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An approximate model to predict near-surface ratcheting of rails under high traction coefficients

G. Trummer [a,*], K. Six [a], C. Marte [a], P. Dietmaier [b], C. Sommitsch [c]

[a] *Virtual Vehicle Research and Test Center, Inffeldgasse 21/A/1, 8010 Graz, Austria*
[b] *Graz University of Technology, Institute of Applied Mechanics, Technikerstraße 4, 8010 Graz, Austria*
[c] *Graz University of Technology, Institute for Material Science and Welding, Kopernikusgasse 24, 8010 Graz, Austria*

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ABSTRACT

A model to predict the ratcheting behavior of the near-surface material layer under high traction coefficients has been developed. The model explicitly takes into account the longitudinal, lateral and spin creep in determining the displacement increment at the surface due to plastic shear deformation. The model is computationally efficient and allows to perform plasticity calculations based on results from multi-body system simulations.

The approximate model has been validated with results from finite element simulations and calibrated for R260 rail steel with data from twin disc tests. In addition, a parametric study has been performed to show the model behavior as a function of creep, in which the interaction with wear as an independent mechanism is taken into account. Application of the model to results of multi-body system simulations of the metro system in Vienna shows that the prediction of the crack pattern at the rail surface is feasible with the chosen approach.

1. Introduction

Rolling contact fatigue has increased in severity and extent over the last decades [1] and nowadays causes significant problems on rails. Among rail vehicle and rail manufacturers, as well as rail operators, there is a need for simple and efficient tools to predict rolling contact fatigue, especially with regard to interaction with wear. Rolling contact fatigue is an important and sensitive topic in the context of, e.g., material selection, maintenance strategies and track access charges.

Rolling contact fatigue affects the running surface and the gauge corner of rails, where it ultimately leads to surface break-outs or even rail fracture. Metallographic analyses of rails show that rolling contact fatigue cracks follow the severely deformed and aligned microstructure near the surface (see Fig. 1). These observations emphasize the prominent role of plastic deformation in the process of rolling contact fatigue crack initiation at the surface.

Plastic strains in the near-surface layer of rails can reach very high values. This severe deformation results from a multitude of small plastic shear strain increments under high hydrostatic pressure due to the passage of railway wheels. In the literature, the associated material response is known as “ratcheting”, characterized by the unidirectional accumulation of plastic strain. Ratcheting failure takes place, when the accumulated plastic strain reaches a critical value [2].

Several models to describe the ratcheting behavior of materials in the context of railway engineering have already been published. Kapoor et al. [3] proposed a ratcheting model for the prediction of wear, based on the critical strain approach [2]. In this model the increment in plastic shear strain is proportional to the (elastic) shear stress exceeding the shear strength of the material. The

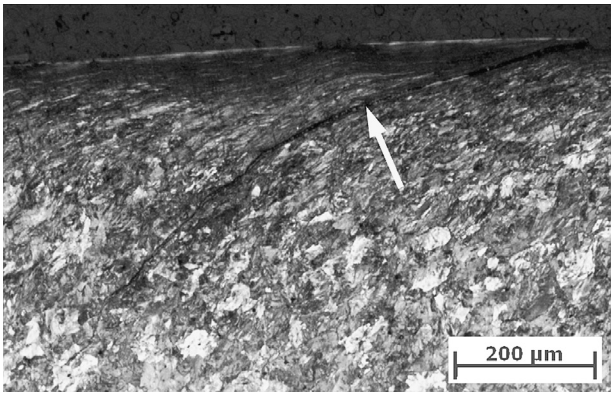

Fig. 1. Metallographic section in lateral direction through a rail from the metro network in Vienna, showing a rolling contact fatigue crack at the gauge corner of the rail. The crack follows the severely deformed microstructure of the material near the surface.

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[*] Corresponding author. Tel.: +43 316 873 9630; fax: +43 316 873 9072.
E-mail address: gerald.trummer@v2c2.at (G. Trummer).

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model has been improved and extended to account for directional plastic shear strain accumulation and the influence of surface roughness [4,5]. Mazzù et al. [6] developed another ratcheting model, implementing non-linear kinematic and isotropic hardening, in which the shear stress is responsible for plastic flow. The model has been applied to two-dimensional problems to calculate the in-plane plastic shear strain.

The main objective of this work has been the development of a fast and approximate, but physically based, ratcheting model, which can be applied to general three-dimensional problems. The model provides plastic shear strain data, which aid in predicting rolling contact fatigue crack initiation. In contrast to other models, it takes advantage of the creep information available from elastic contact calculations in determining the ratcheting strains in longitudinal and lateral directions of the rail. The model has been applied to results of multi-body system simulations [7] and plays a key part in linking the global railway vehicle behavior to local damage on the rail.

2. Predictive model

The proposed ratcheting model is kept as simple as possible, while still being sufficiently detailed to describe the dominant deformation mechanisms on a physical basis. This includes the way the model discretization is chosen, how the subsurface stresses are calculated and how the resulting increment in plastic shear strain is determined.

For a model to be applied to the results of multi-body system simulations of railway vehicles, computation time is a crucial factor. The model has to be computationally as efficient as possible to allow calculations of plasticity on cycle-by-cycle basis for different positions along the track. Each point on the rail head experiences a multitude of different loading conditions, which result, e.g., from varying operating conditions, different vehicle types, different wheel profiles or a change of profile geometry over time as a result of wear. The necessity of low computation time and the high number of load passes prohibit the use of sophisticated finite element (FE) models for the intended application.

2.1. Model discretization

To deal with three-dimensional contact problems, a so-called “2.5D” approach has been chosen, in which two-dimensional sub-models are used to approximate the three-dimensional problem. The two-dimensional sub-model used here is the contact of a cylinder on a plane, referred to as “segment” subsequently. To approximate the three-dimensional rail, the near-surface part of the rail head is divided into equally spaced segments of finite width in lateral direction of the rail. In depth direction, the discretization is always oriented normal to the rail surface. The individual segments of the discretization are all in a state of plain strain and do not interact with one another. This configuration can also be described as a concatenation of line contacts of finite width in lateral direction of the rail.

The stress state in the individual segments depends only on the normal and tangential surface load on top of the segment. This significantly reduces the computation time to calculate the elastic stress field within the near-surface layer compared to a full three-dimensional model.

In rolling direction, the normal and tangential contact stress distributions are well represented by the concept of tractive rolling of a cylinder on a plane. In lateral direction, however, locally changing contact geometry inside the contact may result in non-elliptic contacts with non-elliptic stress distributions in lateral direction. This is significant for the gauge corner of the rail, where rolling contact fatigue cracks are frequently observed in praxis. The 2.5D approach used here allows to approximate such non-elliptic contacts with non-elliptic stress distributions in lateral direction.

2.2. Subsurface stress calculation

Normal and tangential stress distributions, as well as longitudinal, lateral and spin creep for the individual segments in contact must be provided to the model as input data. These data can be calculated by suitable contact models like CONTACT [8], Hertz [9] and FASTSIM [10] or the contact model in [7].

For efficient calculation of the subsurface stress state in the segments, analytic formulas have been derived, based on the Boussinesq–Cerruti equations for the cylinder on plane contact [11], in which the surface tractions are specified by a number of stress values at specific points. The normal stress distribution at the surface is assumed to be parabolic, determined by the maximum normal pressure p_0 in the center of the contact, whereas the longitudinal and lateral tangential stress distributions along the rolling direction are each described by three concatenated parabolas. Hence, 7 points per tangential stress distribution are necessary to define the stress distribution. The points at the leading and trailing edges of the contact experience no traction, leaving 5 stress values inside the contact for the approximation of a given tangential stress distribution. The number of three concatenated parabolas per tangential stress distribution is a good compromise to efficiently approximate complex contact stress distributions, which may occur in cases with combined longitudinal, lateral and spin creep. An example is shown in Fig. 2. In the model, a parabolic traction bound is used. Thus, tangential stress values on an elliptic traction bound in the input data are mapped to the corresponding values on the parabolic traction bound by scaling of the longitudinal and lateral tangential stress distributions (e.g., points at $x = +3.3$ mm in Fig. 2).

To consider the influence of surface roughness on the plastic shear deformation, the Mises stress near the surface is amplified by a factor f_s according to Eq. (1). Parameter A is the stress amplification factor at the surface, whereas B controls the decay of the stress amplification with depth z:

$$f_s(z) = (A-1)\cdot e^{-z/B} + 1 \qquad (1)$$

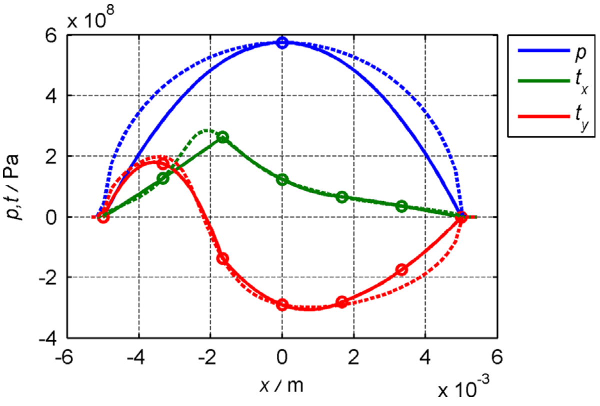

Fig. 2. Example of surface traction for a cylinder, rolling in positive x-direction, in contact with a plane; longitudinal creep $c_x = +0.002$, lateral creep $c_y = -0.003$, spin creep $c_z = +3\ \mathrm{m}^{-1}$; p: normal stress, t_x: tangential stress in longitudinal direction, t_y: tangential stress in lateral direction; dashed lines: CONTACT results, solid lines with points: approximation by parabolas (one parabola for p, three concatenated parabolas for t_x and t_y).

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