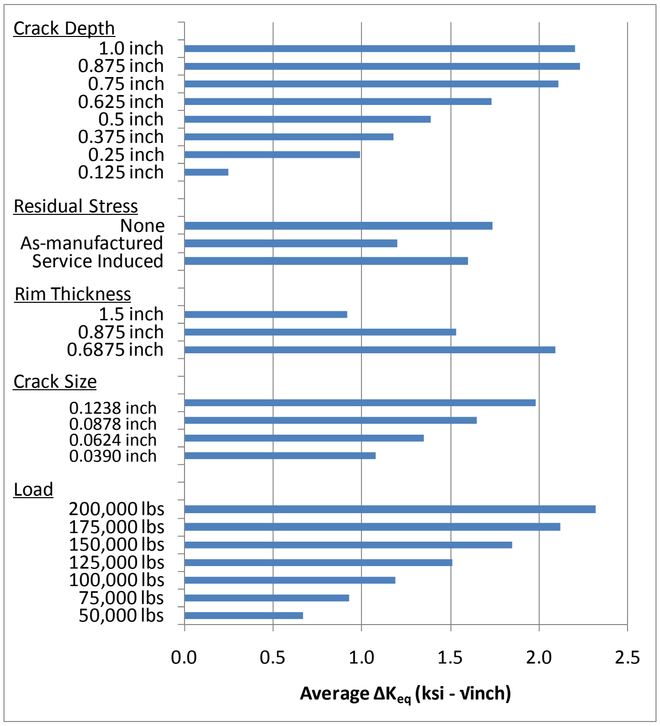

Figure 4. Overall Relative Effect of Each Parameter

In this analysis, it is assumed that the shattered rim crack will propagate when the equivalent stress intensity factor range exceeds the threshold stress intensity factor range. Fatigue crack growth rate testing was recently conducted as part of the FRA's Wheel Research Project. Results indicate that cracks will grow with an equivalent stress intensity factor range as low as 4.06 ksi√in and an R-ratio of 0.5. R-ratio is the ratio between the maximum and minimum applied stress in each loading cycle. Modeling results predict that the wheel environment typically provides an R-ratio between 0.2 and 0.0. Fatigue crack growth rate test results for R-ratios of 0.2 and 0.05 showed critical equivalent stress intensity factor ranges of 5.13 ksi√in and 5.88 ksi√in, respectively.

Considering a wheel with no residual stress (R-ratio = 0), the equivalent stress intensity factor range at the crack tip exceeded 5.88 ksi√in in the model only when the load was at least 175,000 pounds, the rim was 0.875 inch or thinner, and the crack size was 0.088 inch or greater. For wheels with residual stress from manufacturing (0 < R-ratio < 0.2), the equivalent stress intensity factor range at the crack tip exceeded 5.13 ksi√in in the model only when the load was at least 175,000 pounds, the rim thickness was 0.6875 inch, and the crack size was at least 0.088 inch.

Considering wheels with residual stress from manufacturing and service braking (0 < R-ratio < 0.2), the equivalent stress intensity factor range at the crack tip exceeded 5.13 ksi√in in the model only when the load was at least 150,000 pounds, the rim thickness was 0.6875 inch, and the crack size was 0.088 inch or greater. Residual stress states with stress magnitude larger than those modeled could provide a higher R-ratio, and thus a lower critical equivalent stress intensity factor range.

The equivalent stress intensity factor range at the crack tip did not exceed the threshold value (i.e., defects would not be expected to propagate into shattered rims) for all cases in which any of the following was true:

- The wheel/rail load was less than 150,000 pounds
- The defect size was less than 0.088 inch
- The rim was thicker than 0.875 inch

CONCLUSIONS

The authors simulated shattered rim cracking in railroad wheels using elastic-plastic finite element analysis and fracture mechanics. The residual stresses developed during both the manufacturing process and under service conditions were estimated. The methodology developed in this study can help to predict whether a given set of parameters, such as wheel load, rim thickness, crack size, crack depth, and residual stress state can lead to a shattered rim failure.

The findings of this study are summarized as follows:

- Large wheel loads are necessary to initiate shattered rims. The relationship between wheel load and equivalent stress intensity factor range is approximately linear.
- The likelihood of shattered rim initiation increases with increasing in crack size. The ΔK_{eq} at the crack tip is proportional to the square root of the crack size.
- The likelihood of shattered rim initiation increases with decreasing rim thickness. A nonlinear relationship exists between the rim thickness and the ΔK_{eq}.
- In general, the as-manufactured residual stress is beneficial and service-induced residual stresses are detrimental. Consideration of as-manufactured residual stresses decrease the ΔK_{eq} at the crack tip by about 30 percent compared to that of no residual stress state. Consideration of service-induced residual stresses increase the ΔK_{eq} at the crack tip by about 30 percent compared to that of as-manufactured residual stress state.
- Critical depth for shattered rim cracking ranges from 0.75 inch to 1.0 inch below the tread surface. This finding is in good agreement with field observations.

These findings show the combination of AAR requirements for ultrasonic testing of wheels and wheel condemning limits for rim thickness and impact loads are set at appropriate levels to minimize the number of shattered rim wheel defects.

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