Crack propagation in railway wheel rim in a case of rectilinear ride

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ABSTRACT
A computational model of fatigue behaviour of two-dimensional (2D) primary crack situated in a railway wheel (RW) rim was designed. The RW rim was placed on the wheel disc of RW with interference fit. Crack behaviour was analysed in the case of rectilinear ride of a train under rolling contact fatigue (RCF). A direction of crack propagation was predicted using Richard´s criterion [1]. *In this way a relationship between stress intensity factors and crack geometry was obtained. The equivalent cyclic stress intensity is calculated and used in a modified Paris equation to predict the crack's propagation rate.*

INTRODUCTION

It is a matter of fact that fatigue crack growth in railway wheels may lead to the loss of a part of the wheel (spalling) or to radial crack extension. The result can be damage of rails and sleepers or vehicle components or even derailment. Fatigue cracks tend to initiate below the tread [2]. Such an initiation is promoted by the occurrence of material defects. The goal of the contribution is to simulate rolling contact fatigue crack growth for a 2D case using FEM and taking into account a nonproportional mixed-mode loading. A parametric analysis is performed examining the influence of threshold value of fatigue crack growth, ΔK_{th}, a friction of crack faces and the crack direction criterion. Crack growth rate is predicted using a modified Paris law. Fatigue crack growth starts, if the equivalent cyclic stress intensity ΔK_{eq} exceeds ΔK_{th}. The crack's propagation rate $\mathrm{d}a/\mathrm{d}N$ also depends on the fracture-mechanical properties of the material taken from the work [3]. Both, the radial crack extension and spalling are predicted and it is shown how the crack path depends on model parameters.

NUMERICAL MODEL

Numerical model of crack is created in the system ANSYS version 14 (ANSYS Inc., Canonsburg, PA, USA). A rectilinear ride of a train is assumed and no geometric imperfections of rails and/or wheel tread are considered. The wheel rim is considered to be sufficiently wide so that the contact problem can be reduced to plane strain problem. An initial crack of length of 2 mm is inclined to the tangential direction with shallow angle 20°, see Fig.1. Such geometrical configuration is typical for RW wheels [3],[4].The length of crack is increased by 0.03 mm in each loading step defined by the position of the crack mouth with respect to the contact point in the range limited by angles α_1 = -2° and α_2 = 5°, see Figure 1. As it will be shown later, outside this range both SIFs K_I and K_{II} are equal to zero.

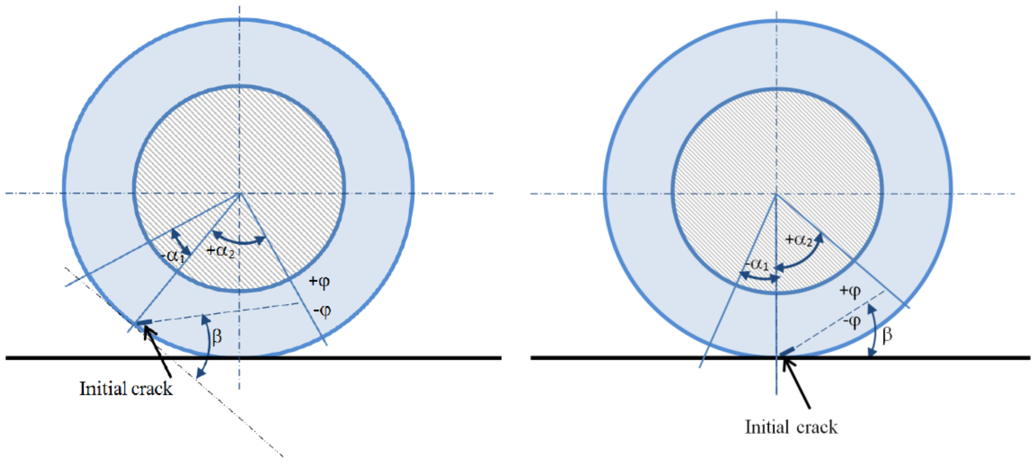


Figure 1 Scheme of railway wheel geometry

The outer diameter of the wheel rim is 920 mm and the thickness of the rim is 75 mm. FE mesh consists of quadratic elements PLANE183, see Figure 2. A sensitivity analysis of mesh has not revealed any substantial changes in the values of stress intensity factors during further mesh refinement.

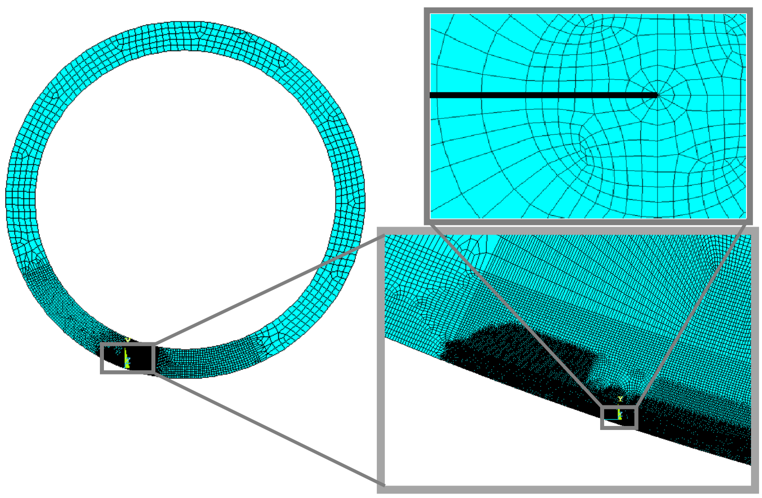


Figure 2. FE mesh and size of discretization

It was shown elsewhere [5] that the concept of linear elastic fracture mechanics is likely to be valid for crack modelling in rolling contact fatigue of railway wheels. Hence, a plastic zone ahead of the crack tip and related stress redistribution is not considered. The material of the wheel is assumed to be homogeneous, isotropic with the Young modulus E =2.1 10^5 MPa and Poisson's ratio ν = 0.3.

Rolling contact in the vicinity of the wheel running circle and at the top of the railhead is considered. The wheel is loaded at the contact patch by a distribution of contact pressures which correspond to the total contact force of 10 tons. The algorithm for Hertzian contact calculation was described elsewhere, see e.g. [6],[7],[8]. The contact pressure data are prescribed in individual nodes of the quadratic element PLANE 183, see Figure 3.

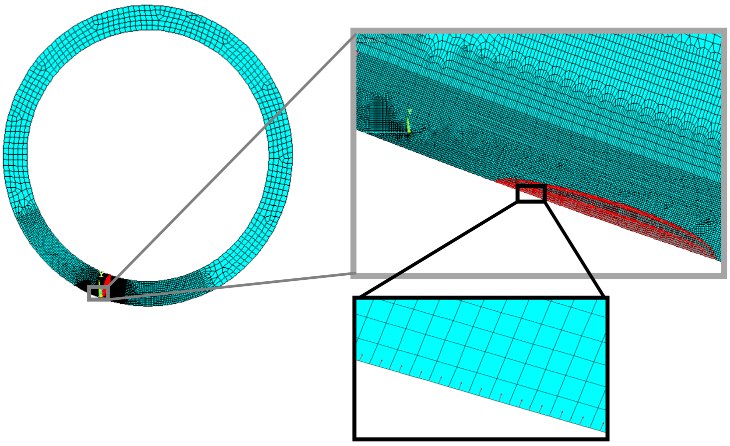


Figure 3 Nodes of quadratic elements where the contact pressure data are prescribed

Rectilinear ride of a train with constant speed of 100 km/h is supposed. Further it is assumed that the rim is set on the wheel with an overlap which corresponds to a relative increase of the inner diameter of the rim of about 1.44 %. In the given case the overlap amounts of about 1.11 mm.

Fatigue crack growth is modelled for two cases of surface friction between the crack faces – i) without friction and ii) with friction utilizing the coefficient of friction μ=0.5.

The procedure of fatigue crack growth prediction under non proportional loading is based on concepts described in [9],[10], which concerns the situation when the K-vector rotates. The out of phase mixed modes I and II loading in the investigated case are illustrated in Figure 4 as functions of relative contact position, see Figure 1.

The procedure of fatigue crack growth prediction is somewhat modified – firstly, a maximum value of K_I is found in a loading step. Then a mean value of K_{II} over the loading step, see Figure 1, is calculated as

$$\overline{K_{II}} = \frac{1}{\alpha_2 - \alpha_1} \cdot \int_{\alpha_1}^{\alpha_2} K_{II}(x)dx . \quad (1)$$

Both values are substituted into Richard's criterion [1] for calculation of the kinking angle φ as

$$\varphi = \mp\left[140° \cdot \frac{|K_{II}|}{K_I + |K_{II}| + |K_{III}|} - 70° \cdot \left(\frac{|K_{II}|}{K_I + |K_{II}| + |K_{III}|}\right)^2\right], \text{ with } K_{III} = 0. \qquad (2)$$

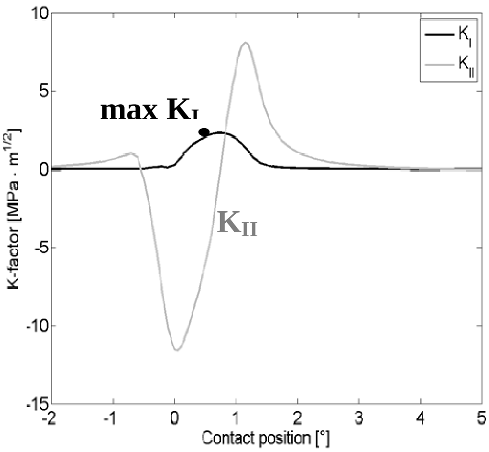


Figure 4 Out of phase mixed modes loading plotted as functions of contact position

In the subsequent loading step the calculated kinking angle φ is used to rotate the local coordinate system x_L, y_L, see Figure 5, and the constant crack increment of the length of 0.03 mm is then imposed.

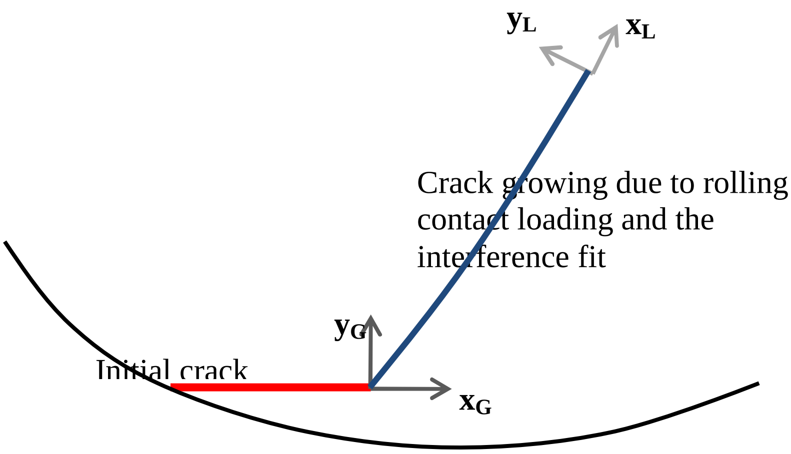


Figure 5. Scheme of the crack configuration

For each crack increment also an equivalent stress intensity factor, see [1], is calculated as

$$K_{eq} = \frac{\max(K_I)}{2} + \frac{1}{2}\sqrt{\max(K_I)^2 + 4\cdot\left(1.155\cdot\overline{K_{II}}^{\,2}\right)} \tag{3}$$

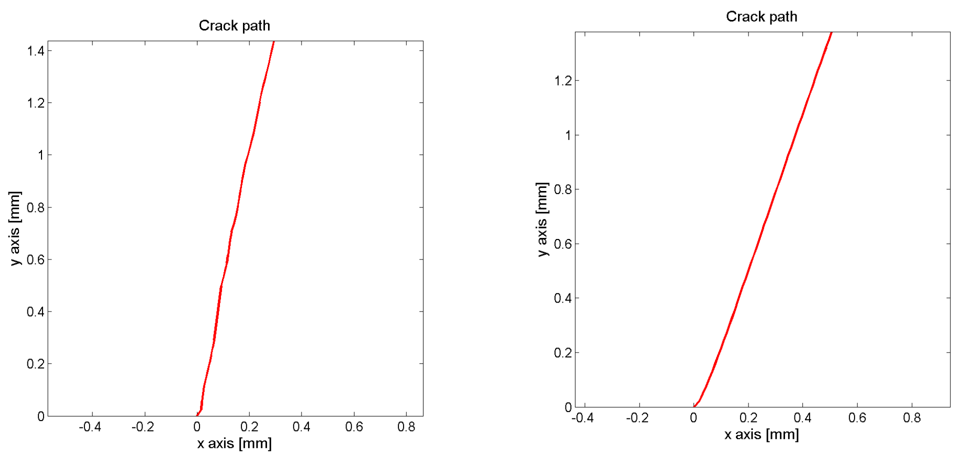
The equivalent stress intensity factor data are used as input data for describing the crack growth rate da/dN. Following modified Paris equation is applied:

$$\frac{da}{dN} = C\cdot\left(\Delta K_{eq} - \Delta K_{th}\right)^n, \tag{4}$$

where the constants C = 1.6475 10^{-11} and n=3 were taken from [3]. By integrating Eq. (4) the crack extension as a function of number of cycles N can be easily obtained.

RESULTS

Figure 6 shows a predicted crack path in the global coordinate system, cf. Figure 5, for the case when friction is not considered and for the case when the coefficient of friction between crack faces μ = 0.5.



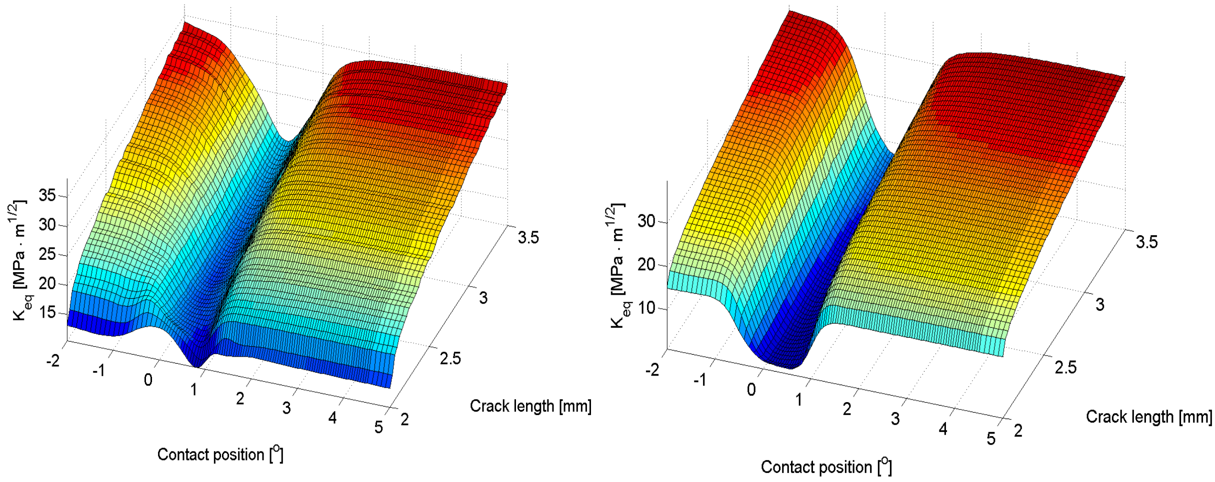
a) Without friction between crack faces

b) Friction coefficient μ=0.5

Figure 6. Predicted crack path in RW rim

Apparently, due to the overlap a radial crack extension is a preferred mode of fracture. In the case of friction, the crack path somewhat diverts from the radial direction in comparison to the case without friction. Likely the friction makes the shear dominated fatigue crack growth more favourable than maximum tensile stress dominated crack growth.

3D graph in Figure 7 shows how K_{eq} depends on the contact position, cf. Figure 1, and on the crack length.

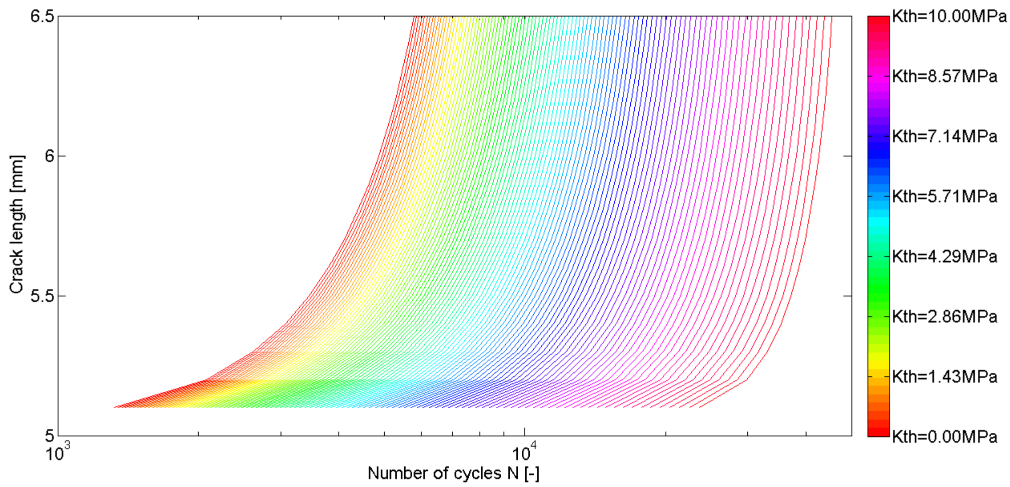


a) Without friction between crack faces

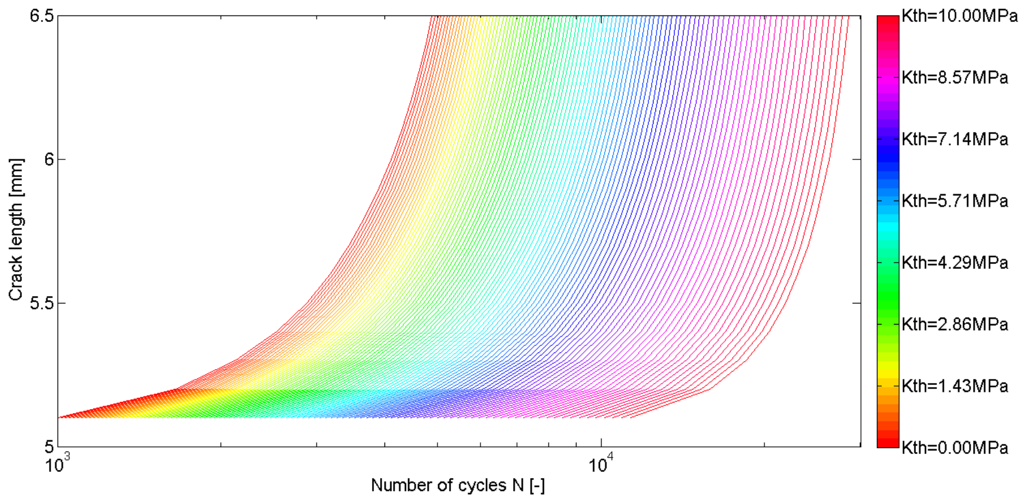
b) Friction coefficient μ=0.5

Figure 7. Equivalent SIF as a function of contact position and crack length

Making use of the equivalent SIF data in the modified Paris equation (4), crack extension as a function of number of cycles *N* is computed for a wide range of threshold values of fatigue crack growth, ΔK_{th}. Results are shown in Figure 8 for both cases - without friction and with friction considered between crack faces. It is seen that the overlap has a major influence – crack accelerates significantly with increasing crack length. It is worth mentioning that virtually same results are obtained when the original Pook's criterion is used, i.e. instead of mean value of mode II SIF, the value of K_{II} corresponding to the maximum value of mode I SIF is applied both in the calculation of the kinking angle φ according to Eq. (2) and in the calculation of equivalent SIF according to Eq.(3). However, simulations show that Pook's criterion is less sensitive to mode II stress intensity in comparison to the mean value mode II based criterion.



a) Without friction between crack



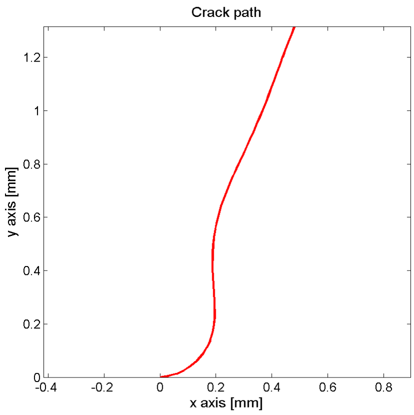
c) Friction coefficient μ=0.5

Figure 8. Crack length as a function of number of cycles N for different value of K_{th} threshold

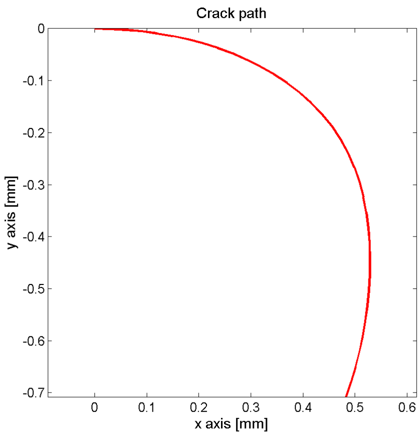
It is a matter of interest to compare the crack growth in the RW rim with a crack behaviour in a solid railway wheel which is not subjected to pre-stress loading.

The initial geometry of the solid railway wheel containing a crack is the same as in the case of rim wheel. Also boundary conditions and the computation algorithm are identical.

Figure 9 shows predicted crack path in the solid railway wheel for the case when friction is not considered and for the case when the coefficient of friction between crack faces $\mu = 0.5$.



b) Without friction between crack faces



c) Friction coefficient μ=0.5

Figure 9. Predicted crack path in solid railway wheel

Crack path simulations in solid railway wheel show that while without friction the crack follows a radial path, spalling is preferred mode of fracture, if friction of crack faces is considered.

CONCLUSIONS

The following conclusions can be drawn:
Crack path simulations in the RW rim show that the overlap between the rim and the wheel influences significantly the crack path. Radial crack extension is preferred mode of fracture and the fatigue crack accelerates significantly with increasing crack length. The friction between crack faces seems to support shear dominated fatigue crack growth, nevertheless the crack path does not change notably with friction. Hence, it may be stated that RW rim always failures in radial direction.
Crack path simulations in solid railway wheel show that spalling is preferred mode of fracture if the friction of crack faces is considered while a radial path occurs if the friction is zero.

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