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A Fracture Mechanics Framework for Predicting Rail Rolling Contact Fatigue Under Varying Operational Conditions

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Abstract

Railway infrastructure is increasingly subjected to higher loads and traffic intensities, leading to degradation mechanisms such as wear and rolling contact fatigue (RCF). Existing damage prediction models, such as the Whole Life Rail Model (WLRM), rely heavily on empirical field data and lack general applicability across varying operational conditions. This paper presents a numerical fracture mechanics-based framework to reconstruct the RCF component of the WLRM. The approach separates fatigue crack formation into crack initiation and propagation, with emphasis on propagation modelled using Extended Finite Element Method (XFEM). Stress Intensity Factors (SIFs) are computed under moving wheel loads, enabling prediction of crack growth rates via Paris-law-based formulations. The resulting damage indices are used to reconstruct RCF curves and analyze the influence of key operational parameters, including axle load, friction coefficient, rail curvature, and train speed.

Keywords: rolling contact fatigue, rail cracks, fracture mechanics, finite element model, damage prediction, crack propagation

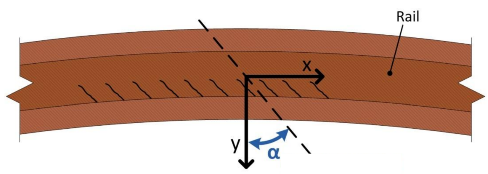
1 Introduction

Railway systems are critical infrastructure components subjected to increasing operational demands. The interaction between wheel and rail induces complex stress states, leading to surface degradation mechanisms such as wear and rolling contact fatigue (RCF). Among these, RCF-induced defects, particularly head checks, pose significant safety risks and increase maintenance costs [1, 2]. Several damage prediction models that include both failure mechanisms were developed in the past decades. These models include the ratchetting model [4], the Whole Life Rail Model (WLRM) [5], and a model in which the shakedown diagram is coupled with a crack propagation law [6]. Visakh Krishna et al. [7] reviewed all the RCF prediction models from the most high-fidelity models to the low-fidelity models and ranked them based on their complexity. They found that the WLRM is less complex, however, it has relatively lower accuracy due to its dependence on specific operating conditions. However, if this dependence is solved, it can be both accurate and efficient. The Whole Life Rail Model (WLRM) is used to estimate rail degradation by relating wear number to a damage index. This study aims to reconstruct the RCF component of the WLRM using fracture mechanics. By integrating numerical simulations with analytical crack growth laws, the research provides a generalized framework for predicting rail fatigue under varying operational conditions.

1.1 Rolling Contact Fatigue in Rails

Head checks are RCF-induced defects and commonly occur on curved tracks with radii less than 3000 m and in switches and crossings, because lateral contact forces and relative spin are generally high at these locations. They are primarily located around the gauge corner of the outer rail and are mostly found with multiple cracks together clustered at equal distances from each other, see Figure 1. These cracks appear at a shallow angle to the rail surface. When the crack grows, these angles can become steeper. These cracks can grow to a length of approximately 30 mm after which the probability of failure becomes very high [3]. In this study, the focus will be on the initiation and propagation of these cracks or so-called head checks.

(a) Severe head checks on rail surface



(b) Head checks in gauge corner of high rail

Figure 1: Examples of head checks on rail surface [3]

As mentioned before, one of the models to predict damage is the Whole Life Rail model (WLRM), developed by Burstow [5]. For a specific rail material and coefficient

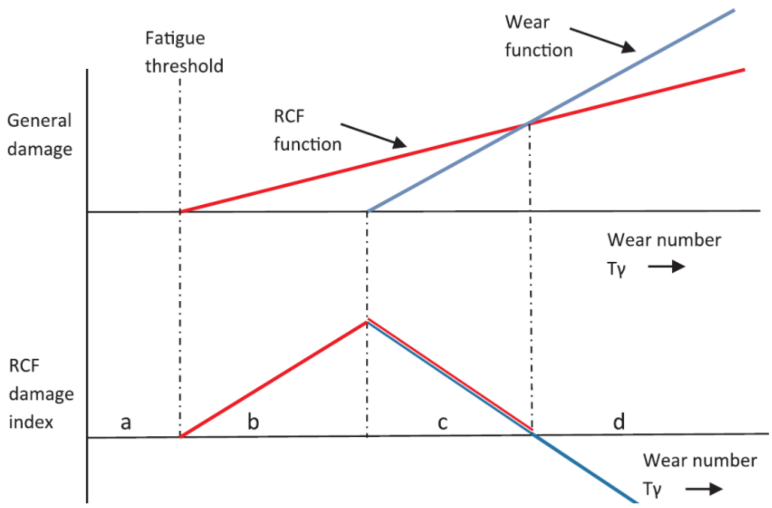


Figure 2: Wear and RCF as competing mechanisms of rail surface degradation [8]

of friction, the WLRM is depicted in Figure 2. By using the WLRM, for a certain contact condition represented by $T\gamma$, the damage index for that contact condition can be found. Based on that, the number of cycles to failure can be determined. The total damage of the rail can be calculated by the accumulated damage under the different contact conditions, as is given in the Palmgren-Miner rule:

$$D = \sum_{i=1}^{k} D_i = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{1}$$

where damage index value D_i for each scenario is the ratio between the actual number of cycles n_i with contact condition i and the total number of cycles to failure N_i for that condition. The fatigue life N_f can be described by the sum of the crack initiation life and the crack propagation life.

2 Crack formation

Fatigue cracks initiate as invisible microcracks in slip bands [9]. This crack nucleation occurs as soon as a cyclic stress exceeds the fatigue limit. After nucleation of the microcrack, the growth rate can still be slow, due to grain boundaries and other microstructure effects. Once the crack has grown away from the nucleation site, usually a linear growth is observed. Microcracks become macrocracks, and eventually the material will fail due to the cracks becoming too large. Schijve [9] divides the different phases into two periods: the crack initiation period and the crack growth period, see Figure 3. As both periods have different variables that influence their behaviour, it is important to differentiate between them. For example, surface conditions can have a significant effect on the initiation phase but will not significantly affect the growth period. As shown in Figure 3, both periods also have different parameters for the pre-

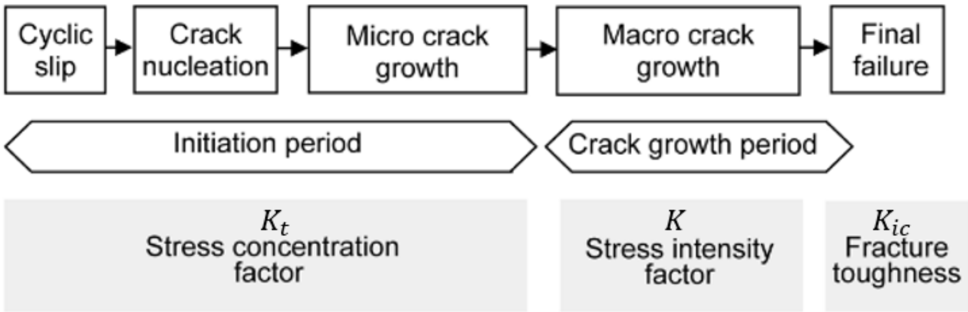


Figure 3: Different phases of fatigue crack formation [9].

diction of formation and growth. The stress concentration factor K_t is used to predict crack initiation, while the stress intensity factor K is used to predict the growth. The fracture toughness K_{ic} is the maximum value for the stress intensity factor; if that is reached, the crack will grow fast and unstable. Crack initiation is mainly determined by the material surface phenomenon, where crack propagation depends on the material as a bulk property and is not influenced by the surface phenomenon [9]. For crack initiation models, it is important to find the location where the crack initiates, as well as the number of cycles until a certain threshold is reached, and thus, the crack is initiated. Where cracks exactly initiate is often difficult to predict because crack initiation is inherently stochastic.

3 Crack growth

To predict the crack growth and the number of cycles until critical crack lengths are reached, crack growth models should be used. Most of these models are based on the Paris law [10]. In 1968, Paris and Erdogan [10] came up with an expression to express the crack growth rate ($\frac{da}{dN}$) using the stress intensity factor K.

$$\frac{da}{dN} = C(\Delta K)^n \tag{2}$$

where, C and n are empirical constants. This equation shows that if the stress intensity factor of a crack is known, the crack growth rate can be determined. Once the growth rate is known, the fatigue life can be calculated, assuming the critical crack length is known. Important to mention here is that the crack growth rate changes during crack growth. The Paris law only accounts for the linear growth of the crack.

By integrating the Paris Law, the number of load cycles until failure can be estimated. The problem, however, is that the stress intensity factor K depends on the crack length and geometry of the structure. For more complicated geometries, such as rail profiles, analytical integration is not viable. Therefore, crack propagation problems are often solved using computational methods [11]. Methods such as the boundary element method (BEM), the finite element method (FEM), the extended finite element method (XFEM), the element-free Galerkin method (EFGM) and combinations of these have been developed to model and simulate fatigue crack growth [12]. In particular, XFEM models are promising due to their ability to model a propagating crack without the need to remesh. Using these methods, the crack propagation is solved step-wise. For each step, the crack is advanced by a small increment, after which the number of cycles for the next increment is estimated using a crack propagation law (e.g., the Paris law). This process is repeated until a critical crack length or a critical stress intensity factor is reached.

4 Abaqus Model

The XFEM capabilities of Abaqus are used to perform the simulations within this study. Abaqus describes XFEM as an analysis which makes it possible to study crack growth along an arbitrary, solution-dependent path without needing to remesh the model. In this Abaqus XFEM implementation model, it is possible to either specify the crack location or let Abaqus determine the crack location based on maximum principal stress or strain. To perform this analysis, the user has to define the crack domain. For a three-dimensional part, this domain is defined as the cells in which the crack could propagate. The user also defines whether the crack can propagate or if it stays stationary. Finally, if the user chooses to define an initial crack location, a face has to be selected. This can be a face of the solid model, a face created by partition or a face from another planar part instance. A simplified drawing of the model, including its sleepers and the predefined crack, is shown in Figure 4. In this Figure, the orange half-circle represents the train wheel running over the rail.

The piece of rail modelled in Abaqus is based on the work of Rodriquez et al. [13]. Rodriquez showed that for a vertical load of 100 kN, the rail piece in the model needed to be at least 6000 mm. With shorter lengths, the numerical results would be influenced by the length of the rail. Because of this, a rail of the same length was taken as input for this model. Furthermore, the rail was constrained by elastic foundations with a stiffness of 75 kN/mm, which is similar to the stiffness used by Rodriquez and the average stiffness of a sleeper. These foundations were placed with 600 mm distance between each other to model the sleepers. Apart from the vertical direction, the rail was constrained in all other directions. At the top of the rail, laterally, in the middle, a semi-elliptical crack was placed between two sleepers, as this is a commonly used crack shape in XFEM modelling, see Figure 5.

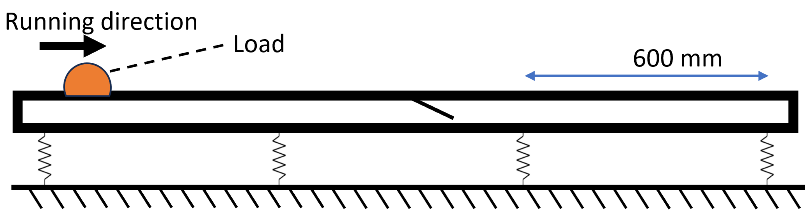


Figure 4: Simplified beam model

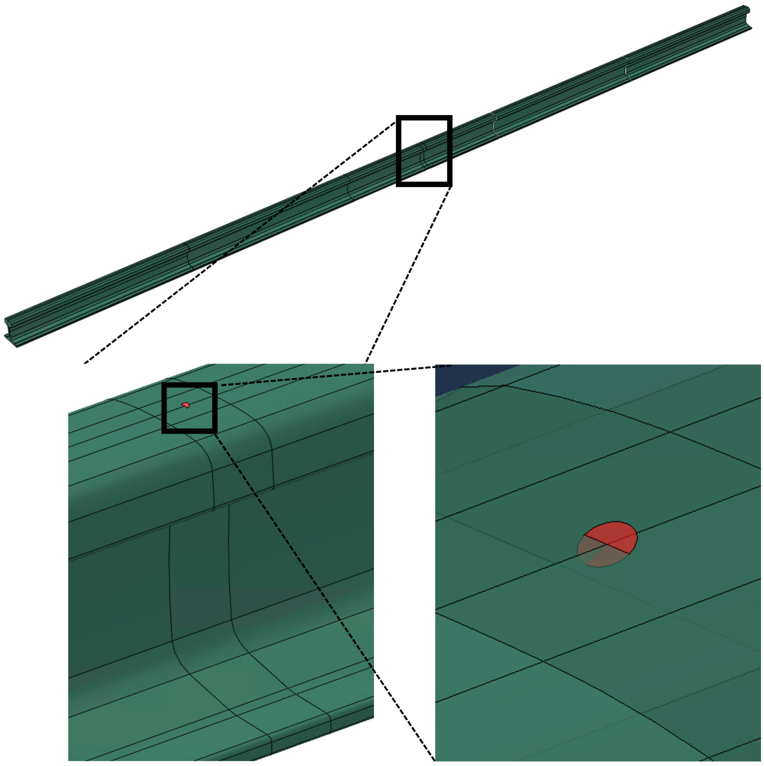
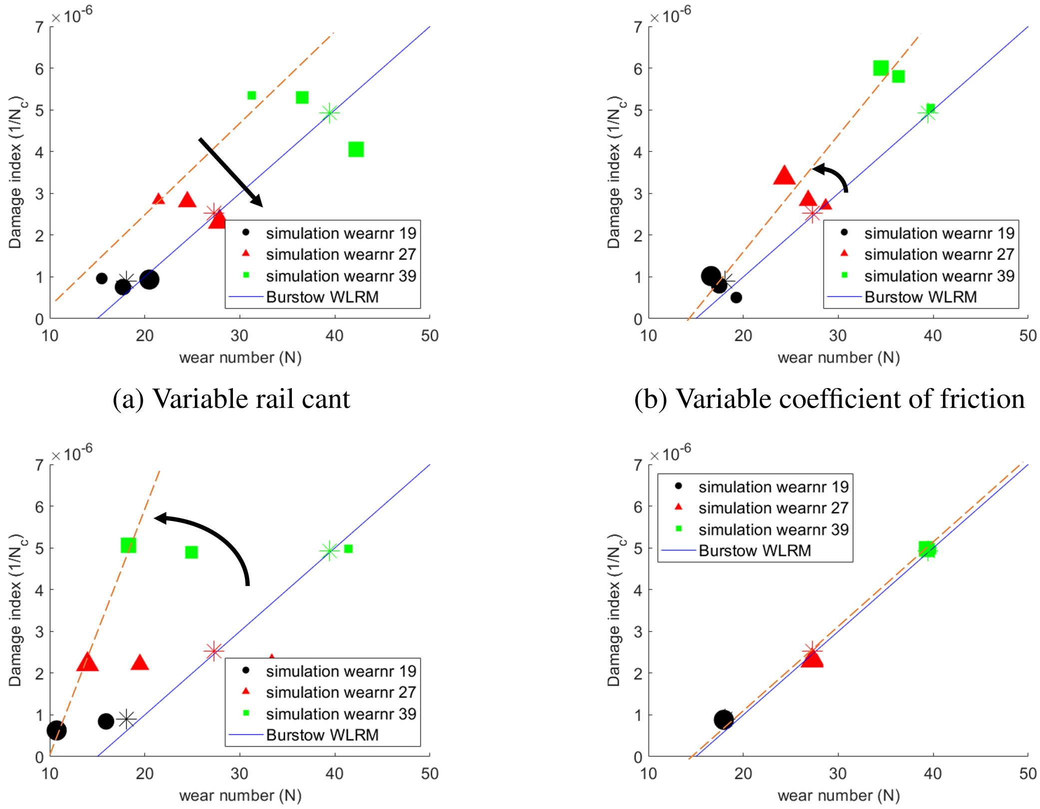


Figure 5: Abaqus FEM model with crack situated at the center.

5 Results and discussion

The influence of operational input parameters is analysed to see how the RCF function in the WLRM changes. The contact conditions were determined by using multi-body dynamics simulations in VI-Rail. In these simulations, the analysed parameter is held fixed, while the other parameters vary across simulations. For the selected simulations, the damage index and wear number were obtained from the Abaqus model and the VI Rail model, respectively. The results are shown in Figure 6. In each of these subfigures, each simulation has its own shape and colour. The star in the corresponding colour shows the original simulation. The size of the shape determines the size of the analysed parameter. The small shape is for the minimum value, the middle shape for the base value and the large shape is for the maximum value. The orange dotted line is drawn into the graph to show how the function changes based on the changing parameter. The black arrow shows the direction in which the RCF function changes if the analysed parameter increases.

Figure 6 demonstrates that the operational parameters considered in this study clearly influence the RCF damage function, as evidenced by changes in the wear number and the damage index. In general, the most pronounced effects were observed for axle load, train speed, curve radius, coefficient of friction, rail cant, and vertical wear depth, whereas the longitudinal and lateral suspension stiffnesses showed only limited influence. Higher axle loads were found to increase the damage index, indicat-



(a) Variable rail cant

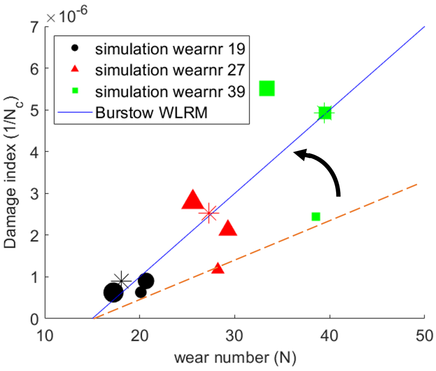
(b) Variable coefficient of friction

(c) Variable curvature

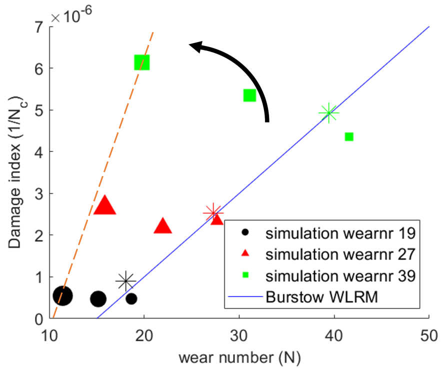
(d) Variable lateral stiffness

Figure 6: Simulations with variable input parameters (part 1).

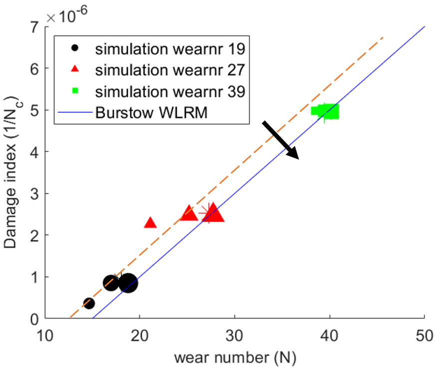
ing fewer cycles to failure, due to the higher stresses and corresponding larger stress intensity factors generated in the rail. Increasing train speed generally reduced the wear number significantly, while its influence on the damage index was more modest, though changes in the slope and position of the RCF curve were still observed. The coefficient of friction and the track curvature also had a substantial effect on the location of points in the WLRM, confirming that contact conditions strongly govern fatigue behaviour. In contrast, changes in longitudinal and lateral stiffness produced only minor variations, suggesting that these parameters are of secondary importance for crack propagation. Finally, vertical wear depth showed a particularly strong and nonlinear influence: increasing wear depth reduced the damage index considerably, implying a larger number of cycles to failure, because greater wear leaves less physical opportunity for cracks to propagate. Overall, the results indicate that the parameters most directly affecting wheel–rail contact conditions and crack-tip loading are the dominant factors controlling fatigue life, while stiffness-related parameters play a comparatively limited role.



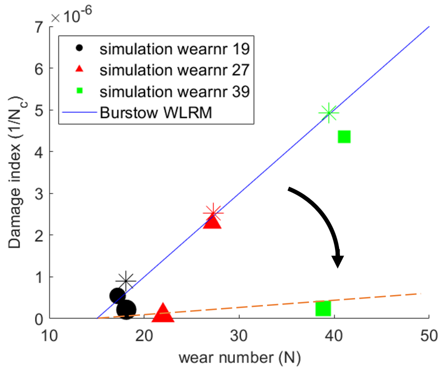
(e) Variable axle load



(f) Variable train speed



(g) variable longitudinal stiffness



(h) variable vertical wear depth

Figure 6: Simulations with variable input parameters (part 2).

6 Concluding remarks

The objective of this study was to find a possible approach to construct the RCF function of the Whole Life Rail Model (WLRM) by using operational data as input values. To set up such an approach, the crack growth on rails was studied and divided into an initiation phase and a propagation phase. From the literature review, it was found that a FEM model would be a preferable method to model crack propagation in rails. An extended finite element method (XFEM) was chosen as this method makes the analysis of propagating cracks easier and requires less computational effort. Using this model, the RCF part was recreated, and the influence of different input parameters was analysed. From the analysed parameters, the vertical wear depth, axle load, train speed and coefficient of friction have a significant influence on the RCF function.

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