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# Modeling of vertical split rim cracking in railroad wheels

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ABSTRACT

Vertical split rim cracking, due to rapid unstable propagation of a shallow sub-surface crack parallel to the front rim face, is one of the dominant mechanisms of railroad wheel failure. Wheel impact load is believed to be a trigger for this unstable crack growth. This rapid crack growth rate depends on several factors, such as wheel geometry (wheel diameter and rim thickness), load magnitude, load location, residual stresses in the rim, worn tread profile, and material defects in the rim (size, shape, location, and orientation). This paper develops a computational methodology to investigate the effect of these parameters on vertical split rim cracking, using finite element analysis and fracture mechanics. Vertical split rim cracking is modeled using a three-dimensional, multi-resolution, elastic–plastic finite element analysis. Material defects are modeled as mathematically sharp cracks. Wheel impacts are simulated by applying high mechanical loads on the tread surface. The residual stresses and wheel wear effects are also included in modeling vertical split rim cracking. The proposed computational methodology can help to predict whether a vertical split rim failure might be triggered for a given set of parameters, such as load magnitude, load location, wheel diameter, rim thickness, residual stress state, crack size, crack location, and crack orientation.



## 1. Introduction

In recent years, vertical split rim failure has become one of the dominant railroad wheel failure mechanisms observed in North America [1]. This failure is brittle in nature and occurs due to rapid unstable crack growth with a piece of either front or back of the wheel rim breaking off from the wheel [2].

### 1.1. Vertical split rim cracking

The vertical split rim crack can originate from existing tread damage (such as shell or spall cracks) or from a very shallow sub-surface crack [3]. The unstable propagation of a vertical split rim crack is believed to be triggered under wheel impact loading. Wheel impact loads can occur due to surface defects on the tread surface or due to track conditions, such as crossing diamonds [1]. This paper focuses on developing a computational methodology to model the vertical split rim cracking.

In the literature, very limited research has been published related to the vertical split failure in railroad wheels. Lonsdale et al. [1] have performed both computational and experimental work to understand the stress levels in the wheel rim under an impact load. This paper found that the load location close to the front rim face generates higher stresses in the rim. The finite element results estimated the axial stresses on the wheel tread surface along the taping line as tensile stresses with magnitudes of 200 MPa (29 ksi) and 393 MPa (57 ksi) for wheels with rim thicknesses 38.1 mm (1.5 in.) and 22.225 mm

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(0.875 in.) respectively, under an impact load of 890 kN (200 kips) at 25.4 mm (1 in.) from the front rim face. However, drop tests with a load of 890 kN (200 kips) on a wheel with a rim thickness of 31.75 mm (1.25 in.) did not trigger a vertical split rim failure.

Stone et al. [2] have discussed the effects of residual stress, wheel geometry, and loading characteristics on vertical split rim failure. This paper suggested that the vertical spilt rim failure occurs due to high bending stresses developed in the rim. These high bending stresses can develop due to track conditions (wheel riding over a curve) or due to wheel conditions (false flange and hollow tread). The field inspection of 24 broken wheels failed due to vertical split rim cracking revealed that the failures were initiated from shell cracks at a depth of 2.5 mm (0.1 in.) below the tread surface and the rim thickness did not appear to a critical parameter in triggering this failure. The contribution of residual stress to the total stress for vertical split rim failure was calculated as approximately 15%. This paper performed a two-dimensional analysis using only bi-axial stresses and recommended a detailed three-dimensional finite element analysis for better understanding of vertical split rim failure.

A couple of Canadian derailment reports [4,5] mention vertical split head failures in rails as the cause of train derailments. The vertical split head failure mechanism of the rail appears to be similar to the vertical split rim failure of the wheel. However, wheels are different and more complex compared to rails due to difference in geometry, and the presence of braking and residual stresses. In these reports, it was mentioned that vertical split heads propagate very rapidly and fail suddenly without any warning. It was also mentioned that the high vertical loads (probably impact loads) are responsible for the vertical split head failures.

### 1.2. Residual stresses

Residual stresses are developed in the wheel rim during both the manufacturing process and under service brake loading conditions. These residual stresses can affect the resultant stresses in the rim under rolling contact loading, and thereby affect the vertical split rim crack growth rate. The axial residual stress developed in the rim during the manufacturing process has been observed to increase the vertical split rim crack growth rate [6]. This axial residual stress can increase the mode I stress intensity factor range at the crack tip (crack parallel to the front rim face), leading to unstable crack growth when the stress intensity factor range at the crack tip is greater than the fracture toughness. The on-tread thermal brake loading under service conditions also develops additional residual stresses and can contribute to the vertical split rim failure.

In the literature, several researchers estimated the residual stresses developed during both the manufacturing process and during the thermal brake loading under service conditions using thermal-structural finite element analyses. Dedmon et al. [7] have estimated the as-manufactured residual stresses in a freight car locomotive wheel rim using a two-dimensional finite element model. The maximum compressive hoop stress in the rim was estimated as −606 MPa (−87.9 ksi). Gordon et al. [8–10] have estimated both as-manufactured and service-induced residual stresses in passenger car wheels using a two-dimensional finite element model. The maximum compressive as-manufactured hoop stress in the rim was estimated as -200 MPa (−29 ksi). This study found that the hoop stress at the tread surface reverses from compression to tension during the thermal brake loading under service conditions. The maximum tensile service-induced hoop stress in the rim was calculated as 350 MPa (51 ksi). Wang and Pilon [11] have estimated both as-manufactured and service-induced residual stresses in freight car wheels using a two-dimensional finite element model. The maximum compressive as-manufactured hoop stress in the rim was estimated as −180 MPa (−26.1 ksi) and the braking duration for stress reversal in the rim under service conditions was estimated as approximately 57 min. Liu and Perlman [12] have performed a study to compare the residual stresses estimated using a two-dimensional and a three-dimensional finite element models in passenger car wheels and found that the results from both models are in good agreement.

Most of the previous studies described above have estimated the residual stress distributions using a two-dimensional finite element model. In this paper, three-dimensional residual stress distributions are developed, considering both the manufacturing process and under service conditions, using decoupled thermal-structural finite element analyses. The estimated three-dimensional residual stress distributions are included as initial stresses for the three-dimensional vertical split rim failure analysis.

### 1.3. Wheel wear

Wheel wear, the process of surface material removal under service conditions, reduces the rim thickness and alters the tread profile. Since the contact stress in a wheel rim depends on the rim thickness and the tread profile, it is important to consider wheel wear. The two dominant types of wear in railroad wheels are adhesive wear and delamination wear. Adhesive wear occurs when thin flakes that are formed on the wheel surface adhere to the asperities on the rail and break off from the wheel. This type of wear is relatively mild and the debris consists of iron oxides and metallic iron. Delamination wear occurs when a surface crack kinks and propagates into the wheel surface and breaks off a piece from the wheel. This type of wear is very severe compared to the adhesive wear [14].

The wear models available in the literature can be classified into two types: energy transfer models and sliding wear models. Energy transfer models estimate the wheel wear (loss of surface material) as a function of energy dissipated in the contact patch. Sliding wear models estimate the wheel wear as a function of material hardness, sliding distance and the normal force [15]. The Archard wear model is one of the most well known wear models used to estimate the wear