NUMERICAL AND EXPERIMENTAL INVESTIGATIONS ON FATIGUE CRACK GROWTH IN A WHEEL OF THE GERMAN HIGH-SPEED TRAIN ICE

H.A.Richard[1], M. Sander[1], M. Fulland[2] and G. Kullmer[1]
[1]Institute of Applied Mechanics, University of Paderborn, Germany
[2]Westfälisches Umwelt Zentrum, Paderborn, Germany

ABSTRACT

This paper deals with the fracture mechanical investigations for the damage of the ICE-tyre. The crack growth began at the ICE-wheel close by the location of the maximum stresses at the inside of the tyre. The crack at first grew merely into the depth of the tyre and later on with a half elliptical shape. Only as nearly 80% of the cross section of the tyre was damaged, the tyre has been broken. On the crack surface colour effects and surface structures can be seen, which is an indicator for a discontinuous crack growth. Within the scope of this paper it will be shown that the crack growth can be explained by means of finite element simulations and experimental investigations.

1 INTRODUCTION

On 3rd of June 1998 the german high-speed train ICE Wilhelm-Conrad Röntgen got into an accident on his trip from Munich to Hamburg. On his tour one wheel broke, the train derailed and parts of it collided with a bridge, which collapsed by this.

The fracture of the tyre of a rubber-sprung wheel was accounted for causing the accident. Such wheels mainly consist of a tyre, the rim and rubber elements, which are pre-stressed in-between. The main load transmission takes place between the contact point of the wheel and the shaft. The highest stresses in the wheel occur on the inside of the tyre. Due to the rotation of the wheels a cyclic loading arises. This leads to an extensive fatigue crack growth and finally to the damage of the tyre.

2 DESIGN AND LOADING OF RUBBER-SPRUNG WHEELS

For many decades rubber-sprung wheels are commonly used worldwide for vehicles of tramways, subways and city railways in order to e.g. minimize wear and noise development, which is caused by small radii of the rails or other specialities of these railway systems. Due to oscillations and noise in the ICE-trains those rubber-sprung wheels also were advanced to standard gage railways and permitted for the use in high speed trains of the Deutsche Bahn in autumn of 1992.

This new type of wheel set in new condition has a diameter of 920mm. As result of wear and thus of necessary re-fluting the diameter notably decreases during the service time of a wheel. The smallest permitted operating diameter was stipulated as 854mm, whereas the broken tyre of the accident had a diameter of 862mm.

A rubber-sprung wheel of the ICE-type consists of a wheel tyre, 34 rubber blocks, a wheel rim and a solid shaft (Figure 1). For the purpose of assembling the wheel rim is divided into two parts, a wheel centre and a detachable ring. At first the rubber blocks are placed equidistantly around the perimeter in the gap between wheel tyre and wheel centre. Finally the detachable ring is bolt together with the wheel centre. Thereby the rubber blocks are distorted, that means they are compressed in radial and axial direction of the wheel and extend in circumferential direction into the existing free spaces. The rubber blocks are protected against shifting by the friction between them and the wheel tyre resp. the rim.

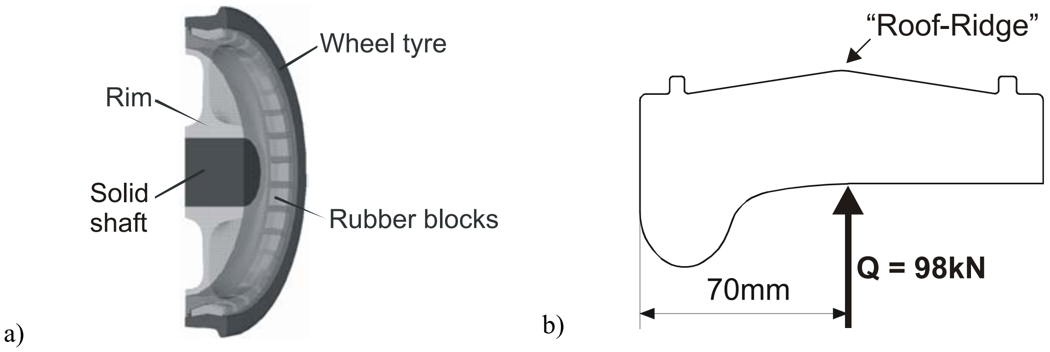

Figure 1: a) Assembly of a rubber-sprung wheel (CAD-model of a half-wheel)
b) Loading of a wheel tyre for loading situation *straightforward driving*

According to the UIC-draft 510-5 [1] following loading cases generally are distinguished: *straightforward driving*, *rolling turn* and *track switch crossing*. For the loading situation straightforward driving a wheel contact force

$$Q = 1{,}25\ Q_0 = 98\ \text{kN}$$

is given (Figure 1b). Thereby Q_0 is the static wheel contact force resulting from the weight of the wagon. The maximum tangential stress, which is most crucial for the crack growth can be found at the inner surface ("roof-ridge") of the wheel tyre with minimal diameter for the loading situation straightforward driving.

3 NUMERICAL STRESS ANALYSIS

For a reliable numerical stress analysis of the wheel tyre a three-dimensional finite-element-analysis is mandatory. This analysis type is enforced due to the geometry of the wheels, the multi-dimensional pre-stress of the rubber blocks as well as the spatial loading situation (especially if all loading situations are under consideration). All following investigations are related to the dimensions of the broken wheel tyre with a diameter of 862mm.

A two-stage approach is necessary for such a finite-element-analysis: At first the wheel has to be "numerically assembled" in order to obtain the pre-stresses resulting from the assembly process. Subsequently an analysis of the stresses caused by the wheel contact force(s) has to be performed. Due to the non-linearity of the FE-system *rubber-sprung wheel* the resulting equation system with more than 450000 equations has to be solved about 60 times for the assembly process and another 50 times for any loading situation.

As consequence of the assembly a circumferential stress can be found, which is constant in circumferential direction (apart from small oscillations due to the rubber blocks) and variable in axial direction due to the unsymmetric shape of the wheel tyre cross section. At the inner surface of the wheel tyre the circumferential stress is about 50MPa.

The analysis of the loading case straightforward driving yields positive circumferential stresses at the inner surface of the wheel tyre, that heavily vary in circumferential as well as in axial direction. The biggest circumferential stress can be observed at the "roof-ridge" of the wheel tyre in the symmetric plane of the loaded wheel.

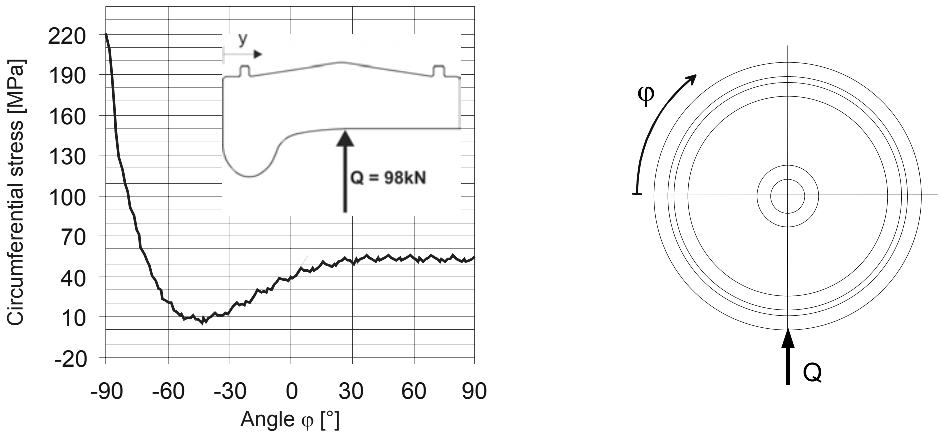

Figure 2: Circumferential stress on the inner surface of the wheel tyre at y=67,5mm (“roof-ridge”) in dependence of the angle φ for the loading case straightforward driving (assembly + Q-Force) for a wheel diameter of 862mm

In the loading case straightforward driving for Q = 98kN a maximum stress σ_{max}=220 MPa and a minimum stress σ_{min}=6 MPa is calculated (Figure 2). From this a stress amplitude σ_a = 107 Mpa, a mean stress σ_m = 113 MPa and an R-ratio R = +0,03 arises.

4 FAILURE ANALYSIS OF THE FRACTURE OF THE WHEEL TYRE

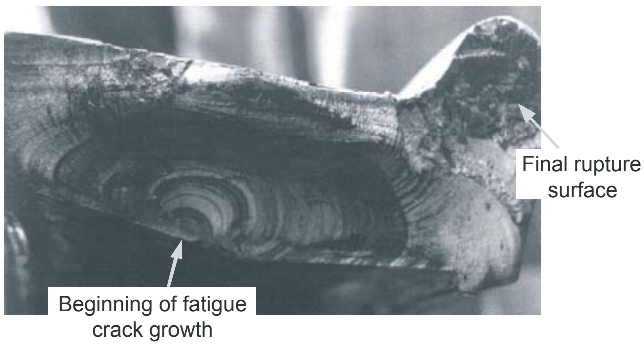

Figure 3: Fracture surface of the broken wheel tyre

The fatigue crack growth at the ICE-wheel initiated in the vicinity of the location, where the maximum stresses in the loading case straightforward driving can be found at the inner surface of the wheel tyre (Figure 3). In the beginning the crack merely grew towards the depth of the wheel tyre, and propagated later on in a half-elliptical shape. Final rupture did not occur before approx. 80% of the cross section had already been damaged by fatigue crack growth.

On the fracture surface arrest lines, colour effects and other fracture surface structures can be observed, that indicate a very discontinuous crack growth behaviour. So e.g. phases of extremely slow crack growth or even crack arrest alternate with phases of quite fast crack growth. Altogether any observation suggests a pronounced phase of stable crack growth.

5 NUMERICAL SIMULATION OF FATIGUE CRACK GROWTH

The fatigue crack growth in three-dimensional structures can be simulated by the use of the Finite-Element-method. Especially the program system ADAPCRACK3D [2] has already proven its applicability to those problems. It consists of 3 modules, that in combination comprise a fully automatic crack growth simulation. As input data basically the description of the uncracked structure and of the initial crack in terms of 3D-FE-meshes as well as material data, which defines the crack propagation behaviour, is needed.

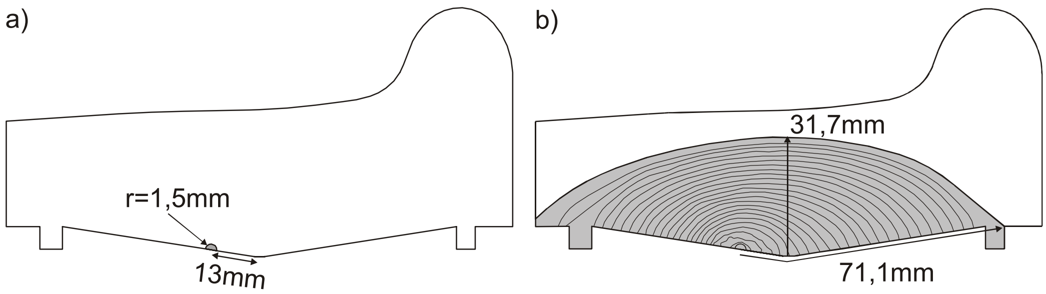

Figure 4: Numerical crack growth simulation for the ICE-wheel tyre with a diameter of 862mm and wheel contact force Q=98kN

a) Location of the initial crack at beginning of the simulation
b) Simulated crack fronts and crack size before beginning of unstable crack growth

For the purpose of simulating the crack growth in the ICE-wheel tyre with diameter of 862mm a segment of the uncracked tyre was discretized. In a first step several initial cracks with different length and depth were inserted in order to determine an appropriate crack size for beginning a crack growth simulation. By these preliminary simulations a semi-circular initial crack with radius r=1.5mm was identified to be best suited. For this crack size the calculated stress intensities exceed the Threshold value $\Delta K_{th} = 8{,}2\ \mathrm{MPam}^{1/2}$ of the wheel tyre material along the whole crack front. Since fatigue crack growth for the broken wheel tyre did not initiate at the “roof-ridge”, but shifted 13mm to the left, the initial crack with a depth of 1,5mm is located accordingly (Figure 4a). The crack growth simulation is performed for a wheel contact force Q = 98kN, which defines the maximum level of the cyclic load during the rotation of the wheel. The whole crack growth simulation covers 26 simulation steps and is performed until the fracture toughness $K_C = 86{,}8\ \mathrm{MPam}^{1/2}$ is reached.

The crack fronts, that are calculated during the simulation, can be gathered from Figure 4b. In the beginning the crack preserves its semi-circular shape, but later on the propagation along the surface is distinctly faster. Immediately before the beginning of unstable crack growth, the crack has a depth of 31.7mm and a length along the inner surface of 71.1mm. A comparison of the simulated crack growth with the real crack growth in the broken wheel tyre shows very good agreement [3].

6 EXPERIMENTAL SIMULATION OF THE FATIGUE CRACK GROWTH

Fatigue crack growth will occur under cyclic loading under certain circumstances. The crack growth rate da/dN and the cyclic stress intensity are characteristic values for fatigue crack growth. The relation of those values is depicted in a crack growth rate curve and can be experimentally determined according to the ASTM E 647 by means of appropriate specimens, e.g. CT-specimen [4]. Figure 5 shows the crack growth rate curve da/dN = f(ΔK) for the material of the wheel tyre. The Threshold value of fatigue crack growth was measured as ΔK_{th} = 8,2 MPam$^{1/2}$, the fracture toughness is given by K_C = 86,8 MPam$^{1/2}$.

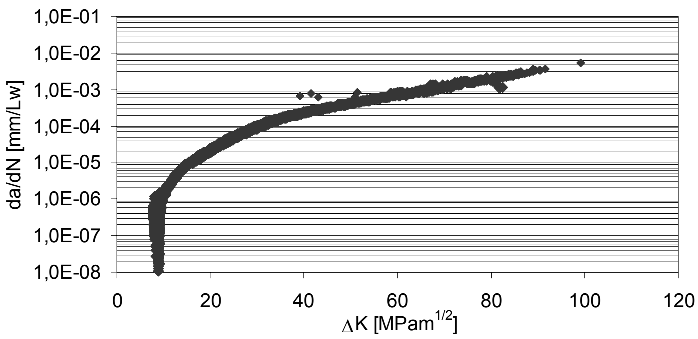

Figure 5: Crack growth rate curve for the wheel tyre material (B5)

During the experiments it becomes apparent, that the fatigue crack growth surface is distinctly more light-coloured for high crack growth rates than for low crack growth rates. Moreover a noticeable difference between the relatively smooth fatigue crack growth surface and the very rough rupture surface is evident. Light and dark colourings can also be observed under cyclic loading with variable amplitude. So e.g. modifications of the load amplitude in general create arrest lines or lighter and darker surface structures.

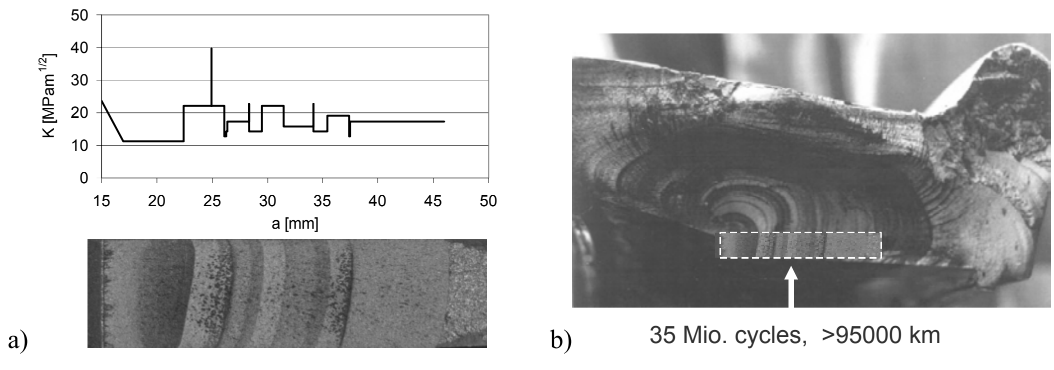

Figure 6: a) Relationship between loading and fracture surface in the experiment
b) Comparison of fracture surfaces for wheel tyre and CT-specimen

Such marks and arrest lines can also be found on the fracture surface of the ICE-wheel tyre (Figure 3). So the colourings of the CT-specimen, that were used for the evaluation of the da/dN-curves, can also be applied for the determination of the crack growth rate and the stress intensities during the crack growth in the broken wheel tyre. Those perceptions of the comparison of the colourings of the crack surfaces were applied in experiments with CT-specimen, where the probable loading history of the wheel tyre was applied (Figure 6a). For a crack growth of 30mm a lifetime of more than 35 million cycles was determined, which equals a driving length of 95000km for the ICE. Figure 6b shows a comparison of the fracture surfaces for the wheel tyre and the CT-specimen. The excellent agreement suggests, that in the wheel tyre a very discontinuous fatigue crack growth occurred.

7 CONCLUSIONS

In the case of the ICE-wheel tyre failure according to the majority of experts a sufficient security against fatigue fracture was given. This finding is true for the new as well as for the worn-off tyre with a diameter of 862mm. The initiation of the crack consequently cannot be explained by conventional strength concepts. So with the utmost possibility the fracture of the wheel tyre is an incidental event, that was absolutely not to be predicted.

Fracture mechanical evaluations show, that an initial crack with a depth of 1.5mm at the inner surface of the wheel tyre will start to grow under operational loading conditions along the whole crack front. At the beginning the crack grew semi-circular, and shifted its shape later on towards semi-elliptical with increasing crack length along the surface. After an extensive phase of stable fatigue crack growth, the final rupture occurred very late. Also an excellent agreement can be found for a crack growth simulation with wheel contact force Q= 98kN and reality.

The fatigue crack growth in the wheel tyre occurred in a very discontinuous manner, that means that phases of fast crack growth alternated with phases of slow crack growth or even temporary crack arrest. Experiments, that were performed in the Institute of Applied Mechanics at University of Paderborn with the wheel tyre material B5, suggest, that the crack growth in the wheel tyre occurred over a quite long time.

8 REFERENCES

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