FINITE ELEMENT ANALYSIS OF CRACKS PROPAGATION IN RAILWAY WHEELS

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ABSTRACT

In this paper, a new FE crack propagation method called SMART was studied in order to make a proper validation for further probable implementation. The target application field is the rail-way contact phenomena where the thermal RCF problem is required to be investigated from the crack propagation point of view on a more efficient way. Experimental test was performed previously by Peixoto to validate a sub-surface crack propagation model. The validation was performed on a CTS specimen with mixed-mode loading conditions, evaluating the crack propagation angle. Correspondingly, we used the same test apparatus but we calculated with a different method. During the analysis, Paris' law was used to model the constant propagation phase of the crack. The comparison of the previous and current results indicate that the new method performs well and shows similar values as the experimental evaluation and other FE methods. However, some of its' assumption entraps the tool from being able to analyse certainly complicated environments but the testing on a bit higher level can be started.

INTRODUCTION

In case of railway wheels, several reason can cause wheel failure which could have significant effect on the safety operation and maintenance costs.
During an intensive braking process stick-slip phenomenon can occur which causes undesirable high thermal loads on the wheel tread. On wheels where the trains are equipped with Wheel Slide Protection system (WSP) more serious temperature can arise in some specific hot-spots. This load makes to expand the wheel surface and volume under the surface as well (Zwierczyk and Váradi, 2014).

The heat expansion and the following rapid cooling makes destructive residual stresses in the material.
These occasionally occurring thermal loads and the continuous cyclic stress from the rail-wheel contact together leads to so-called Rolling Contact Fatigue (RCF) and thermal crack initiation. Such a defect on a wheel tread can be seen on Figure 1.

Figure 1: Thermal cracks on the wheel tread
(Handa and Morimoto, 2012)

Several researches investigate the mechanism of the RCF phenomena in order to estimate more and more accurately the fatigue time. These investigations are essential for ensure the vehicles to operate on even higher speeds and at the same time to be more reliable from the safety and maintenance point of view.
The aim of the paper is to represent a new efficient easy-to-use crack propagation Finite Element (FE) method which could be implemented later to examine various RCF and other fracture mechanical problems.

EXAMINATION OF FATIGUE CRACKS

In case of structural cracks, the probability of uni-directional loading is really small. Most of the times there are at least two main direction where the loading acts. As well as in case of the rolling contact between rail and wheel where the contact pressure and traction pressure cause Mode I. - opening and Mode II. - in plane shear crack loading but also Mode III - out of plane shear loading (Figure 4) for instance when a train goes through on a curved rail track part (Ekberg and Kabo, 2005).

When uni-directional load becomes a mix of tensile and shear stress (mixed mode loading) the plane of the crack propagation path changes (Biner, 2001) (Figure 2).

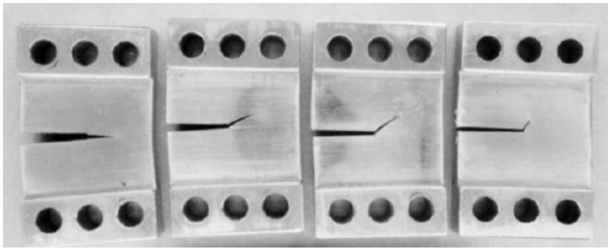

Figure 2: The direction of crack propagation in different loading directions on CTS test pieces (Biner, 2001)

The experimental evaluation of material parameters in case of mixed mode loading does not have an own standard so it is difficult and not obvious to compare the different test apparatuses.

One of the most used method is the experiment by Richard (Richard, 1985), which gives reliable information about the material properties of the crack propagation by the evaluation of the Contact Tension Shear (CTS) specimen with the proper loading device (Figure 3).

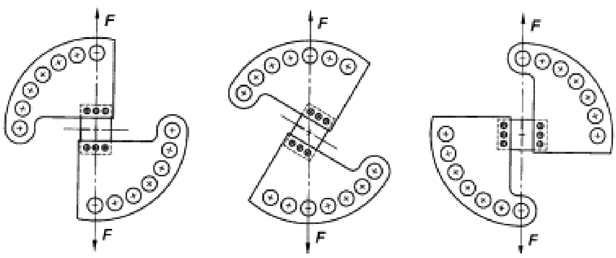

Figure 3: The geometry of the Compact Tension Shear (CTS) specimen and the loading device (Biner, 2001)

Peixoto and de Castro (Peixoto and de Castro, 2017) used this method to validate material properties of a railway wheel to perform RCF sub-surface crack propagation simulation. The validation was based on the crack propagation angle in CTS specimens. Experimental results were compared to the different numerical models.

In this paper the new so-called S.M.A.R.T. (Separation Morphing and Adaptive Re-meshing Technology) (ANSYS) crack propagation modelling method is being validated by simulating a CTS specimen in FE environment and comparing the results with the ones from the study of Peixoto and Castro (Peixoto and de Castro, 2017).

THE VALIDATION

The experiment is performed in three different loading angles: 30°, 45°, 60°, according to the article of Peixoto and de Castro (Peixoto and de Castro, 2017).

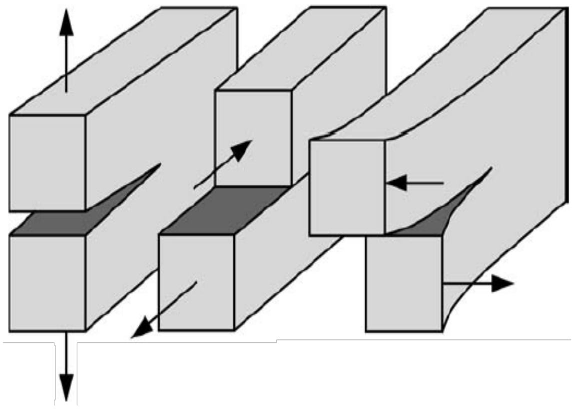

Figure 4: The loading modes of crack propagation (Ekberg and Kabo, 2005)

The crack propagation method – S.M.A.R.T.

The advantage of the S.M.A.R.T. crack propagation modelling tool is that during the crack tip movement the model is being updated simultaneously both the geometry and the FE mesh at each solution step. Also, standard elements can be used to mesh the bodies and the vicinity of the crack. Furthermore, the crack propagation studies can be scaled up, because the remeshing is only restricted to a small area in a specific radius around the crack tip. These features make the method easy-to-use for every user. Compared to other techniques the simulation can be set up by several clicks so it is no need for long preprocessing and mesh generating time to examine the path and propagation preferences of a predefined crack. The method is ready to be used for static crack growth analysis and examine J-integral or critical stress-intensity factor as fracture criteria or on the other hand, it is able to simulate fatigue crack growth as well. It is also beneficial that the user is allowed to enter any kind of crack growth law into the software for various materials. Basically, the method calculates fatigue according to the Paris' law (1), which determines the crack growth rate (Paris et al., 1961) for specific materials and load cases in the linear and stable phase (II) of the crack propagation (Figure 5):

$$\frac{da}{dN} = C\,\Delta K^m \quad (1)$$

The values of C and m are the constants of Paris' law (a is the length of the crack, N is the number of load cycles, ΔK is the stress intensity factor range), which depends on the material properties and the characteristic of the crack.

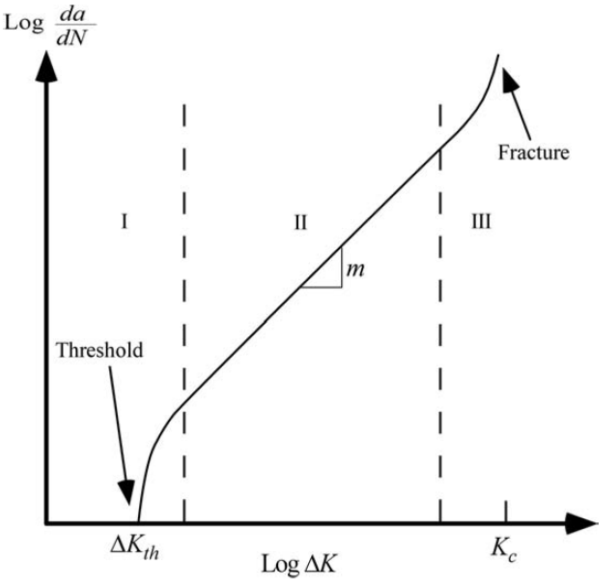

Figure 5: The behaviour of fatigue cracks in metals (Anderson, 2005)

Although the method can handle various new features it has to deal with several assumptions as well which are the followings (ANSYS):

- Multiple load steps are not supported,
- Only one crack can be defined,
- Linear Elastic Fracture Mechanics is presumed,
- 3-D Mode I dominant crack growth only,
- Large-deflection, crack-tip plasticity and crack-tip closure are ignored.

The material properties

According to the crack propagation model the material of the specimen is assumed to be homogeneous isotropic steel with linear elastic behaviour $E = 210$ GPa, $\nu = 0{,}3$.

Table 1: The constants of Paris' law for the three load cases (Peixoto and de Castro, 2017)

α	C	m
30°	2.87E-11	4.81
45°	7.49E-11	4.45
60°	3.24E-11	4.82

The geometry of the CTS specimen and the defined initial crack

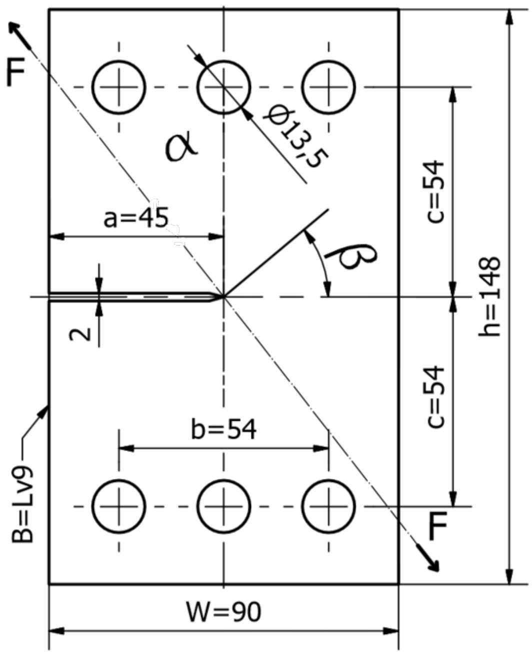

Figure 6: The CTS specimen with its' dimensions

The FE mesh

The mesh is made from tetraeder elements. The global element size is 3 mm. In the crack tip vicinity by 10mm radius the crack is condensed with 1 mm elements (Figure 7).

Boundary conditions and loads

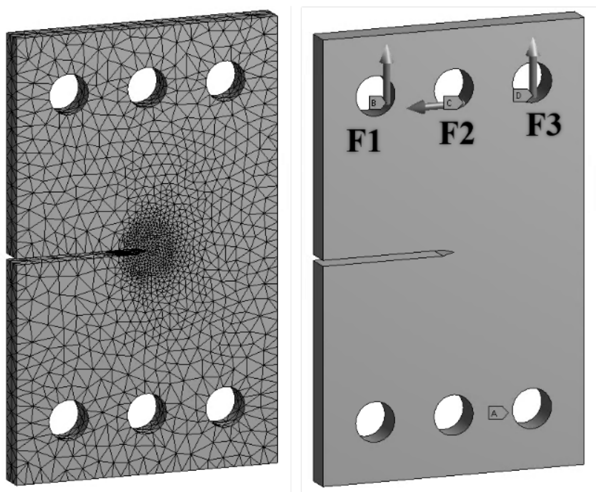

Figure 7: The mesh and the boundary conditions on the CTS specimen.

The specimen is fixed with cylindrical constraints in radial and axial directions in the holes below. The acting load is $F = 1000\,N$ force, which is divided between the three upper holes (F_1, F_2, F_3) according to the following equations (Richard, 1985):

$$F_1 = F \cdot \left(\frac{1}{2}\cos\alpha - \frac{c}{b}\sin\alpha\right), \qquad (2)$$

$$F_2 = F \cdot \sin\alpha, \qquad (3)$$

$$F_3 = F \cdot \left(\frac{1}{2}\cos\alpha + \frac{c}{b}\sin\alpha\right). \qquad (4)$$

Results

The evaluation of the study was not made from stress point of view but from physical one. Therefore, the scales on the figures are not relevant, they are only exposed to emphasize the location of the crack tip. As can be seen on Figure 8 and on Figure 9, the angle of crack propagation increases with the loading angle increasement so the tendency is corresponding as expected.

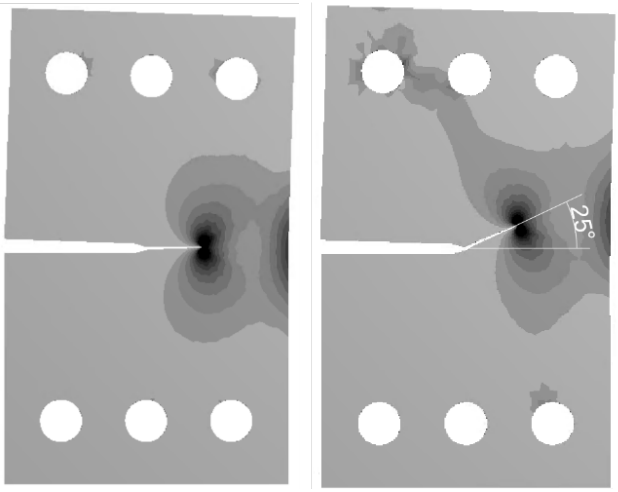

Figure 8: The β angle of crack propagation in case of $\alpha = 0°$ and $\alpha = 30°$

Table 2 summarizes the previously calculated results from (Peixoto and de Castro, 2017) and the results which is given by the new S.M.A.R.T. module in Ansys. It can be seen, that the differences between the experimental evaluation is only 1-2 degrees and compared to the other numerical studies is also not considerable.
So, it can be stated that the method calculates the angles of propagation properly related to previously published results.
It can be seen also that results given by the new S.M.A.R.T. method has minimal difference compared with the experimental results and also compared to the simply numerical and the method used by Abaqus which is applied frequently for such problems.

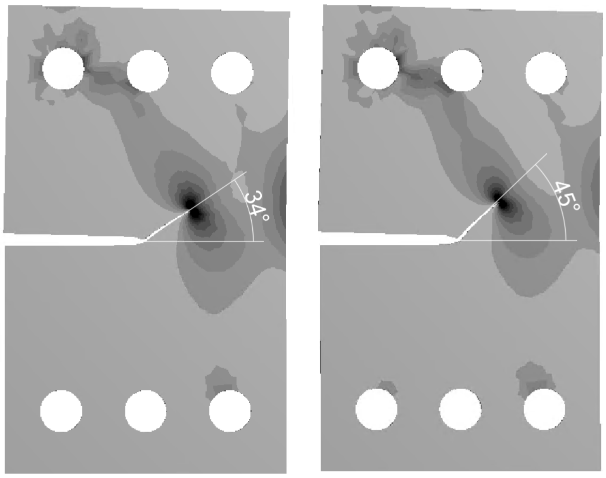

Figure 9: The β angle of crack propagation in case of $\alpha = 45°$ and $\alpha = 60°$

Table 2: The comparison of the result of Peixoto and de Castro (Peixoto and de Castro, 2017) and the SMART method

α	**30°**	**45°**	**60°**
β - Numeric	26°	37°	49°
β - Abaqus (MTS)	25°	36°	48°
β - Experimental	23°	34°	46°
β - S.M.A.R.T.	25°	34°	45°

THE IMPLEMETATION FIELD

In the presence of high temperature loads thermal micro-cracks occur on the wheel tread. By the following various cyclic loading, fatigue cracks can start from the wheel tread (Figure 10) and cause serious inconveniencies for the operators of the trains.

Figure 10: Thermal microcracks on the wheel tread and a far gone fatigue crack originated also from a micro-crack. (Wuhrer et al., 2006)

This phenomenon has been already investigated by Zwierczyk (Zwierczyk, 2015) and Váradi (Zwierczyk and Váradi, 2014) from the stress point of view. Furthermore, several efforts have been made also to investigate the thermal crack initiation phase (Figure 11) for instance by Handa et al. (Handa et al., 2010; Handa and Morimoto, 2012). But in order to understand the mechanisms of the problem a more comprehensive view is needed where the crack propagation also have to be taken into account. The future goal is to apply the method to investigate thermal crack behaviour on railway wheels in case of stopping brake circumstances.

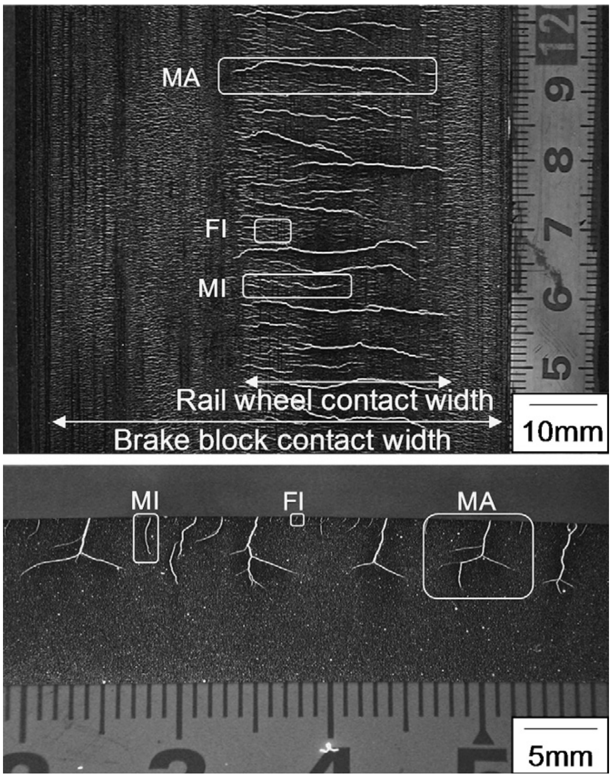

Figure 11 Thermal crack distribution on the wheel tread and the propagation paths from section view of the wheel (Handa et al., 2010)

CONCLUSIONS

The SMART method performed well in the validation with the CTS specimen. However, a fact has to be taken into account in line with the FE study. The loading from the view of the whole CTS specimen is mixed mode (Mode I., Mode II.) loading which wouldn't be possible to simulate with the method because of its' assumption. However, from the crack point of view after the change in the direction of the crack propagation path the loading mode is becoming Mode I. dominant so the tool is able to perform the study.

At the moment the method is not convenient to simulate RCF thermal cracks because of some of its' assumptions for example the ignorance of the crack-tip closure or the limited loading modes. Later, if at least the above-mentioned assumptions are going to leave off a great and really easy-to-use tool will be available to help the investigations in the field.

SUMMARY

In this study a new crack propagation modelling tool called the S.M.A.R.T. was investigated. The advantage of the module is that it automatizes the solving process by changing the geometry and remeshing the model with low effort in every iteration step continuously, so it makes the work considerably more time effective and easy-to-use.

The goal was to validate the new method according to a previous experimental evaluation of CTS specimens with mixed mode loading (Mode-I, Mode-II) by Peixoto and de Castro (Peixoto and de Castro, 2017). Based on the performed studies, it can be stated that the method completes the requirements by simulating the experimental results with only small mistakes.

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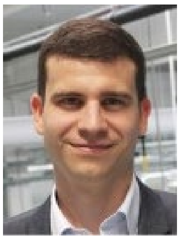

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