Modelling of the fracture of a railway wheel

Daniel F. C. Peixoto a,b,*; Paulo M.S.T. de Castro a

a - Faculdade de Engenharia da Universidade do Porto, Rua Dr Roberto Frias, 4200-465 Porto, Portugal
b - Institute of Science and Innovation in Mechanical and Industrial Engineering, Campus da FEUP, Rua Dr. Roberto Frias, 400, 4200-465 Porto, Portugal

Abstract

Fatigue crack propagation in railway wheels occurs under mixed mode (I-II) conditions, and frequently the crack is initiated at some subsurface small defect.

This paper presents the modelling of the propagation of a crack initiated inside the tire of a Spanish AVE train wheel. The work is based upon the time dependent stress state of the wheel, and mechanical properties of the wheel steel measured using Compact Tension Shear specimens. In order to generate data for use in the simulation of the wheel fracture, mixed mode I-II fatigue crack growth tests were performed on 9 mm thick CTS specimens using a servo-hydraulic MTS fatigue testing machine. These tests were modelled using the finite elements method. The crack propagation direction (angle) was experimentally measured and numerically calculated, and the obtained results were then compared in order to validate the used numerical techniques.

The data obtained using conventional Fracture Mechanics specimens was then used to model crack growth in the wheel. The modelled crack growth, up to final fracture in the wheel, is consistent with the expectation for the type of initial damage considered.

© 2016 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the Scientific Committee of ECF21.

Keywords: railway wheel; fracture; fatigue; mixed mode; CTS specimen

1. Introduction

In this work the subsurface crack propagation under rolling contact fatigue (RCF) of a train wheel is modelled with particular attention dedicated to the propagation direction of the crack at every increment of its length.

* Corresponding author. Tel.: 351 229578710; fax: +351 229537352.
E-mail address: dpeixoto@imegi.up.pt
Wheel shelling and rail squats are examples of defects originated in cracks that cause loss of large pieces of metal from wheel treads and rail head as a result of wheel-rail rolling contact fatigue. Fatigue tests performed to obtain the fatigue crack growth rate under the mixed loading (mode I+II) can be helpful to increase safety and reduce railway industry costs related with maintenance of wheels and rails. It was found that a crack would turn to the direction perpendicular to the higher tensile load if it was initially perpendicular to the lower tensile load. Under shear only loading, the crack turned to the direction perpendicular to the maximum principal stress, Qian and Fatemi (1996).

Considering the results and numerical methodology's validated by the experimental work on the mixed mode fatigue crack propagation, presented in Peixoto and de Castro (2016), the Erdogan and Sih (1963) Maximum Tangential Stress (MTS) criterion was used to calculate the mode I and II stress intensity factors and the crack propagation direction along the crack tips loading cycle.

The commercial finite element package ABAQUS was used to build and analyze the model. As rolling contact induces complex non-proportional mixed-mode conditions at crack tips, the evolution of mode I and mode II stress intensity factors was followed along the loading cycle. It can be assumed that the crack is far enough to be out of the near surface layer that is heavily plastically deformed by rolling contact. According to this, linear elastic fracture mechanics concepts can be considered and the crack propagation can be analyzed under these assumptions, Dubourg and Lamacq, (2002).

2. Finite element model

The commercial finite element package ABAQUS 6.12-3 was used to build and analyze the 2D model. To improve the performance of the simulation, it was decided to build a different part were the crack will growth and were the mesh is more refined apart from wheel model and then this part was “tied” to the wheel. This construction is shown in Figure 1.

![Figure 1: Finite element model construction](image)

Plane strain quadrilateral with 8-node elements (CPE8) were used to build a 2D finite element mesh of the wheel. Since the objective of this work is to simulate the propagation of a subsurface crack in the wheel, the rail was modeled as a rigid line. Singular elements with nodes at quarter-point positions were considered at the crack tip. As the crack will be loaded in compression it was necessary to use self-contact formulations to avoid interpenetration of the crack faces node. In this study the penalty method was considered as contact enforcement in the crack faces contact.

No hydrodynamic or entrapment fluid effect or interfacial crack friction was considered between crack faces. As boundary conditions, the rail was fixed and the wheel was loaded against the rail by a vertical force of 11.5 kN and translated 40 mm in small increments. This translation associated with the friction force generated by the friction makes the wheel to turn around its geometric center that is free to rotate. The penalty method was also used has contact enforcement on the contact between the wheel and the rail and a friction coefficient of $\mu = 0.1$ was considered.

The material was assumed to be homogeneous, isotropic with linear elastic behavior. The elastic properties considered were Young modulus $E = 210$ GPa and Poisson ratio $\nu = 0.3$. 
3. Methodologies

Since the finite element model have a great local transition on the mesh refinement between the wheel and crack parts, it was decided to perform an analysis of the contact stresses distribution on an un-cracked model to verify if that transition has any important influence on the stress field. In Figure 2 the un-cracked model finite element mesh is shown and the obtained Tresca and minimum stress fields are shown in Figure 3 and Figure 4 respectively, where no influence of the great local transition on the mesh refinement is observed.

Table 1 shows some variables as the applied normal force ($F_N$), the considered friction coefficient ($\mu$). Other variables obtained with the un-cracked model are also listed as the maximum Hertz pressure ($P_0$), the contact width ($a_{contact}$), the maximum value of the Tresca stress ($\tau_{Tresca\ max}$) and the depth at which it occurs ($Z_s$).

<table>
<thead>
<tr>
<th>$F_N$ [kN]</th>
<th>$\mu$</th>
<th>$P_0$ [GPa]</th>
<th>$a_{contact}$ [mm]</th>
<th>$Z_s$ [mm]</th>
<th>$\tau_{Tresca\ max}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,5</td>
<td>0,10</td>
<td>1,39</td>
<td>5,52</td>
<td>3,98</td>
<td>905,10</td>
</tr>
</tbody>
</table>

The depth at the maximum value of the Tresca stress occurs ($Z_s$) is an important variable for this work, as the initial crack was positioned at that depth. From the un-cracked model, the same applied load and the friction coefficient were used in the cracked model to guarantee the same contact conditions.

The initial crack has 10 mm in length and is located at the depth of the maximum value of the Tresca stress, in this case at 4 mm.

At every increment each crack tip was analyzed independently, and the crack length was increased 1mm, at each crack tip, in the direction of the calculated maximum mixed mode equivalent stress intensity factor along the load cycle, observed at the correspondent crack tip.

The maximum tangential stress criterion, available in the software ABAQUS, was used to calculate the mode I and mode II stress intensity factors as the direction of the crack propagation.
For homogeneous, isotropic elastic materials the direction of cracking propagation can be calculated using the maximum tangential stress criterion as

$$\theta = \cos^{-1}\left( \frac{3K_H^2 + \sqrt{4K_I^2 + 8K_I^2K_H^2}}{K_I^2 + 9K_H^2} \right)$$  \hspace{1cm} (1)

The Richard/Henn criterion, Richard et al., (1991), Henn et al., (1988), was considered to calculate the equivalent stress intensity factor ($K_V$), as:

$$K_V = \frac{K_I}{2} + \frac{1}{2} \sqrt{K_I^2 + 6K_H^2}$$  \hspace{1cm} (2)

It was defined that the process of increasing the crack will be repeated until the maximum mixed mode equivalent stress intensity factor reaches the threshold or reaches a value that can be considered that is within the unstable crack propagation zone.

4. Results

As results, in the next paragraphs the obtained crack path and the evolution of the stress intensity factor will be shown in Figures 5 to 11. In Table 2 the obtained crack propagation angles are listed. These angles are measured relatively to the horizontal plane.

In this case the calculation process ended when the maximum mixed mode equivalent stress intensity factor reached a value considered in the unstable propagation zone, see Figure 11, which implies that the crack will growth rapidly until it reaches the wheel surface, in this case, considering the propagation angle the crack will reach the wheel tread.

In Figure 12 the maximum value of $K_V$ recorded for each crack length is represented as a function of crack length.

<table>
<thead>
<tr>
<th>crack length [mm]</th>
<th>left crack tip angle [deg]</th>
<th>right crack tip angle [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>67</td>
<td>-58</td>
</tr>
<tr>
<td>12</td>
<td>-58</td>
<td>62</td>
</tr>
<tr>
<td>14</td>
<td>-53</td>
<td>-60</td>
</tr>
<tr>
<td>16</td>
<td>61</td>
<td>68</td>
</tr>
<tr>
<td>18</td>
<td>-58</td>
<td>-43</td>
</tr>
<tr>
<td>20</td>
<td>-54</td>
<td>59</td>
</tr>
</tbody>
</table>

left tip
Figure 6: Stress intensity factors evolution during load passage on the initial straight 10mm crack.

Figure 7: Stress intensity factors evolution during load passage on the 12 mm crack.
Figure 8: Stress intensity factors evolution during load passage on the 14 mm crack.

Figure 9: Stress intensity factors evolution during load passage on the 16 mm crack.
Figure 10: Stress intensity factors evolution during load passage on the 18 mm crack.

Figure 11: Stress intensity factors evolution during load passage on the 20 mm crack.
Concluding remarks

The commercial finite element package ABAQUS 6.12-3 was used to build and analyze a 2D model of a subsurface crack propagation on the wheel/rail contact. The Maximum Tangential Stress (MTS) criterion was used to calculate the mode I and II stress intensity factors and the crack propagation direction along the crack tips loading cycle. Particular attention was dedicated to the propagation direction of the crack at every increment of its length.

As can be observed in the presented results the crack change its direction from approximately $+60^\circ$ to $-60^\circ$ at every increment of the crack length. This will promote a very irregular crack surface until the final fracture occurs.

As rolling contact induces complex non-proportional mixed-mode conditions at crack tips, the evolution of mode I and mode II stress intensity factors was followed along the loading cycle and no dominant mode at the crack tip was observed despite of the equivalent stress intensity factor being very sensitive to the variation of the mode II stress intensity factor.

In this study the calculation process ended when the maximum mixed mode equivalent stress intensity factor reached a value considered in the unstable propagation zone, which implies that the crack will growth rapidly until reaches the wheel surface.

Acknowledgements

Daniel Peixoto acknowledges a Calouste Gulbenkian Foundation PhD grant, number 104047-B. The Portuguese Science and Technology Foundation FCT project PTDC/EME-PME/100204/2008 “Railways” is acknowledged. ALSTOM kindly supplied the Spanish AVE high speed train wheel for this study.

References

ABAQUS, ABAQUS v6.12-3 documentation, Dassault Systèmes.