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I+II mixed mode fatigue crack propagation under combination of tensile loading and corrosion in a HSS specimen

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Abstract

Both fatigue and corrosion are two phenomena that can be very often found in metallic components. Thus, it is necessary to study their mutual effect. In this paper, a high strength steel specimen was modelled via finite element method in order to investigate the interaction of a fatigue crack and a corrosion pit. Particularly, a rectangular specimen with a corrosion pit and a nearby angled crack under remote tensile loading was modelled and the crack deflection angle was investigated via MTS and SED criteria for various crack lengths and various crack inclination angles. The results obtained clearly show how the crack behavior is affected by the presence of the corrosion pit.

Keywords: High-strengt steels; finite element analysis; corrosion pits; stress concentration

1. Introduction

Lots of engineering components are often subjected during their service life to various unfavorable working environment. It is well known, that any contact of a common metal structure with water can cause development of corrosion pits in its surface area which is undesirable and it can lead to degradation of the lifetime of such a component. Some studies on corrosion phenomenon have been published by Rajasankar and Iyer (2006), Singh

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(2015), Kubzová et al. (2020). Additionally, mechanical and/or other kind of loading strains the component as well. Therefore, there is a large demand to investigate how corrosion defects interact with other ones, such as notches, cracks etc. Particularly, mutual interaction between corrosion and a fatigue crack is investigated within this work. Whereas in works of Klesnil & Lukáš (1992), Schütz (1996), Cui (2002) or Zerbst et al. (2002) are devoted solely to investigations on fatigue phenomenon, other publications by DuQuesnay et al. (2003), Jiang et al. (2009), Kunz et al. (2012), Brennan (2014), Wang et al. (2014), Jiang et al. (2018), Seitl et al. (2019) or Xue et al. (2020), Chen et al. (2021) or Shojai et al. (2022) contain some basic research on combination of both kinds of damages. Bodd et al. (1992), Richard (2001) and Richard et al. (2014) take attention on fatigue crack growth in steels under mixed mode I and II loading.

Particularly, a rectangular specimen with an angled crack subjected to remote tensile loading is modelled numerically via finite element method and the main goal is to analyse how the crack propagation is influenced by the presence of a corrosion pit located in the very close vicinity (0.1 mm) of the sharp edge-crack in High Strength Steel (HSS) specimen. Two selected fracture criteria are applied for estimation of the initial crack propagation angle and various geometry parameters of both defects can be easily changed in order to investigate the effect of individual parameters. See the following sections for more details.

Nomenclature

a	crack length
const	distance between the crack and the corrosion pit edge
D	corrosion pit depth
E	Young's modulus
K_{I}	mode I stress intensity factor
K_{II}	mode II stress intensity factor
L	specimen length
P	corrosion pit half-length
W	specimen width
γ	initial crack inclination angle
κ	Kolosov's constant
μ	shear modulus
ν	Poisson's ratio
θ	crack deflection angle
Σ	strain energy density factor
$\Delta\sigma_{\mathrm{appl}}$	applied stress range
σ_{rr}	radial stress
$\sigma_{\mathrm{r\theta}}$	shear stress
$\sigma_{\theta\theta}$	tangential stress

2. Geometry and numerical model

The numerical study was performed on a rectangular specimen subjected to remote tensile loading. A passing loading cycle was considered with the stress ratio $R = 0$. In the center of the specimen, an angled crack was modelled and nearby, a corrosion pit as a circular segment with defined parameters was created. The dimensions used within the numerical analysis can be seen in Fig. 1 and their values are introduced in Tab. 1.

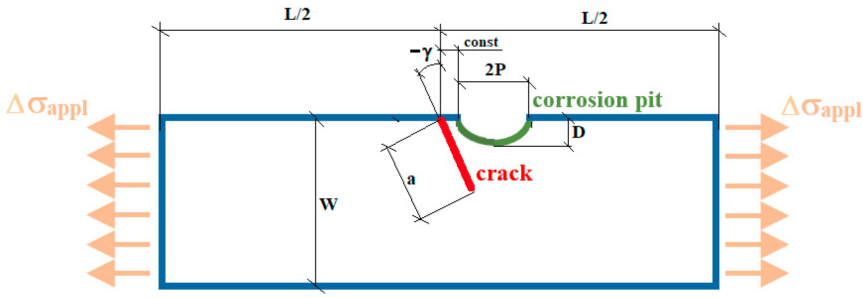

Fig. 1. Scheme of the cracked geometry with the nearby corrosion pit subjected to remote tensile loading.

Whereas the basic geometric parameter (such as specimen length and width, corrosion pit length and depth, distance between the fatigue crack and the corrosion pit) were kept constant, the crack length and its initial angle varied parametrically (see Tab. 1 for more details) and their influence on the crack behavior (crack deflection angle) was studied.

Table 1. Values of the parameters used within the numerical simulations, see Fig. 1 for more details about the symbols.

Parameter	Value	Unit
Specimen length, L	100	mm
Specimen width, W	10	mm
Corrosion pit length, $2P$	2	mm
Corrosion pit depth, $D = P/2$	0.5	mm
Distance between the crack and the corrosion pit, *const*	0.1	mm
Crack length, a	0.1 to 4	mm
Initial crack angle, γ	-45 to 45	°
Young's modulus, E	210	GPa
Poisson's ratio, ν	0.3	-
Applied stress range, $\Delta\sigma_{appl}$	300	MPa

The material of the model was considered as linear elastic and its elastic properties correspond to common values defined for high strength steels.

The 2D numerical model was created in a commercial finite element computational system ANSYS. The specimen was considered as two-dimensional under plane strain conditions and modelled via PLANE183 elements. Numerical simulations were performed in order to obtain basic fracture parameters necessary for application of fracture criteria for estimation of the initial crack deflection angle.

3. Fracture criteria

Two main basic fracture criteria were applied in order to estimate the initial crack deflection angle in dependence on the crack length and its original orientation with respect to the corrosion pit. The criteria are mentioned in the next subsections and note that a literature survey about mixed mode criteria could be found for instance in Qian and Fatemi (1996), Rozumek and Macha (2009) etc.

3.1. Maximum Tangential Stress (MTS) criterion

MTS criterion, see more details in Erdogan and Sih (1963), is generally based on the idea that a crack will propagate in the direction of the maximum tangential stress. This condition can be mathematically formulated as:

$$\frac{\partial \sigma_{\theta\theta}}{\partial \theta} = 0 \text{ and } \frac{\partial^2 \sigma_{\theta\theta}}{\partial \theta^2} < 0 \,. \tag{1}$$

The angle, where this condition is fulfilled, can be searched either purely numerically (when the tangential stress is known at a certain radial distance from the crack tip) or an explicit solution can be found if it is assumed that the crack-tip stress field is controlled only by the first singular terms of the Williams series expansion:

$$\theta = 2\arctan\frac{-2K_{\mathrm{II}}}{K_{\mathrm{I}}+\sqrt{K_{\mathrm{I}}^2+8K_{\mathrm{II}}^2}} \,. \tag{2}$$

K_{I} and K_{II} represent the stress intensity factors corresponding to mode I and II, respectively.

3.2. Strain Energy Density (SED) criterion

SED criterion, described for instance in Sih (1973) or Sih (1974), assumes that a crack will deflect into a direction where the strain energy density is minimum. Mathematical expression of such a condition looks like:

$$\frac{\partial \Sigma}{\partial \theta} = 0 \;\; and \;\; \frac{\partial^2 \Sigma}{\partial \theta^2} > 0 \,, \text{ where } \Sigma = \frac{1}{2\mu}\left[\frac{\kappa+1}{8}(\sigma_{rr}+\sigma_{\theta\theta})^2 - \sigma_{rr}\sigma_{\theta\theta} + \sigma_{r\theta}^2\right] \,. \tag{3}$$

As can be seen from Eq. 3, knowledge of stress tensor components in the cylindrical coordinate system is necessary. μ represents the shear modulus, κ stands for Kolosov's constant and Σ denotes the strain energy density factor.

4. Results and discussion

During the analysis, crack deflection angles were studied by means of the above-mentioned fracture criteria considering its one-parameter form. The values were calculated both for various initial crack lengths and for various initial crack inclination angles. The results can be seen in Fig. 2, where also the positive/negative sign of the crack deflection angle is schematically showed.

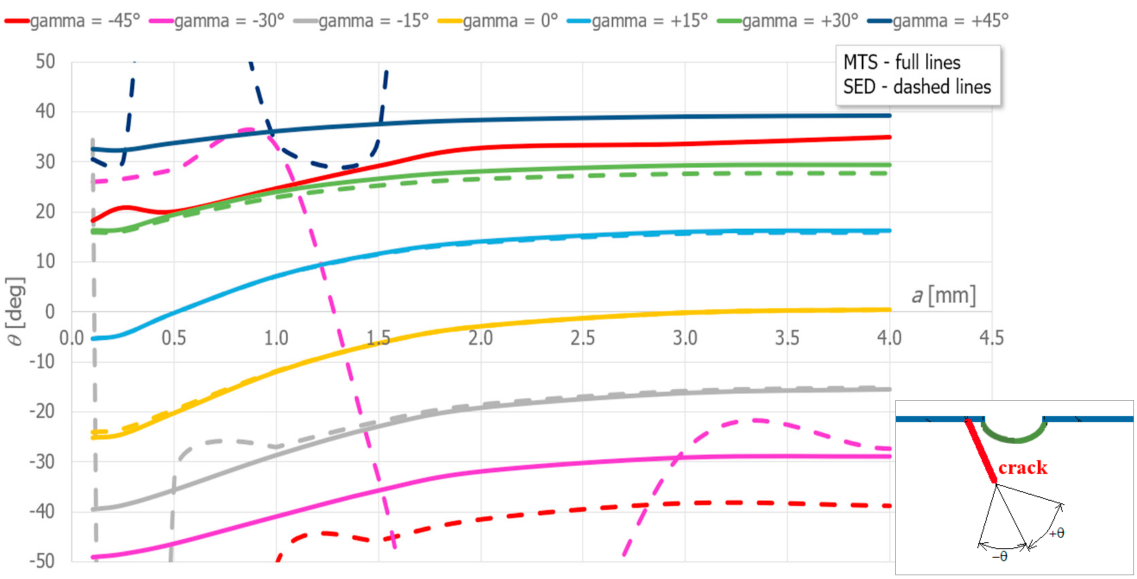

Fig. 2. Crack deflection angle in dependence on the initial crack length for various initial crack inclination angles obtained via MTS and SED criterion.

The dependences plotted in Fig. 2 enable to formulate following statements:

- There exist numerical instabilities in the solution for several configurations (typically when the SED criterion is applied or the results from the MTS criterion for the angle $\gamma = 45°$ should be negative not positive).
- Longer cracks behave in agreement with the assumption of their propagation perpendicularly to the remote tensile loading.
- The decreased values of the crack deflection angle calculated for shorter cracks indicates the influence of the corrosion pit on the crack propagation:
  - Particularly, the corrosion pit tries to deflect the crack away from the location where it exists.
  - This effect is more obvious for cracks initially inclined towards the corrosion pit (with negative γ angle as plotted in the specimen scheme).

Note that the results presented are a part of a more complex (numerical + experimental) analysis on corroded HSS specimens, see for instance works as Malíková et al. (2022a), Malíková et al. (2022b) etc.

5. Conclusion

Numerical analysis on a rectangular cracked and corroded specimen was performed to investigate the effect of a corrosion pit on further propagation of a nearby inclined fatigue crack. One-parameter form of MTS and SED criterion was applied to estimate the crack deflection angle and the results show that especially short cracks are deflected to a direction away from the corrosion pit. This behavior is more apparent when the initial crack is oriented towards the corrosion pit location. Thus, the mutual interaction of both defects is proved and needs to be taken into account when such a damaged component is assessed.

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References

Bodd, P. E., Brown, M. W., Allen. R. J., 1992 A review of fatigue crack growth in steels under mixed mode I and II loading. Fatigue and Fracture of Engineering Materials and Structures 15, 965–977.

Brennan, F. P., 2014. A framework for variable amplitude corrosion fatigue materials tests for offshore wind steel support structures. Fatigue and Fracture of Engineering Materials and Structures 37(7), 717–721.

Chen, Ch., Jie, Z., Wang, K., 2021. Fatigue life evaluation of high-strength steel wires with multiple corrosion pits based on the TCD. Journal of Constructional Steel Research 186, paper 106913.

Cui, W., 2002. A state-of-the-art review on fatigue life prediction methods for metal structures. Journal of Marine Science and Technology 7(1), 43–56.

DuQuesnay, D. L., Underhill, P. R., Britt, H. J., 2003. Fatigue crack growth from corrosion damage in 7075-T6511 aluminium alloy under aircraft loading. International Journal of Fatigue 25(5), 371–377.

Erdogan, F., Sih, G. C., 1963. On the crack extension in plates under plane loading and transverse shear. Journal of Basic Engineering 55, 519–525.

Jiang, C., Wu, C. Jiang, X., 2018. Experimental study on fatigue performance of corroded high-strength steel wires used in bridges. Construction and Building Materials 187, 681–690.

Jiang, J. H., Ma, A. B., Weng, W. F., Fu, G. H., Zhang, Y. F., Liu, G. G., Lu, F. M., 2009. Corrosion fatigue performance of pre-split steel wires for high strength bridge cables. Fatigue and Fracture of Engineering Materials and Structures 32(9), 769–779.

Klesnil, M, Lukáš, P., 1992. Fatigue of Metallic Materials. Elsevier Science Publishers, Amsterdam. 270 p.

Kubzová, M., Křivý, V., Kreislová, K., 2020. Probabilistic prediction of corrosion damage of steel structures in the vicinity of roads. Sustainability. BASEL: MDPI Open Access Publishing, 12(23), paper 9851.

Kunz, L., Lukáš, P., Klusák, J. 2012. Fatigue Strength of Weathering Steel. Materials Science 18(1), 18–22.

Malíková, L., Doubek, P., Juhászová, T., Klusák, J., Seitl, S., 2022a. Interaction of a fatigue crack and a corrosion dimple in a high-strength steel specimen. Procedia Structural Integrity 42, 1082–1089.

Malíková, L., Doubek, P., Juhászová, T., Seitl, S., 2022b. Fracture parameters of a perpendicular crack with its tip close to a corrosion pit. Transactions of VSB – Technical University of Ostrava, Civil Engineering Series 22(2), 30–34.

Rajasankar, J., Iyer, N. R., 2006. A probability-based model for growth of corrosion pits in aluminium alloys. Engineering Fracture Mechanics 73(5), 553–570.

Schütz, W.A., 1996. A history of fatigue. Engineering Fracture Mechanics 54(2), 263–300.

Seitl, S, Miarka, P., Pokorný, P., Klusák, J., 2019. Influence of corrosion on fatigue behaviour of old crane runway steel. Journal of Strain Analysis for Engineering Design 54, 416–423.

Shojai, S., Schaumann, P., Braun, M., Ehlers, S., 2022. Influence of pitting corrosion on the fatigue strength of offshore steel structures based on 3D surface scans. International Journal of Fatigue 164, paper 107128.

Sih, G. C., 1973. Some basic problems in fracture mechanics and new concepts. Engineering Fracture Mechanics 5, 365–377.

Sih, G. C., 1974. Strain energy density factor applied to mixed mode crack problems. International Journal of Fracture Mechanics 10, 305–321.

Singh, A. K., Reddy, G. M., Rao, K. S., 2015. Pitting corrosion resistance and bond strength of stainless steel overlay by friction surfacing on high strength low alloy steel. Defence Technology 11(3), 299–307.

Qian, J., Fatemi, A., 1996, Mixed mode fatigue crack growth: A literature survey, Engineering Fracture Mechanics 55(6), 969–990.

Richard, H. A., 2001. Experimental and numerical simulation of mixed-mode crack growth. In Proceedings of the Sixth International Conference on Biaxial/Multiaxial Fatigue & Fracture, 623–630.

Richard, H. A., Schramm, B., Schirmeisen, N. H., 2014. Cracks on mixed mode loading–theories, experiments, simulations. International Journal of Fatigue 62, 93–103.

Rozumek, D., Macha, E., 2009. A survey of failure criteria and parameters in mixed-mode fatigue crack growth. Materials science 45(2), 190–210.

Wang, S., Zhang, D., Chen, K., Xu, L., Ge, S., Corrosion fatigue behaviors of steel wires used in coalmine. Materials and Design 53, 56–64.

Xue, S., Shen, R., Chen, W., Miao, R. 2020. Corrosion fatigue failure analysis and service life prediction of high strength steel wire. Engineering Failure Analysis 110, paper 104440.

Zerbst, U., Vormwald, M., Pippan, R., Gänser, H.-P., Sarrazin-Baudoux, Ch., Madia, M., 2016. About the fatigue crack propagation threshold of metals as a design criterion–a review. Engineering Fracture Mechanics 153, 190–243.