

Crack propagation analysis in selected railway bogie components

Adam Mystek

Institute of Railway Vehicles, Faculty of Mechanics, Cracow University of Technology

adam.myslek@poczta.onet.pl |  <https://orcid.org/0000-0002-2292-9393>

Scientific Editor: Andrzej Sobczyk, Cracow University of Technology

Technical Editor: Aleksandra Urzędowska, Cracow University of Technology Press

Language Editor: Tim Churcher, Big Picture

Typesetting: Anna Basista, Cracow University of Technology Press

Received: April 9, 2019

Accepted: June 9, 2020

Copyright: © 2020 Mystek. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing interests: The authors have declared that no competing interests exist.

Citation: Mystek, A. (2020). Crack propagation analysis in selected railway bogie components. *Technical Transactions*, e2020017.

Abstract

This paper presents the practical application of fracture mechanics in investigating the possibility of crack propagation in a brake calliper bracket mounted in a vehicle bogie. The extended finite element method available in the Abaqus software was used. This method allows the modelling of material damage and its propagation independently of the finite element mesh. Damage can arise in any area of finite elements without changing the mesh. Numerical simulation of crack propagation was performed in order to analyse how crack changes as a result of the location change of damage initiation.

Keywords: Fracture mechanics, XFEM, Abaqus

1. Introduction

In classical durability calculations, material structure is considered as solid and without any defects. It is also assumed that its properties are homogeneous and compatible with catalogue data. The calculation of stresses, even with the use of safety factors, may be associated with the risk of making an error related to the change of material properties during service, the influence of shape (effect of notches) and the discontinuity of the structure. These factors can contribute to the formation of cracks. Damage is known to occur in places where stresses do not exceed the critical value for a given material (German, 2011). Crack generally grows on a macroscopic level usually perpendicular to the main or principal stress. This is dependent on the material properties, material thickness, and the orientation of the crack relative to principal material directions (Zuo, Huang, 2018). The railway bogie is one of the critical safety components of the entire railway vehicle. It is the main power- and load-transmission component; therefore, reliability evolution is critical for the design and maintenance of the bogie components (Yamamoto, 2013). In recent years, the tendency has been to develop vehicles with lighter structures in order to increase load to tare weight ratios (Luo, Gabbittas, Brickle, 1994). There are many examples and pieces of research in literature concerning service failures and tests performed according to applicable norms for components e.g. wheel axles, side beams, and bogie frames (Cera, Mancini, Leonardi, Bertini, 2008; Seo, Hur, Jun, Kwon, Lee, 2017; Lu, Xiang, Dong, 2018).

The aim of this paper was to investigate the possibility of crack formation and propagation in welded joints used in railway bogies. As an example, the brake calliper bracket of the category II railway vehicle bogie (EN 13749:2011) was selected. The geometry of the bracket and the point where the crack was tested (ROI) are shown in Fig. 1.

The boundary conditions and loads acting on the bracket derived from the braking force and discrete model are shown in Fig. 2.

Table 1 shows the values of the forces calculated according to (EN 13749:2011) for B-II category bogies for the considered braking case.

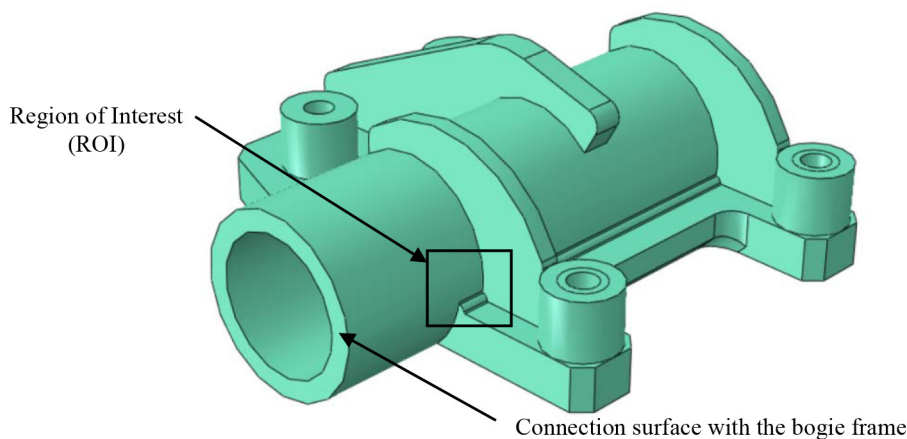


Fig. 1. Brake calliper bracket of railway bogie (own study)

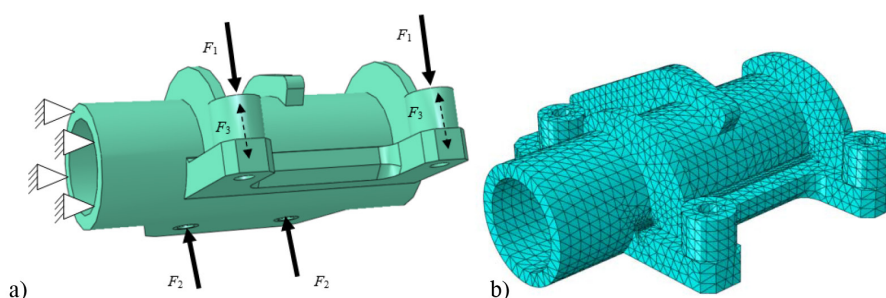


Fig. 2. Fig. 2. a) Boundary conditions and loads in calliper bracket during brake application (F_3 force acts in bolts), b) Finite element mesh with 10-node tetra-type elements used in calculations (own study)

Table 1. The values of loads acting on the bracket

F1	The force acting on the bracket from the top during braking	51.1 kN
F2	The force acting on the bracket from below during braking	12.4 kN
F3	Assembly preload of M20 bolts (VDI 2230 norm)	109 kN

The standard FEM verification for the considered case did not show a stress value that could damage the structure in the ROI (Fig. 1) for the S355 material. Figure 3 shows distributions of von Mises stresses and displacements. Stress values do not exceed the yield point. However, in real objects there could be cracks in the faces of welds at the places shown in Fig. 1, which could be caused by reasons other than excessive stresses. Therefore, there is a need to check whether or not the initiated notch would cause further development of the crack in an unfavourable direction.

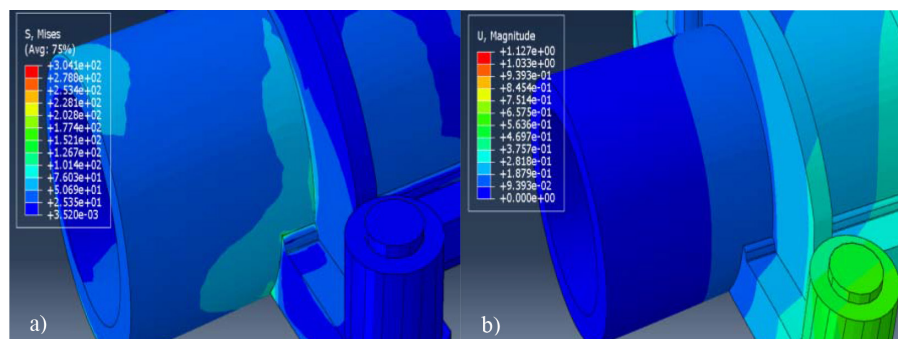


Fig. 3. Results of standard FEM calculations in the Abaqus/CAE 2018 environment: a) von Mises stress distribution for ROI~180 MPa, b) displacement distribution (own study)

2. Simulation of the crack propagation using XFEM

The total fatigue process of a mechanical component material can be divided into the following steps: microcrack nucleation, short crack growth, long crack growth and occurrence of the final failure. The first two stages are usually termed as the crack initiation period, while further stages are termed as the crack propagation period (Podrug, Glodež, Jelaska, 2011). Figure 4 shows the dependence of the limit stress σ in relation to the number of cycles of fatigue load N . The total number of stress

cycles N can then be determined from the number of stress cycles N_i required for crack initiation and the number of stress cycles N_p required for a crack to propagate to the critical crack length ($N = N_i + N_p$), in other words, to the point of final failure.

In order to better design a given mechanical element subjected to variable loads over time, it should be predicted how the propagation of cracking will affect it. For this purpose, the XFEM (extended finite element method) can be used; this is an extension of the standard finite element method. The basic concept of this method is expressed by the equation (Fries, Baydoun, 2012):

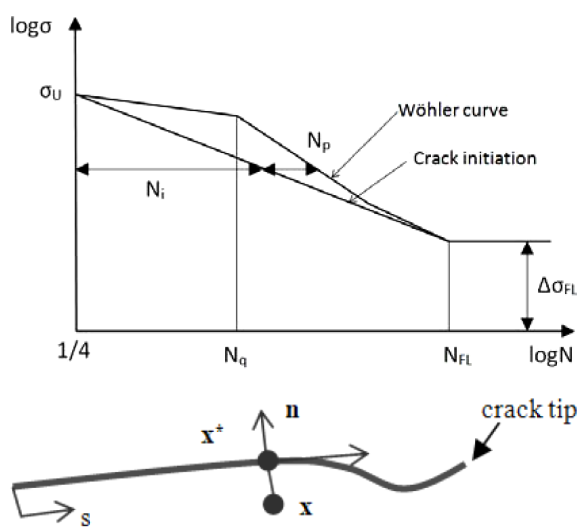


Fig. 4. Schematic representation of service life of mechanical elements with variable loads over time (Podrug, Glodež, Jelaska, 2011)

Fig. 5. Enriched nodes with additional degrees of freedom (Vu-Bac, et al., 2011)

$$\mathbf{u} = \sum_{i=1}^N N_i(\mathbf{x}) \left[\mathbf{u}_i + H(\mathbf{x}) \mathbf{a}_i + \sum_{\alpha=1}^4 F_{\alpha}(\mathbf{x}) \mathbf{b}_i^{\alpha} \right] \quad (1)$$

where:

- \mathbf{u} – displacement vector;
- N_i – shape functions;
- \mathbf{u}_i – nodal DOF vector for conventional shape functions N_i ;
- H – jump function;
- \mathbf{a}_i – additional nodal degrees of freedom vector corresponding to jump function;
- F_a – crack tip asymptotic functions (valid only for stationary crack);
- \mathbf{b}_i^a – additional nodal degrees of freedom vector corresponding to near-tip function.

The jump function associated with the crack line for enriched nodes (Fig. 5) describes the equation (acc. to Vu-Bac, et al., 2011).

$$H(\mathbf{x}) = \begin{cases} 1 & \text{for } (\mathbf{x} - \mathbf{x}^*) \cdot \mathbf{n} > 0 \\ -1 & \text{for } (\mathbf{x} - \mathbf{x}^*) \cdot \mathbf{n} < 0 \end{cases} \quad (2)$$

where \mathbf{x} is the point on the surface for which it is necessary to determine the position in relation to the location of the crack. The point \mathbf{x}^* is the nearest point of interest to the curvature of the crack, \mathbf{n} defines the normal vector to the crack at point \mathbf{x}^* .

Damage modelling is achieved through the use of a traction-separation law across the fracture surface (Fig. 6). Damage properties are specified as part of the bulk material definition.

Cracks typically propagate in a direction perpendicular to the maximum principal stress (Wang, Ren, Xie, Xie, Ai, 2016).

In this case, the crack initiation follows the criterion of a cohesive initiation of damage based on the maximum principal stress criterion (MAXPS – according to the Abaqus software environment). The crack initiation occurs when the failure criterion is met $f = 1$

$$f = \frac{\sigma_n}{\sigma_{\max}^0} \quad (3)$$

where:

- σ_{\max}^0 – maximum allowable principal stress;
- $\langle \sigma_n \rangle$ – state of purely compressive stress which doesn't lead to any damage initiation (Gigliotti, 2012).

Figure 7 shows a mixed mode stress state at the front of the crack in the cylindrical coordinate system in the context of linear elastic fracture mechanics (Wang, Ren, Xie, Xie, Ai, 2016).

The stress field in the vicinity of the crack tip for linear elastic and homogeneous materials can be described by the following equations (acc. to Wang, Ren, Xie, Xie, Ai, 2016):

$$\sigma_{rr} = \frac{1}{\sqrt{2\pi r}} \left[\frac{K_I}{4} \left(5 \cos \frac{1}{2} \theta - \cos \frac{3}{2} \theta \right) - \frac{K_{II}}{4} \left(5 \sin \frac{1}{2} \theta - 3 \sin \frac{3}{2} \theta \right) \right] \quad (4)$$

$$\sigma_{\theta\theta} = \frac{1}{\sqrt{2\pi r}} \left[\frac{K_I}{4} \left(3 \cos \frac{1}{2} \theta + 3 \cos \frac{3}{2} \theta \right) - \frac{K_{II}}{4} \left(3 \sin \frac{1}{2} \theta + 3 \sin \frac{3}{2} \theta \right) \right] \quad (5)$$

$$\tau_{r\theta} = \frac{1}{\sqrt{2\pi r}} \left[\frac{K_I}{4} \left(\sin \frac{1}{2} \theta + \sin \frac{3}{2} \theta \right) - \frac{K_{II}}{4} \left(\cos \frac{1}{2} \theta + 3 \cos \frac{3}{2} \theta \right) \right] \quad (6)$$

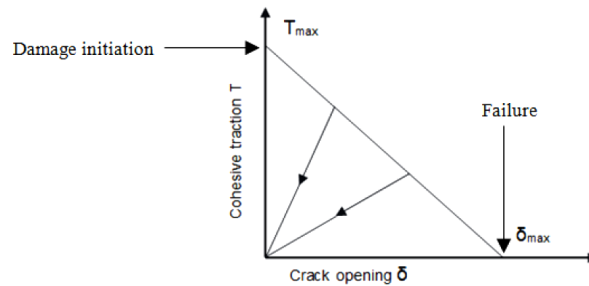


Fig. 6. Modelling fracture and failure

$$\tau_{rz} = \frac{K_{III}}{\sqrt{2\pi r}} \sin \frac{1}{2}\theta \quad (7)$$

$$\tau_{\theta z} = \frac{K_{III}}{\sqrt{2\pi r}} \cos \frac{1}{2}\theta \quad (8)$$

$$\sigma_{zz} = \begin{cases} \nu(\sigma_{rr} + \sigma_{\theta\theta}) & \text{for plane stress} \\ 0 & \text{for plane strain} \end{cases} \quad (9)$$

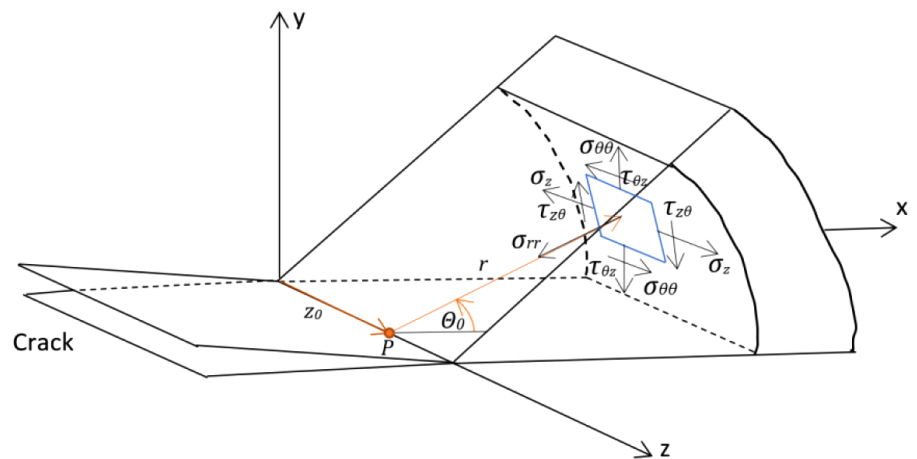


Fig. 7. 3D Crack front in cylindrical coordinates (Wang, Ren, Xie, Xie, Ai, 2016)

Polar coordinates θ , r and z are centred at the crack tip in a plane orthogonal to the crack front, ν is Poisson's ratio. K_I , K_{II} and K_{III} are the stress intensity factors for three modes. Maximum principal stress σ_1 represents the virtual cylindrical surface around the crack tip and can be written as:

$$\sigma_1 = \frac{\sigma_{\theta\theta} + \sigma_{zz}}{2} + \frac{1}{2} \sqrt{(\sigma_{\theta\theta} - \sigma_{zz})^2 + 4\tau_{\theta z}^2} \quad (10)$$

Direction of the crack propagation is perpendicular to σ_1 ; therefore, deflection angle θ^* corresponds to the extreme value of σ_1 :

$$\frac{\partial \sigma_1}{\partial \theta} = 0, \text{ and } \frac{(\partial^2 \sigma_1)}{\partial \theta^2} < 0. \quad (11)$$

The twist angle can be described by:

$$\theta^{**} = \frac{1}{2} \text{atan} \left\{ \frac{2\tau_{\theta z}}{(\sigma_{\theta\theta} - \sigma_{zz})} \right\} \Big|_{\theta=\theta_0} \quad (12)$$

3. Crack propagation study in the welded joint of the bracket

Simulation of crack propagation was performed in the Abaqus/CAE 2018 environment using the XFEM method. The software provides the solutions for stationary and non-stationary cracks. The stationary crack is characterised by the lack of the possibility of propagation and the occurrence of singularities at the tip of the fracture; the elements are enriched by asymptotic functions near the crack tip. The non-stationary (propagating) crack is characterised by the enrichment of elements in the vicinity of the intersecting crack through the jump function.

In this study, the propagation of non-stationary cracking in five positions on the bracket's joint was examined. The software provides the function PHILSM, which allows visualisation of the surface of the crack. This parameter is non-zero only for the enriched elements; it might be interpreted as the nodal coordinates of the enriched nodes in a coordinate system centred at the crack tip. The axes of this coordinate system are tangent and normal to the crack surfaces at the crack tip (Gigliotti, 2012). The STATUSXFEM function shows the status of the enriched element: for value 1, the element is completely cracked, and for 0, the element contains no crack. If the element is partially cracked, the value lies between 1 and 0.

Figure 8 shows the simplified shape and location of the weld connecting the calliper bracket elements in the ROI, as in Fig. 1. There are many of examples in the literature showing this kind of connection (filled weld) with the occurrence of cracks under loads shown in Fig. 2 (crack opening) (Sanecki, 2010; Frank 1971; Sampos, 1996). Locations 1 to 5 and the angle of the crack initiation on the weld were marked in relation to the axis of the bracket tube. Figures 9–13 show the propagation direction of the crack depending on its initial location on the face of the weld. The level of enrichment of the element is shown on the left (STATUSXFEM), on the right is the function of PHILSM.

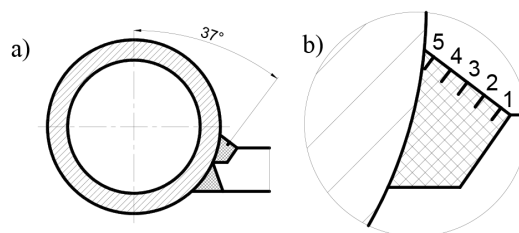


Fig. 8. Sketch of weld with initial cracks: a) tilt angle, b) 5 locations' (own study)

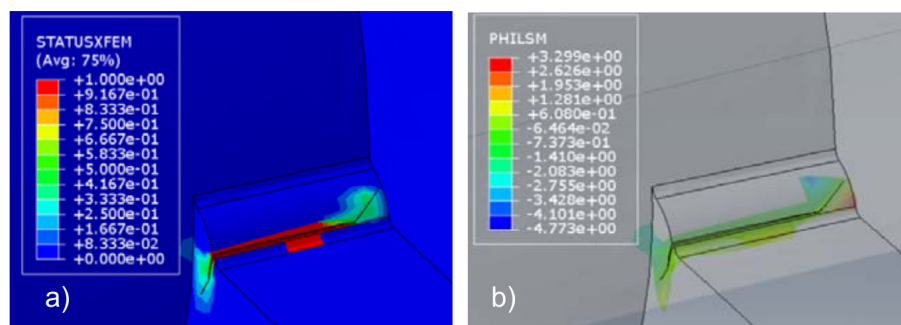


Fig. 9. Propagation of the crack in location <1> (own study)

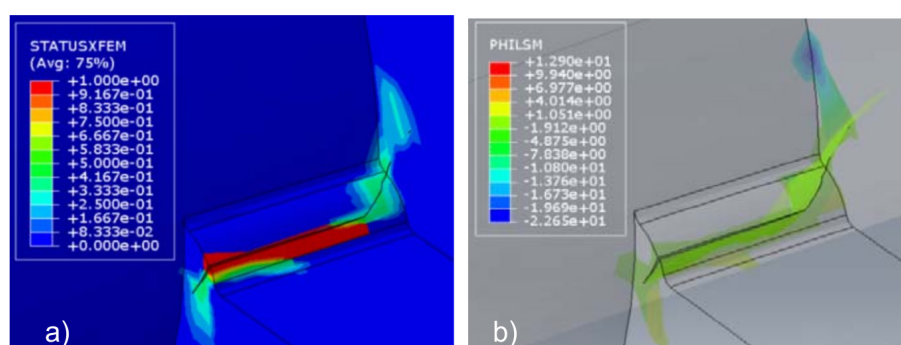


Fig. 10. Propagation of the crack in location <2> (own study)

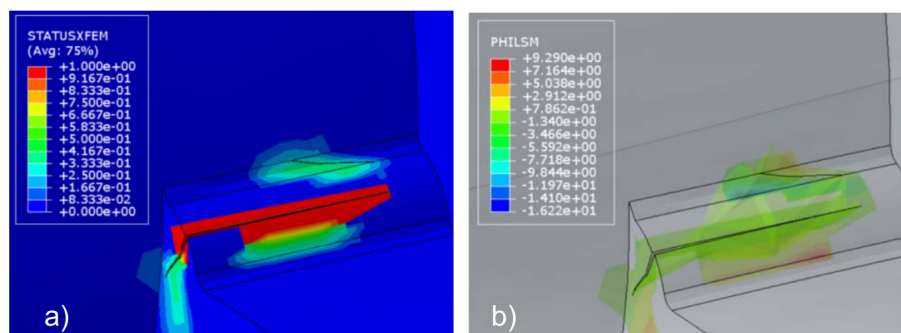


Fig. 11. Propagation of the crack in location <3> (own study)

Fig. 12. Propagation of the crack in location <4> (own study)

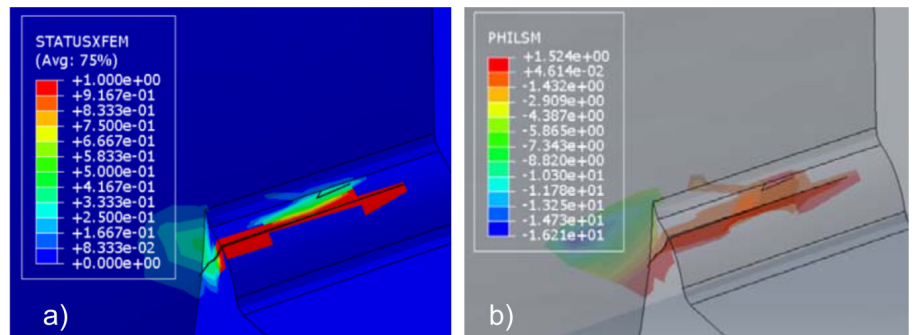
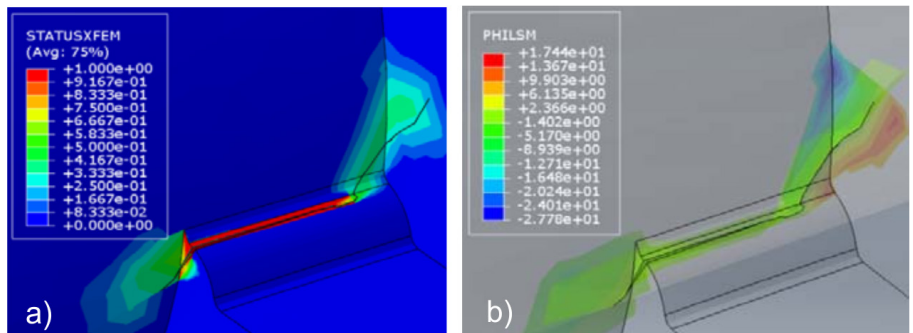


Fig. 13. Propagation of the crack in location <5> (own study)



Figures 15–17 show the results of the analysis of propagation direction of the fracture in a critical position <5> with the change of the angle inclination (Fig. 14) of the crack in relation to the initial angle of the crack (as in Fig. 8).

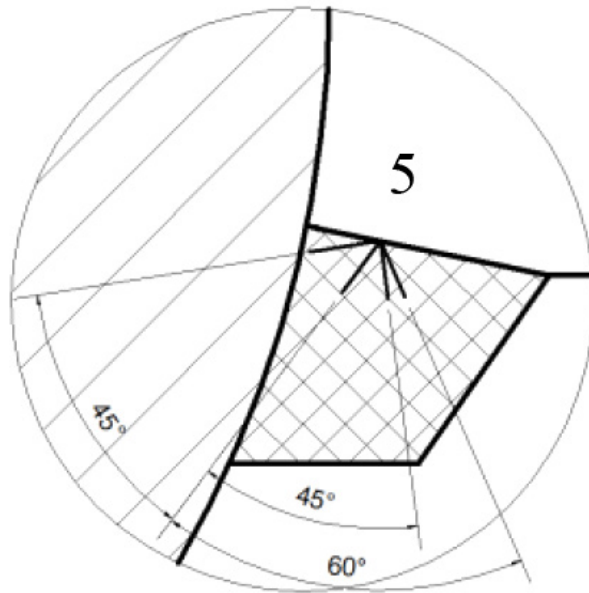
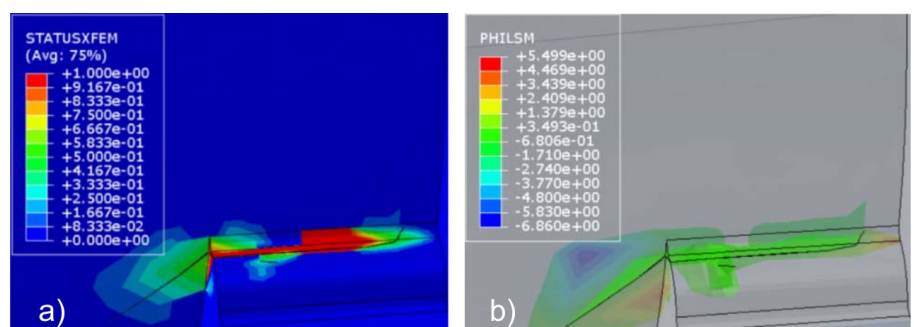


Fig. 14. Sketch of angle inclination change in relation to initial <5> position of the crack (own study)

Fig. 15. Effect of change of angle inclination of up to 45° on the course of crack propagation (own study)



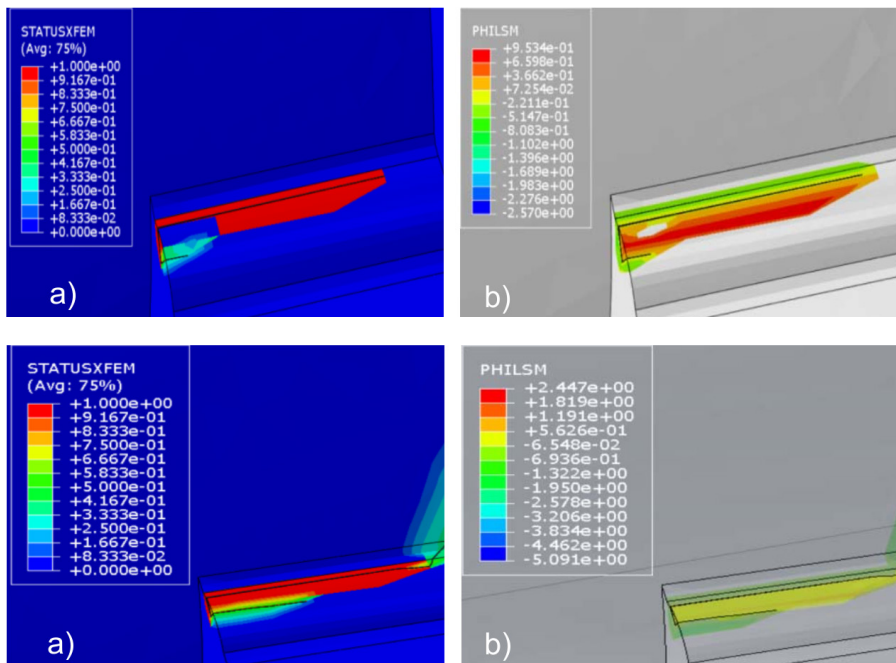


Fig. 16. Effect of change of angle inclination of up to -45° on the course of crack propagation (own study)

Fig. 17. Effect of change of angle inclination of up to -60° on the course of crack propagation (own study)

4. Conclusions

This paper presents the simulation results of fracture propagation using the XFEM method in welded joints used in railway bogies. For this purpose, five fracture initiation locations were examined and a qualitative damage risk assessment of the element was made. On the basis of Figs. 9–13, it can be concluded that the “extreme” locations of the crack initiations <1>, <2> and <5> on the weld cause propagation which gives the risk of complete failure of the mechanical structure. The results of the tests shown in Figs. 15–17 prove that the risk of damage decreases when the angle of initiation of the crack is changed counter-clockwise – the damage then only covers the face of the weld. The method gives the opportunity to trace more similar connections and can effectively contribute to the improvement of the quality of designed devices exposed to fatigue loads.

References

- Cera, A., Mancini, G., Leonardi V., Bertini L. (2008). Analysis of Methodologies for Fatigue Calculation for Railway Bogie Frames. *8th World Congress on Railway Research R.1.1.3.2*, Seoul.
- EN 13749:2011. Railway applications. Wheelsets and bogies. Methods of specifying structural requirements of bogie frames.
- Frank, K.H. (1971). *The fatigue strength of fillet welded connections*. Lehigh: Lehigh University.
- Fries, T.P., Baydoun, M. (2012). Crack propagation with the extended finite element method and a hybrid explicit-implicit crack description. *International Journal for Numerical Methods in Engineering*, 89(12), 1527–1558. doi: <http://dx.doi.org/10.1002/nme.3299>
- German, J. (2011). *Wprowadzenie do mechaniki pękania*. Kraków: Politechnika Krakowska.
- Gigliotti, L. (2012). Assessment of the applicability of XFEM in Abaqus for modelling crack growth in rubber. Master Thesis, Sweden: Royal Institute of Technology.

- Leven, M.R., Daniel, R. (2012). Stationary 3D crack analysis with Abaqus XFEM for integrity assessment of subsea equipment. Master Thesis, Sweden: Chalmers University of Technology.
- Luo, R.K., Gabbitas, B.L., Brickle, B.V. (1994). Fatigue Life Evaluation of a Railway Vehicle Bogie Using an Integrated Dynamic Simulation. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 208(2), 123–132. https://doi.org/10.1243/PIME_PROC_1994_208_242_02
- Podrug, S., Glodež, S., Jelaska, D. (2011). Numerical Modelling of Crack Growth in a Gear Tooth Root. *Strojniški vestnik - Journal of Mechanical Engineering*, 57(7–8), 579–586. <http://dx.doi.org/10.5545/sv-jme.2009.127>
- Samos, A.G. (1996). *Fracture of fillet welds under extreme loading*. Massachusetts: Massachusetts Institute of Technology.
- Sanecki, H. (2010). Propagacja szczeliny. In H. Sanecki (Eds.), *Problemy kontaktu i pękania w analizie wytrzymałościowej elementów maszyn* (pp. 128–146). Kraków: Politechnika Krakowska.
- Seo, J.W., Hur, H.M., Jun, H.K., Kwon, S.J., Lee, D.H. (2017). Fatigue Design Evaluation of Railway Bogie with Full-Scale Fatigue Test, *Advances in Materials Science and Engineering*, 2017, 1–11. <https://doi.org/10.1155/2017/5656497>.
- VDI 2230 norm. (2015). Systematic calculation of highly stressed bolted joints with one cylindrical bolt, Annex A. Calculation tables.
- Vu-Bac, N., et al. (2011). A Node-Based Smoothed eXtended Finite Element Method (NS-XFEM) for Fracture Analysis. *CMES-Computer Modeling in Engineering & Sciences*, 73(4), 331–356. <https://doi.org/10.3970/cmcs.2011.073.331>
- Wang, J., Ren, L., Xie, L.Z., Xie, H.P., Ai, T. (2016). Maximum mean principal stress criterion for three-dimensional brittle fracture. *International Journal of Solids and Structures*, 102–103, 142–154. <https://doi.org/10.1016/j.ijsolstr.2016.10.009>
- Yamamoto, M. (2013). Research and Development of Fatigue Issues for Railway Steel Products and Future Prospects. *Nippon steel and sumitomo metal technical report*, 105, 24–40.
- Y Lu, Y.H., Xiang, P.L., Dong, P. et al. (2018). Analysis of the effects of vibration modes on fatigue damage in high-speed train bogie frames. *Engineering Failure Analysis*, 89, 222–241.
- Zuo, F., Li, Y., Huang, H. (2018). Reliability analysis for fatigue damage of railway welded bogies using Bayesian update based inspection. *Smart Structures and Systems*, 22(2), 193–200. <https://doi.org/10.12989/sss.2018.22.2.193>

Analiza propagacji pęknięć w wybranych elementach wózków kolejowych

Streszczenie

W artykule przedstawiono praktyczne zastosowanie mechaniki pęknięcia w badaniu możliwości propagacji pęknięć w wsporniku zacisku hamulca zamontowanym w wózku pojazdu. Zastosowano rozszerzoną metodę elementów skończonych dostępną w oprogramowaniu Abaqus. Ta metoda umożliwia modelowanie uszkodzeń materiału i jego rozprzestrzenianie się niezależnie od siatki elementów skończonych. Uszkodzenie może powstać w dowolnym obszarze elementów skończonych bez zmiany siatki. Przeprowadzono numeryczną symulację propagacji pęknięć w celu analizy zmian propagacji w wyniku zmiany lokalizacji inicjacji uszkodzeń.

Słowa kluczowe: mechanika pęknięcia, XFEM, Abaqus