A VCCT APPROACH OF CRACK PROPAGATION IN RAILWAY WHEELS

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KEYWORDS

Railway wheel, RCF - Rolling Contact Fatigue, Crack propagation, Thermal cracks, FEM - Finite Element Method, Ansys, VCCT – Virtual Crack Closure Technique

ABSTRACT

In this paper, Rolling Contact Fatigue (RCF) crack propagation in the case of a railway wheel was studied in the presence of significant thermal loading. The complexity of the phenomena and the several assumptions and boundaries of the existing crack propagation modeling methods induce particular difficulties in the creation of this specific kind of contact problem. The primary purpose of the investigation was to reveal the relevancy of the Virtual Crack Closure Technique (VCCT) to see the further implementation opportunities and capabilities of the technique in solving railway RCF based problems.

INTRODUCTION

During the operation of railway vehicles, several reasons can cause wheel and rail failures, which can have a significant effect on passenger comfort and, in a worse case, on the safe operation. Consequently, continuous monitoring is required to be performed to reveal the potential source of failures. Many principles of maintenance rules are in daily use, but none of them are proved scientifically. These, rather practically defined norms, can result in inaccurate timing and also in the unnecessary scale of the maintenance, which significantly increases the costs. Furthermore, latency also can occur in the required maintenance, which can result in more severe damages that influence the operation and cause delays so indirectly affect the costs.
This investigation is a part of my research which goal is to develop a finite element crack propagation model that is able to model specific failure forms in well-defined circumstances to provide more accurate information in order to specify maintenance instructions.
In this investigation, the Virtual Crack Closure Technique (VCCT) (Krueger et al., 2013; Pirondi et al., 2015) is scoped and studied to reveal the relevancy in modeling such a complex phenomenon as the contact problem between the rail and the wheel.
The study supposed an intensive braking situation when the stick-slip phenomenon could occur, which causes undesirable high thermal loads on the wheel tread. In the case of those vehicles that are equipped with the Wheel Slide Protection system (WSP), more severe temperatures can arise in some specific hot-spots. This thermal load makes to expand the wheel surface and the thin inner volume under the surface as well (Zwierczyk and Váradi, 2014). The heat expansion and the following rapid cooling make destructive residual stresses in the material, which raises the complexity of the stress situation and the understanding of the crack propagation.

VIRTUAL CRACK CLOSURE TECHNIQUE

The VCCT is based on the assumption that the energy needed to separate a surface is the same as the energy needed to close the same surface. It was initially developed to calculate the energy release rate of a cracked body. Since then, it is widely used in case of investigating interfacial crack-growth or delamination. This method uses interface elements to simulate the fracture by separating the interface elements along a predefined path according to one or more user-specified fracture criteria, for example, the critical energy release rate. ("VCCT-Based Crack-Growth - ANSYS," Ansys - Help)

Advantages:

- Several fracture criteria are available, including a user-defined option.
- Multiple cracks can be defined in an analysis.
- The crack can be located in the material or along with the interface of the two materials.

Assumptions:

- Crack growth occurs along a predefined crack path.
- The path is defined via interface elements.

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- The analysis is quasi-static and does not account for transient effects.
- The material is linear elastic and can be isotropic, orthotropic, or anisotropic.
- Heat loading cannot be defined.

THE FE MODEL

To implement the contact problem with the VCCT method, we had to create a modeling procedure to reveal the difficulties of the investigation process. Since the technique is not able to deal with the direct heat loads in the model, an indirect way was used to include the effect of the braking process. In the first step of the procedure, a coupled transient thermal - stress analysis was performed to calculate the deformation, which is caused by the occurring heat stresses. In the second step, this additional deformation is used as the indirect heat load input of the submodel that was joined with the VCCT crack propagation method. In order to meet the fundamental drawbacks and difficulties of the method and to keep the need for the calculation capacity low at the beginning, we started the investigation with 2D models. These models need further assumptions, and a problem like RCF cannot be appropriately investigated in this way, but on the other hand, 2D models can reveal various problems which, if we are aware of the set-up time of the 3D models can be decreased drastically. The structure of the investigation process can be seen in (Figure 1). In this article, only the 3D analyses are detailed with the result of the VCCT submodel. The simulation was performed in Ansys 18.2 Workbench.

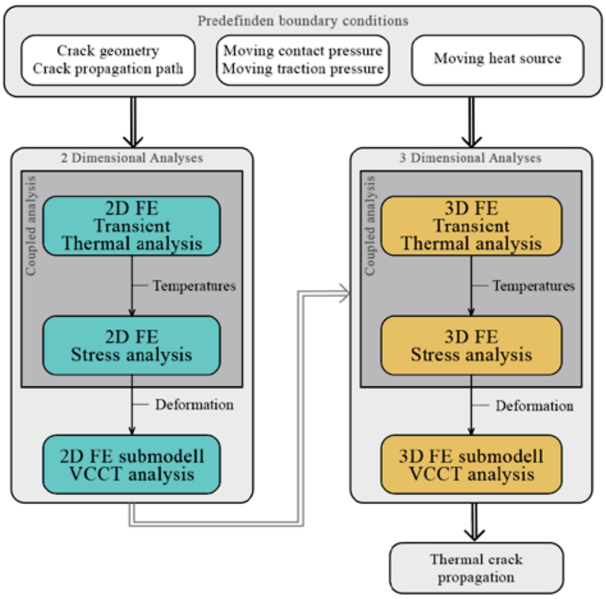


Figure 1 Schematic structure of the modeling procedure

Crack and Path as Boundary Condition

To examine crack propagation, the initial geometry of the crack has to be placed in the model. Furthermore, to perform a VCCT study, the crack propagation path is also needed to be defined.

Thermal cracks initiate from the surface and are oriented perpendicularly on the wheel thread (Figure 2). As it is an RCF phenomenon, not only the thermal loading, but the rolling contact pressure and traction pressure are also needed to develop the cracks. From the experiment of Handa et al., (Handa et al., 2010), it can be clearly seen that thermal cracks only develop within the rail-wheel contact width (Figure 2).

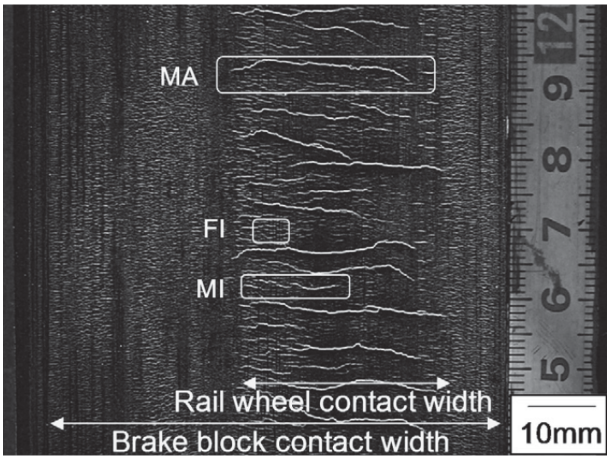


Figure 2 The distribution of thermal cracks on the wheel tread (Handa et al., 2010)

Thermal cracks propagate from the surface of the wheel nearly radial direction, then around in 3-5 mm depth (near the maximum shear stress zone) deviate (and maybe branch) and continue to propagate in the (almost) circumferential direction (Handa et al., 2010). When the cracks meet under the surface, the phenomenon of pitting can occur. Figure 3 presents different life states of thermal cracks that can be seen in the section view.

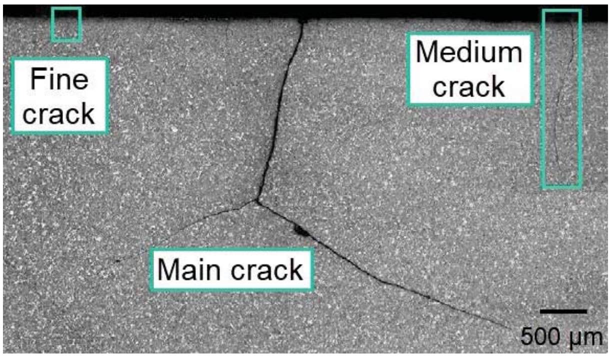


Figure 3 Different life states of thermal cracks from a longitudinal cross-section view (Handa et al., 2010)

As the boundary condition for the simulation a semi-elliptical crack was used, with the semi-axes of 0.5mm and 2 mm, placed in the middle of the rail-wheel contact width in a perpendicular position.
The crack path is assumed to start in a radial direction and then deviating into the circumferential direction in the depth of 4 mm. In this study, the first radial direction of the path was investigated.

Operational Factors

In the investigation, the wheel of a passenger car was studied during the braking process. The operational factors of the examined car are the following.

Table 1 Operational factors of the train

Train speed	v	120 km/h
Wheel slip	s	15%
Wheel sliding speed	Δv	18 km/h
Traction coefficient	μ	0.15
Vehicle weight	m	51 t

In a railroad wheel, the contact stress distribution is very complex and depends heavily on the friction forces between the two contacting surfaces and on the applied tangential forces.
In the study, the contact loading conditions of a 4-axle passenger carriage car (510 kN) were used, which were previously calculated and validated by Zwierczyk (Zwierczyk, 2015). The vertical load per wheel is F = 63,750 N. The contact pressure distributions - $p(s_t; s_p)$ on the wheel tread can be seen in Figure 7. The maximum pressure value is 1011 MPa. The size of the semi-axes of the ellipsoidal contact patch is 10 mm and 12.6 mm.

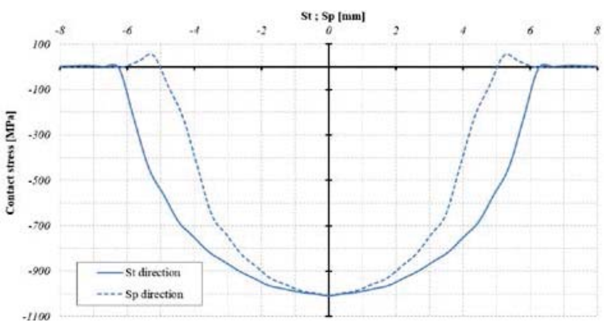


Figure 4 Contact stress distribution on the wheel tread – St - tangential; Sp - perpendicular (Zwierczyk, 2015)

The Geometry of the Examined Wheel and the Predefined Initial Crack

In the investigation, a 920 mm railway wheel was used with simplifications as the flange of the wheel rim, and the conical shape of the tread was neglected. The investigation focuses only on the near vicinity of the crack, so a smaller 20° piece (Figure 5) of the wheel was examined during the simulations.

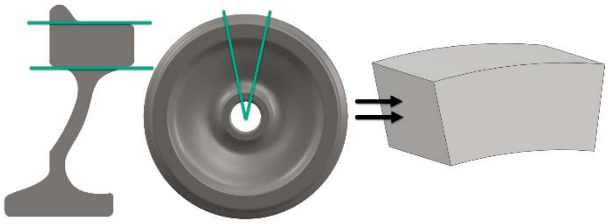


Figure 5 The major simplifications of the wheel

The simplificated 20° piece was sliced up to more sections in order to ensure the proper sectors for the meshing (Figure 6) and to apply the loads and boundary conditions.

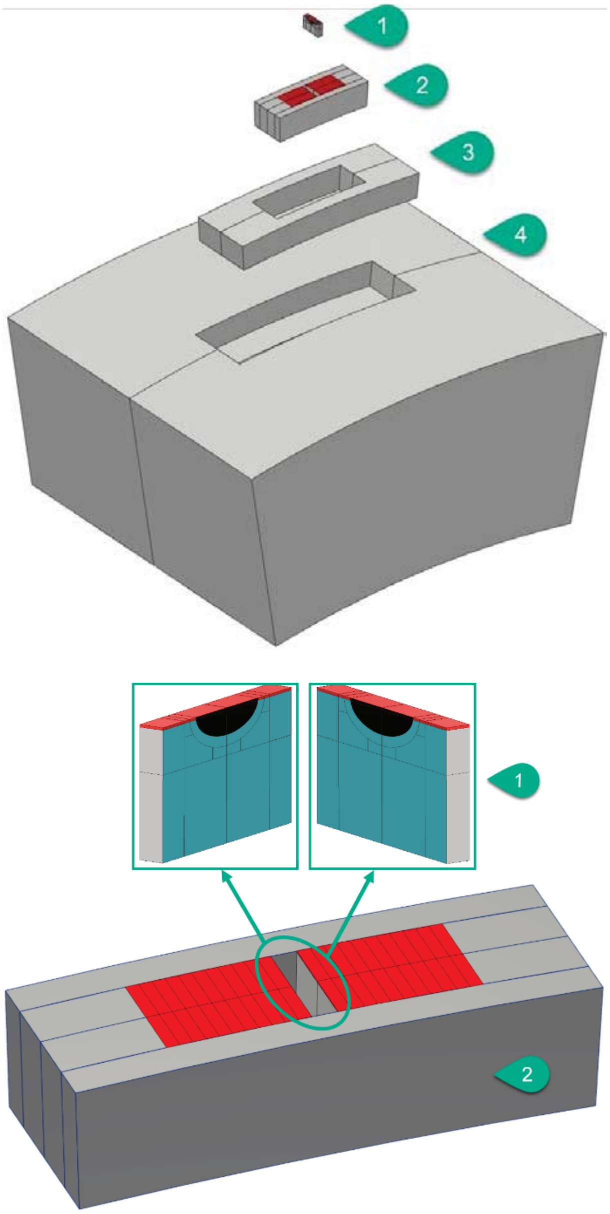


Figure 6 The sectioned wheel geometry is representing the four zones. The loading zone (red)

and the pre-defined semi-elliptical thermal crack (black) in the Crack zone

Four sections were defined according to the distance from the crack:

- 1 - *Crack Zone*: where the crack (black) and the path (turquoise) is placed.
- 2 - *Pressure Zone (red)*: where the mechanical and thermal loading is applied.
- 3 - *Further Vicinity*: transition to the further parts of the wheel.
- 4 - *Wheel Zone*: further areas of the wheel.

Loads and Boundary Conditions

The loading condition consists of three main elements:

- rolling contact pressure from the weight of the vehicle,
- tangential traction pressure caused by the sliding,
- thermal load also caused by the wheel sliding.

The Hertzian contact between the rail and wheel assumes the elliptical contact area, but to make the implementation more straightforward, the shape of the contact patch was considered to be rectangular in the model. The area of the simplified patch matches the size of the elliptical one (Figure 7) (Zwierczyk, 2015). To be able to discretize the loading on the patch, it was divided into 12 sections by 1 mm (Figure 8).
A further simplification in the model is that the rectangular patch only assumes the tangential pressure distribution, so the evaluation is based on the tangential distribution of the loadings.

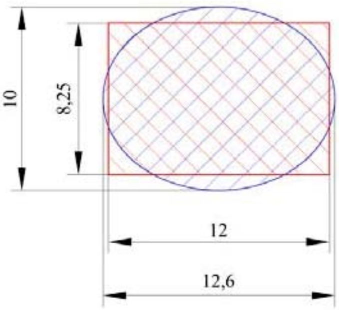


Figure 7 The simplification of the contact patch (Zwierczyk, 2015)

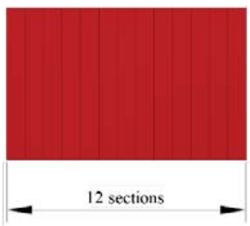


Figure 8 Sectional contact patch

The defined loads in the study were the followings:

- the contact pressure (Figure 9 / red) by Zwierczyk (Zwierczyk, 2015) in discretized form,
- the traction pressure calculated from the contact pressure (Figure 9 / blue),

$$p_t(s_t;s_p) = \mu \cdot p(s_t;s_p) \qquad (1)$$

- the discretized heat flux (Figure 9 / orange), which was based on the friction that is caused by the speed difference between the rail and the wheel during the braking condition,

$$q = \frac{Q}{A} = \frac{\mu \cdot \Delta v \cdot F}{A} \qquad (2)$$

- and the cooling effect of the air as thermal conduction all around on the surface of the wheel.

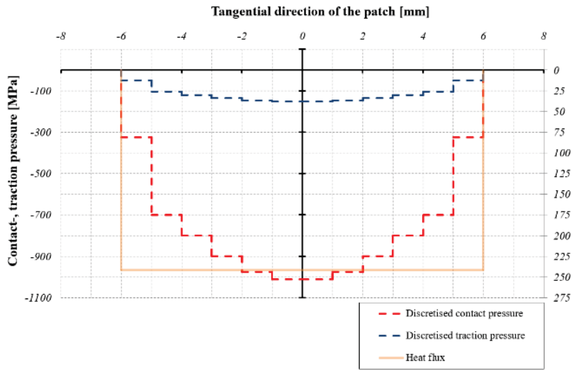


Figure 9 The discretized loading on the contact patch and their response pressure distribution

All the loads, except the colling effect, which was constant during the study, were defined on the moving patch. The patch starts from exactly before the crack (Figure 10 / green), and in the last step, it just passes. The contact patch moves 1 mm in every load cycle. The time steps were set according to the relative speed between the rail and the wheel.
To complete the model, a fixed constraint was placed on the lower edge of the geometry (Figure 10).

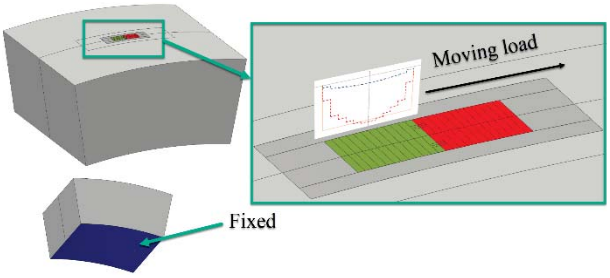


Figure 10 The applied moving loads and the fixed constraint on the bottom

Material properties

During the analysis, linear elastic material model was used. To model the wheel, the SSW-3QS wheel steel was supposed. The mechanical and thermal material properties are listed in Table 2. Also, the temperature-dependent thermal expansion coefficient was taken into account.

Table 2 Material properties of SSW-3QS steel

Poisson ratio	0.3
Young's modulus	206,000 MPa
Density	7,850 kg/m^3
Thermal conductivity	54 W/mK
Specific heat	465 J/kgK

Contacts in the FE model

All the segments of the geometry (Figure 6) were connected with bonded contacts, with Multi-Point Constraint (MPC) contact formulation theory, except the semi-elliptical thermal crack. Between the crack faces, frictionless contact was defined with Augmented-Lagrange contact formulation theory and increased stiffness to avoid the significant penetration of the surfaces into each other.

The mesh of the FE model

The mesh size changes in every sector of the geometry. In order to focus on the calculation capacity, the further areas from the crack meshed with less density, but in the crack vicinity, finer and finer mesh was defined. To match the requirements of the VCCT crack propagation method, linear hexagonal 8-nodes elements were used to mesh the geometry.

The Result of the Transient Thermal Study

The surface reached its' highest temperature in that specific load steps and locations where the whole length of the load passed. The temperature rise was only significant in close surface range in 0.1-0.2 mm deepness. The highest temperature zone was moving together with the load, but it was late by 6 segments compared to the magnitude of the mechanical load. The peak temperature was ~380 °C. After the load passed, the heat was dissipating to the air and to the deeper parts of the wheel. The temperature distribution can be seen in Figure 11.

The VCCT submodel

In the sub-simulation, the aim was to combine the results of the previous coupled study with the VCCT crack propagation method. Since the method cannot deal with direct heat loads, we imported the deformation of the coupled thermal stress study and used it as a heat representation input for the model. The sub-geometry contained the Pressure zone and the Crack zone (Figure 6), which were derived from the master model. The investigation was restricted to one load cycle because of calculation capacity restrictions. Therefore, only one load cycle was examined.

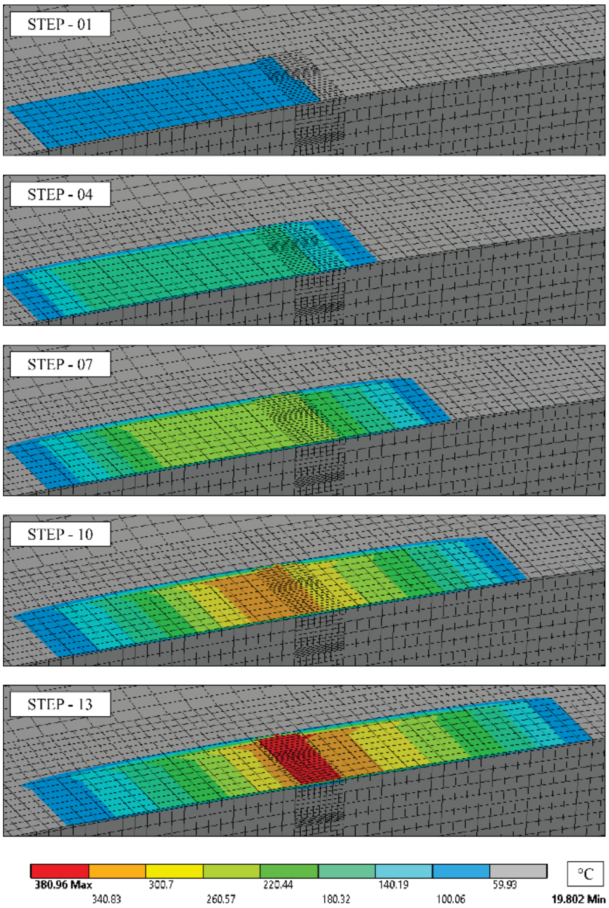


Figure 11 Temperature distribution during the passing of the load

To force the crack to propagate in already one cycle, a different Energy Release Rate had to be defined to move the propagation forward and show the behavior of the crack. The value of the Energy Release Rate was set to 100 J/m^2 in all three dimensions.
To set up the VCCT study, the crack path had to be defined. Below the crack, a 4 mm deep surface was set with interface elements that can separate in case of enough energy accumulation. Furthermore, a frictionless contact was also defined between the surfaces to avoid penetration after the moving of the crack front (Figure 12).

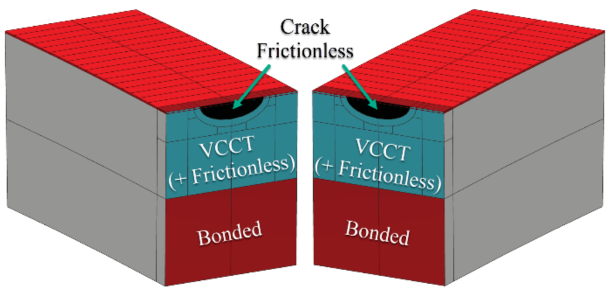
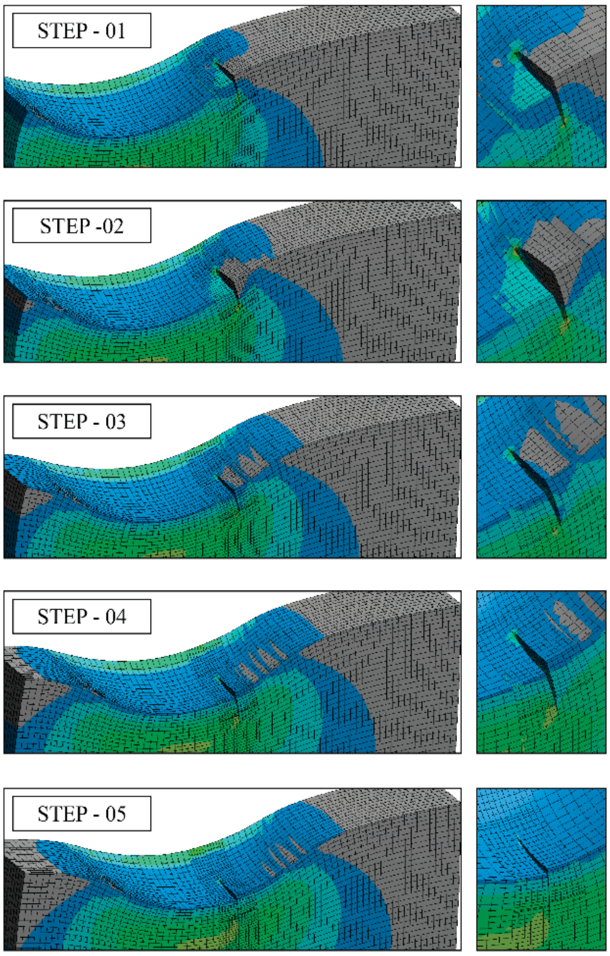


Figure 12 The delamination zone as the crack path and the bonded zone in the plane of the crack

RESULTS - CONCLUSION

The stress results are highlighted during the load pass in every time step during the load movement because the crack also propagates during the first time steps as well. The results are displayed by half geometry, split on the symmetry plane to get insight into the under-surface state of deformation and stress. The stress distribution can be seen in Figure 13.
It can clearly be seen that the crack started to propagate when the magnitude of the load approached the crack-zone, and when it was right there, the propagation stopped. When the load moved forwards and left the Crack zone, the propagation started again. From the results, the crack propagation length ratio between the two phases could be estimated. The first propagation phase from STEP-02 to STEP-05 and the second phase from STEP-09 to STEP-13 in crack growth length is proportional to each other as 1:2. The first phase is mainly driven by Mode II. shear propagation, while the second phase is rather a mixed-mode (Mode I. – Mode II.) propagation. Furthermore, the second phase propagation is longer in time because of the crack-closing effect of the braking traction pressure.
The crack does not propagate in the axial direction only in the radial. This fact is a failure in the model because the crack meant to spread in the width of the contact pressure.



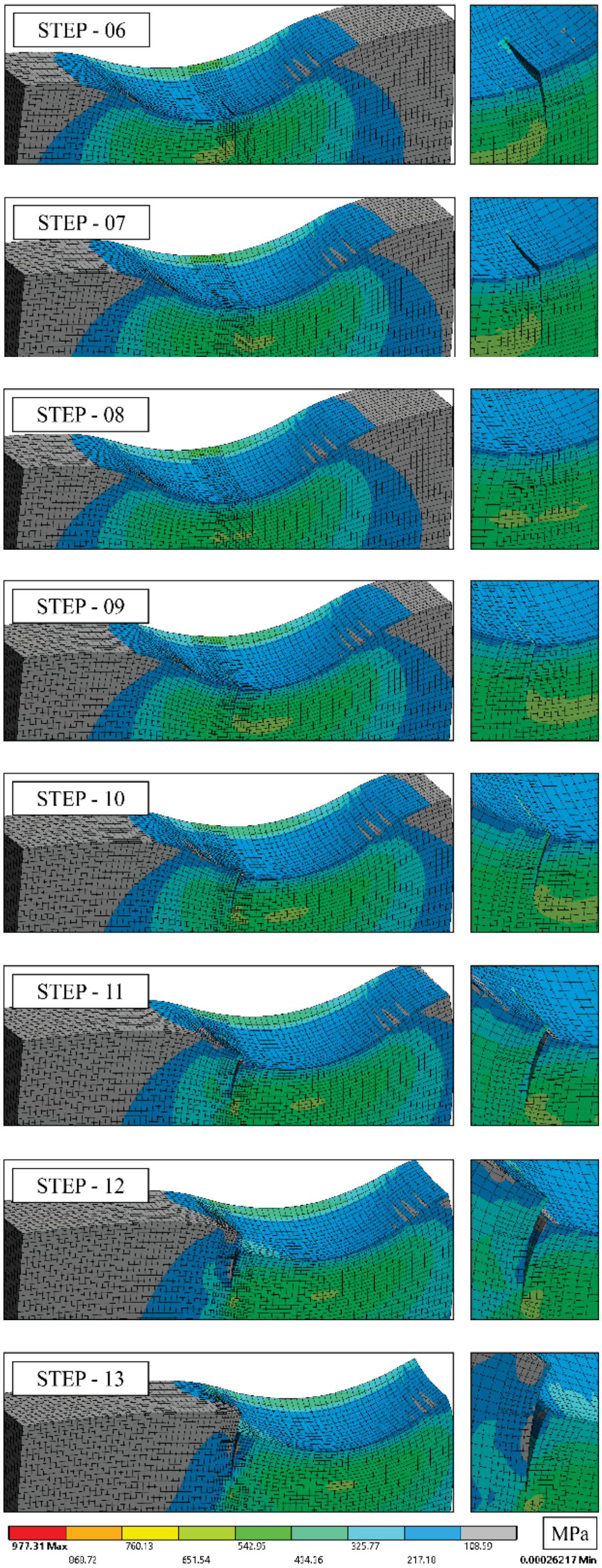


Figure 13 The von Mises stress during the passing of the load (scale: 125)

SUMMARY

The developed FE procedure is successfully implemented to the 3D environment to examine thermal crack propagation with VCCT crack growth simulation method.
The 3D model provides accurate deformation response for the contact pressure and has an appropriate answer in Hertzian stress distribution. Furthermore, the predefined energy release rate – to make the growth process even more spectacular – which helps to open the crack during one cycle of load passing showed better propagation results in the quasi-static study. Therefore, conclusions could be drawn from the connection between the two phases of the propagation.

For further developments of the model, the followings could be applied:

- Longer evaluation path to separate the different loading zones more clearly, to get a more stable temperature distribution on the surface, and to investigate the effect of the moving load when it is in the further vicinity of the crack.
- Examining more than one cycle of load pass with a modified energy-release rate to lengthen the crack propagation for the interval of the extended cycles. (If there is opportunity to use a vast amount of calculation capacity the typical energy-release rate could be used with more thousands of load cycle in the study).
- Examining a slightly bigger sub-environment of the wheel and using finer mesh in the crack vicinity.
- Application of frictional contact between the crack faces.
- Assumption of discretized pressure in the axial direction as well.
- Evaluation of the circumferential part of the thermal crack.
- Using non-linear material models.

This model can be optimized and improved from many aspects, but it has to be kept in mind that in Ansys WB environment, there is no option to perform fatigue analysis with the VCCT crack growth simulation method. Consequently, to approach the problem from fatigue point-of-view, the study has to be programmed in Ansys APDL environment.

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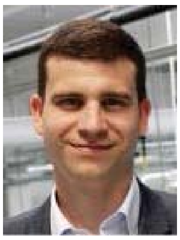

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