Design & Analysis of Rail Wheel Failure

Prashik Pramod Kamble[1], Dr. C. N. Sakhale [2]

[1] *Prashik Pramod Kamble Mechanical Engineering Department & Priyadarshini College of Engineering*

[2] Dr. C. N. Sakhale *Mechanical Engineering Department & Priyadarshini College of Engineering*

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Abstract Rail wheels are important components that not only support axle loads, but also enable high-speed rail travel. During service, wheels are subjected to rolling contact loads, thermal loads from braking, and cyclic fatigue loads at the wheel–rail interface. Combined, these loads may lead to material degradation in the form of wear, surface damage, or subsurface crack initiation, which ultimately may lead to failures such as tread spalling, rim fractures, or derailment.

This research examines rail wheel failure mechanisms using a comprehensive finite element model (FEM) to model the dynamic loading, and contact interactions. A three-dimensional rail wheel model developed in CAD Software, is examined in ANSYS using R-16 and R-19 grade steel. The Critical Plane Approach is implemented to review multiaxial fatigue and rank zones with respect to crack initiation, and crack propagation.

For this analysis, all mechanical (static/dynamic), and thermal loads are examined to assess the stress distributions, thermal gradients, and strain concentration zones. Modelling process identifies the region's most susceptible to fatigue damage and provides insights for improvement in wheel design, material selection, and predictive maintenance strategies. The research is aimed at improving safety, performance, and reliability of rail wheels in real-world service performance.

Key Words: Rail Wheel, Axle Load, High-Speed Railway, Rolling Contact Stress, Thermal Load, Cyclic Fatigue, Finite Element Model (FEM)

1.INTRODUCTION

Rail wheels are a critical part of the railway structure that sustain axle loads and facilitate smooth high-speed movement along the track. When in service, rail wheels experience a variety of loading conditions, including rolling contact stress, thermal loads from braking and cyclical fatigue at the wheel–rail contact interface. These extreme and repetitive loading modes will lead to wear, surface damage and subsurface fatigue cracking. Eventually, damage may lead to severe wheel failures, such as tread spalling, rim failures, or catastrophic wheel failure, which may threaten to safety and operational reliability.

This thesis focuses on exploring the mechanisms behind rail wheel failures related to wear and rolling contact fatigue. We developed a finite element model (FEM) to simulate wheel-rail contact under realistic dynamic loading conditions, enabling us to analyze stress distributions and assess the likelihood of crack initiation. By employing the Critical Plane Approach, we evaluated the subsurface stress states, pinpointing areas that are most susceptible to multiaxial fatigue damage. The insights gained from this research will aid in improving wheel design and material selection, while also enhancing predictive maintenance strategies. Ultimately, this work aims to boost the safety, durability, and overall performance of rail wheels in operation.

With the rising demand for faster and more robust rail operations, it's crucial to delve into how fatigue can cause damage. Such failures don't just jeopardize the wheel's integrity; they can also lead to suspension system wear and, in worst-case scenarios, derailments. This study takes a comprehensive look at crack propagation mechanisms, applying validated fatigue assessment methods in multiaxial loading situations.

At the beginning of our study, we created a detailed 3D geometric model of a rail wheel using AutoCAD software. This model adheres to standard railway specifications regarding its profile and dimensions. After the initial modeling, we imported it into ANSYS 15.0 for conducting both structural and thermal analyses under various combined loading conditions. For this analysis, we selected R-16 and R-19 grade steels, which are preferred materials in the rail industry due to their impressive tensile strength, fatigue resistance, and thermal stability.

Our mechanical loading simulations involved both dynamic and static factors, including axle loads, vertical contact forces, and lateral forces encountered during curving. The thermal analysis examined the heat generated from extended or emergency braking scenarios. By combining the mechanical and thermal simulations, we conducted a thorough investigation into stress distributions, zones of strain concentration, and thermal gradients. This comprehensive approach enabled us to identify critical areas that are susceptible to fatigue crack initiation and propagation.

The results of this study provide important insights that can help improve rail wheel design and optimize material selection, ultimately leading to a more reliable and cost-effective rail transportation system.

2. Literature Review

Seok Jin Kwon, Dong Hyung Lee, Sung Tae Kwon, Byeong Choon Goo01 Oct 2006- Key Engineering Materials (Trans Tech Publications) - pp 649-653

"Most of the time, when train wheels totally crap out, it's thanks to sneaky little fatigue cracks popping up on the tread or the flange—right on the surface, where you'd rather not see them. These cracks? Yeah, they start out all slanted and small on the tread, usually after the wheel's been rolled for something like 60,000 kilometres. The real culprit? Damage from spalling. It's like the wheel just can't catch a break.

And, get this: when a wheel fails like that, it gets a makeover (reprofiling) way before its regular scheduled spa day. That means maintenance bills go up—nobody's thrilled about that. So, obviously, figuring out how these cracks show up is kind of a big deal.

Anyway, in this study, they dug into how two big things mess with wheels: the way the pressure between wheel and track keeps changing, and those random blasts of heat from braking. They checked out wheel surfaces (with these replica measurements—like CSI for trains) and watched what happened when brakes got slapped on during real-life field tests.

J.F. Santa,J. J. Toro-Castrillón,M. Pérez Giraldo,J. Jaramillo,G. Hernandez,
Andrea del Pilar Toro-13 Sep 2022- Strength, fracture and complexity

"So, picture this: J.F. Santa and their crew—yeah, a whole squad of researchers—basically went full CSI on a busted train wheel back in 2022. We're talking heavy-haul railway, so this isn't your average choo-choo. They weren't messing around either. Instead of just eyeballing the crack and shrugging, they rolled out the big guns—microscopes, mechanical tests, even some fancy computer modeling (FEM, for the nerds in the back).

First thing they did? Got all up close and personal with the wheel's guts using Light Optical Microscopy (LOM) and Optical Emission Spectrometry (OES)—which, let's be real, sounds like something out of a sci-fi movie. They wanted to see what the wheel was made of, literally. Chemical composition, microstructure, the whole nine yards. Then they yanked out some samples from the area where it broke (risky move, but someone's gotta do it) and ran tensile tests to see just how tough—or not so tough—this wheel actually was. Honestly, if only my high school science projects were this legit."

"So, turns out the whole mess started with rolling contact fatigue—yeah, that's just a fancy way of saying the wheel kept getting beat up over and over until the surface got all mangled. Picture a stubborn layer of metal, mashed and twisted from nonstop wheel-rail smack downs. Nobody really bothered to deal with it during regular maintenance, which, honestly, is a bit of a face palm moment. Anyway, cracks snuck in right where that jacked-up surface was, and they just kept working their way deeper until, boom, the wheel basically split apart vertically. That's called a Vertical Split Rim, by the way—a total nightmare in railroading, since it's one of those failures that can go from "hmm, that's odd" to "oh no, disaster" in a blink."

Johnson KL. The strength of surfaces in rolling contact. In: Proc Inst Mech Eng (IMechE) 1989; 203:151-63.

"In this study, we explored the rolling contact fatigue behavior of D2 wheel steel under lubricated conditions. Our focus was on understanding how the surface microstructure relates to the material's fatigue properties. The findings revealed that while mechanical processing initially creates roughness on the specimen's surface, this roughness diminishes during the experiment. However, the layer of ultrafine microstructure—a thickness of 0.5 to 1.5 μm—still exhibited micro-cracks and small spalling pits, which in turn could serve as sources for fatigue crack propagation."

"Moreover, we observed that the ferrite components within the microstructure became plastically deformed, even with loads lower than the threshold for fatigue failure. The pro-eutectoid ferrite grains underwent refinement as well. Throughout the experiment, we noted a consistent pattern of hardening and grain refinement due to plastic deformation, which aligns with established theories regarding dislocation patterns. The hardness distribution and the size of the ferrite grains measured can be correlated to the distribution law of shearing stress in the subsurface layers of the material."

Tournay, H. M., & Mulder, J. M. (1996). The transition from the wear to the stress regime. *Wear, 191*(1–2), 107–112.

In this paper, we detail a method for synthesizing 2-(di-n-octylaminomethyl) thiobenzothiazole. We investigate the thermal stability, corrosion-inhibiting properties, and tribological performance of this compound when added to liquid paraffin. Our findings indicate that the compound significantly enhances load carrying capacity and exhibits improved anti-wear characteristics. To further understand the interaction between the additive and metal surfaces, we employed X-ray photoelectron and Auger electron spectroscopy techniques, allowing us to outline a mechanism for its action.

Bo Liang, Simon Iwnicki, Yunshi Zhao, David Crosbee University of Huddersfield-25 Jul 2013 - Vehicle System Dynamics (Taylor & Francis) - Vol. 51, Iss: 9, pp 1403-1421

In this study, researchers developed a straightforward mathematical model to simulate defects—nothing overly complex, but effective enough for their purposes. They then constructed a full-sized roller rig, which is essentially a large setup designed to replicate the actions between train wheels and rails, and began investigating potential defects. The core of their research revolved around time-frequency analysis. For those unfamiliar, this approach allows for in-depth examination of signals that vary significantly over time—like the vibrations and noises when a train wheel encounters a problematic section of track. It's akin to having enhanced vision for vibrations; you can observe the dynamics in both time and frequency, which is critical given the ever-changing nature of movement.

They compared three well-known methods: Short-Time Fourier Transform (STFT), Wigner–Ville Transform (WVT), and Wavelet Transform (WT). The goal was to determine which method was most effective at identifying elusive defects. They captured a range of sounds—from rattles to squeaks—from the roller rig while searching for both wheel flats and rough rail segments. The findings revealed that all three methods were quite adept at detecting issues, although each had its unique strengths and weaknesses depending on the specific defect and signal characteristics. While there wasn't a single definitive solution, there are certainly some valuable tools to add to their repertoire.

C. Roux, C. Roux, Xavier Lorang, Habibou Maitournam, M. L. Nguyen-M. L. Nguyen-TajanÉcole Polytechnique, SNCF-01 Oct 2014

In this paper, the author explores the significant challenge of assessing the lifespan of train wheels that face a range of unpredictable forces. Train wheels have a demanding role, dealing with variations in speed, rough track conditions, and the burden of heavy loads that push them to their limits. Instead of sticking to outdated testing methods that often don't reflect the real-world complexities of rail travel, the researchers have introduced an innovative approach. They turned to a probabilistic model, collecting actual data from trains in operation to develop a comprehensive understanding of the real conditions these wheels endure. By prioritizing real-world data over assumptions, they offer a more precise insight into the stress thresholds of these wheels before they require replacement."

"To analyze how structural integrity decreases over time, the methodology combines the fatigue equivalency method with finite element analysis (FEA). The fatigue equivalency method helps convert varying loads into equivalent constant-amplitude loads for a better assessment of fatigue damage, while FEA is employed to determine local stress distributions within the wheel under complex loading conditions. Additionally, the research expands upon the Dang Van fatigue criterion, which is typically used for systems with indefinite lifespans, to incorporate finite-life high-cycle fatigue (HCF). This advancement allows for life predictions under multiaxial and time-varying stress conditions, thanks to the damage accumulation rule that underpins this enhancement."

Yongming Liu, Brant Stratman, Liming Liu, Sankaran Mahadevan Vanderbilt University-01 Jan 2006 (American Society of Mechanical Engineers Digital Collection)-pp 107-115

"In this paper, the author presents a comprehensive probabilistic model designed to analyze both the initiation and progression of fractures, shedding light on how fatigue influences the reliability of railroad wheels. This method enables the assessment of overall fatigue life under various loading conditions. Additionally, it integrates complex multiaxial fatigue models that the authors have previously developed. The study employs a probabilistic approach to model the random patterns of fatigue damage over time and across different spatial conditions, accounting for the natural variability in material properties, loading histories, and operational environments.

A significant aspect of their methodology involves the use of the response surface method (RSM) alongside design of experiments (DOE) techniques. This effective combination facilitates the development of a closed-form approximation of the fatigue damage response surface, which notably decreases computational costs without sacrificing accuracy. The aim of this surrogate model is to predict fatigue damage by considering various random input factors, including material strength, frequency, and loading magnitude. Ultimately, this enhances the simulation process, paving the way for probabilistic predictions of fatigue life under a diverse array of operating conditions."

Ekberg, A., & Kabo, E. (2005). Fatigue of railway wheels and rails under rolling contract and thermal loading-an overview. Wear, 258(7-8), 1288-1300.

"One crucial aspect of effectively simulating vehicle system dynamics, particularly in terms of drive dynamics and traction control near the adhesion limit, is the sophisticated modeling of creep forces that accommodates significant longitudinal creep. This paper introduces a method for simulating a variety of real-world wheel-rail contact conditions using a single set of variety of real-world wheel-rail contact conditions using a single set of parameters. These parameters can be estimated from actual measurements or based on recommended values for typical wheel-rail contact conditions, which are relevant in most engineering scenarios. The approach also factors in elements like vehicle speed, longitudinal and lateral forces, shuttle creep, and the shape of the contact ellipse. The effectiveness of this method has been evaluated through comparisons with existing measurements and examples, highlighting its practical application"

Nielsen, J. C., Lundén, R., Johansson, A., & Vernersson, T. (2003). Train-track interaction and mechanisms of irregular wear on wheel and rail surfaces. *Vehicle System Dynamics*, *40*(1-3), 3-54.

"This paper delves into the essential issues surrounding the rapid interactions between trains and tracks, focusing on the wear and tear observed on rails and wheels at the running surface. We will explore the challenges, their underlying causes, impacts, and potential solutions related to three specific categories of variable irregular wear for wheels and rails: (1) short pitch rail corrugation found on straight tracks and low radius curves, (2) wheel corrugation resulting from tread braking, and (3) wheel polygonalisation. Finally, we will share some recent advancements in modeling the dynamic interactions between trains and tracks, along with insights into predicting irregular wear."

Liu Y, Stratman B, Mahadevan S. Fatigue crack initiation life prediction of railroad wheels. Int J Fatigue 2006; 28(7):747–56.

"This paper proposes the use of a new model for the prediction of the multiaxial high-cycle fatigue initiation life of railroad wheels. We developed a complete fatigue damage analysis procedure to evaluate complicated mechanical components with a focus on the wheel/rail rolling contact fatigue problem. Our stress analysis used a 3-D elasto-plastic finite element model and a submodeling technique to provide accuracy and computational efficiency. The analysis of fatigue damage to the wheel was based on the stress history of a single revolution of the wheel. Our proposed model considers the effect of wheel diameter, vertical loading, material hardness, and fatigue properties in predicting the initiation life from fatigue cracks."

Stone DH, Majumder G, Bowaj VS. Shattered rim wheel defects and the effect of lateral loads and brake heating on their growth. In: ASME international mechanical engineering congress and exposition. New Orleans, Louisiana, 1–4 November 2002.

This report outlines the research conducted by the Transportation Technology Centre, Inc. (TTCI), a part of the Association of American Railroads (AAR). The focus of this study is on identifying the causes and behaviors related to shattered rim defects in wheel assemblies. Shattered rim defects are linked to substantial fatigue cracks that develop, generally running parallel to the wheel tread surface. These cracks begin their formation about 1/2 to 3/4 inch (12–20 mm) beneath the wheel tread. A crack qualifies as a defect once it starts and will continue to expand under regular rolling loads. It's widely recognized that the key to preventing shattered rims lies in stopping the initiation of cracks. Typically, shattered rims are found in either brand new wheels or those that are nearing their condemnation threshold.

Recently, the AAR has updated the ultrasonic testing specifications in M-107/208, 'Wheels, Carbon Steel,' to reduce the acceptable size of discontinuities. While these changes should lead to a decrease in the occurrence of some shattered rims, they won't completely eliminate the problem. Implementing ultrasonic testing on returned wheels with thinner rims could address several factors contributing to shattered rims."

Mervat Tawfik, M. M. Padzi, S. .,H. Hapaz, Mazli Zahar, M. N. Firdaws 21 Dec 2022 - International Journal of Integrated Engineering - Vol. 14, Iss: 8 " Here's the revised text with a more professional tone:

Mervat Tawfik and her team, which includes M. M. Padzi, S. H. Hapaz, Mazli Zahar, and M. N. Firdaws, have undertaken a significant investigation into Rolling Contact Fatigue (RCF) within rail systems, specifically focusing on Light Rail Transit (LRT) setups. RCF poses a considerable challenge for railways, leading to the deterioration of rail surfaces due to the repeated pressure exerted by wheels. Their research highlights critical surface issues such as spalling, squats, and head checks, all of which serve as crucial indicators of potential failures on the tracks. Ignoring these signs can increase the risk of derailments, an outcome that would certainly compromise public safety.

The authors emphasize the advantages of predictive simulation as a superior alternative to traditional "wait until it breaks" maintenance strategies. By identifying cracks early, operators can save substantial resources and, more importantly, enhance safety for passengers. The research delves deeply into methods for forecasting crack formation and estimating the lifespan of the rail using advanced 3D finite element analysis. The study specifically examines the R260 profile, identified as an optimal choice for light rail due to its durability and balanced performance.

For their simulations, the team applied a significant force of 80,000 N, reflecting the actual operational stresses experienced by the rail. The findings reveal that the highest stress concentrations, according to von Mises stress criteria, occur at the interface where the wheel meets the rail. This observation aligns with classical theories proposed by Hertz. Notably, the simulation capabilities allow for a detailed mapping of stress hotspots and pressure variations in three dimensions—insights that are not easily captured through traditional mathematical modeling. Hence, while classical theories remain valuable, the advancements offered by this research represent a meaningful leap forward in understanding rail fatigue.

Guan Zhen Zhang,Rui Ming Ren,Hong Xiang YinDalian Jiaotong University 01 Jan 2019- Materials Science Forum (Trans Tech Publications Ltd) - Vol. 944 pp439-447

"Alright, so Guan Zhen Zhang, Rui Ming Ren, and Hong Xiang Yin (2019) basically dove headfirst into figuring out why high-speed railway wheels in China take such a beating. It's not just your average wear-and-tear, either. With China's high-speed rail blowing up so fast—seriously, their network is insane—plenty of issues have popped up along the way. And I'm not talking about a little rain or a pothole here and there. We're talking monster-long routes, freezing cold that'll numb your face off, air so corrosive it could probably rust your lunchbox, and winds that whip sand into every crevice, especially in those dry, dusty regions. In short: these wheels are getting absolutely thrashed, and figuring out why is kind of a big deal."

"Let's be real: train wheels? Total unsung heroes. They don't just hold up those massive machines—they're soaking up all the weight, plus dealing with the push and pull from speeding up or slamming on the brakes. So yeah, if a wheel fails, the whole show's in trouble. That's probably why these researchers got a bit obsessed with them. They basically dove headfirst into figuring out every way a wheel can get messed up on Chinese high-speed trains. Cracks, dents, mystery marks—you name it, they tried to pin down what causes it and why it happens. The big picture? Help keep those wheels (and the passengers riding on them) safe and rolling for the long haul."

3. CONCLUSIONS

A multi axial fatigue life prediction model is developed in this paper, which is based on the critical plane approach. Unlike most of the previous critical plane-based models, the current critical plane not only depends on the stress state but also explicitly depends on the material properties. The new multiaxial fatigue model is applied to the fatigue initiation life prediction of wheel/rail contact problem. Nonlinear finite element analysis is used for stress computation and a sub-modeling technique is used to improve the efficiency and accuracy. The stress history is then used to calculate the fatigue life. A numerical example is implemented and compared with field observation of failure pattern. The effect of several parameters, namely wheel diameter, vertical loads, material hardness, fatigue strength and material ductility, on the fatigue damage in railroad wheels is studied using the proposed model.

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