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Fatigue crack front curvature due to the plasticity induced crack closure

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Numerical modelling of cracked bodies is required for many research and engineering applications. Majority of cases is satisfied with two-dimensional (2D) modelling assuming plane strain or plane stress conditions. When three-dimensional (3D) model is created, it contains mostly only straight crack front. For the purpose of most of the applications it seems to be good enough. However in reality, fatigue crack front doesn't propagate as a straight line, but it is always curved. Basic reason for the crack front curvature is the presence of so called vertex point singularity, which is appears at the intersection of the crack front with free surface. Vertex point singularity affects stress distribution close to the free surface, resulting in the curvature of fatigue crack front. This effect might be observed at high asymmetry loadings, description may be found in [2]. It seems that additional curvature is caused when plasticity induced crack closure effect is present. Elber [1] was the first describing this phenomenom, which is caused by residual plastic strains left behind propagating fatigue crack. Residual strains form plastic wake and causing the crack faces come to the contact before the crack is actually closed. Advanced computational possibilities enable closer insight into the closure mechanics, leading to improving the physical background and ability to develop accurate models for fatigue life prediction.

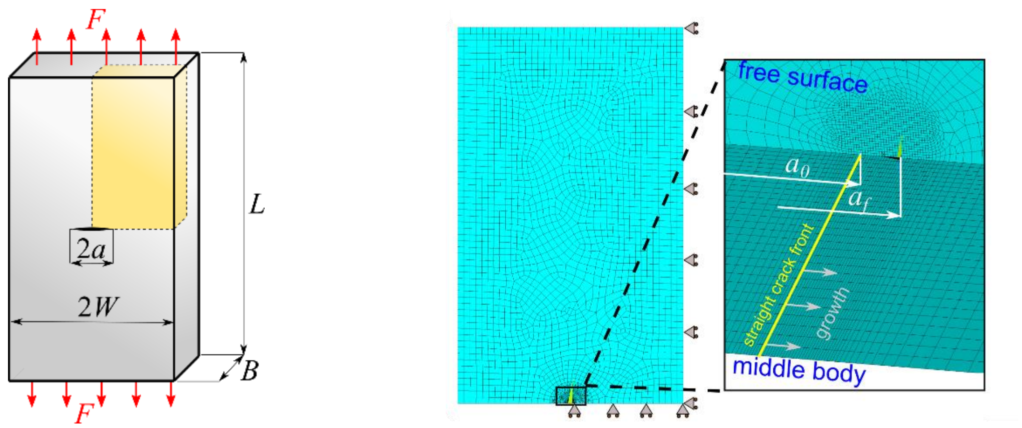

Fig. 1. Middle tension specimen geometry a) and numerical model b)

The methodology of numerical modelling of plasticity infuced crack closure was adopted from previous studies [3]. For the purpose of the study, MT specimen with dimensions 2L = 200 mm, 2W = 60 mm, B = 10 mm was used (Fig. 1). In order to compare the results, 2D finite model was created by using PLANE182 finite elements, while 3D finite element was build with SOLID185 finite elements. Material model assumed elastic-plastic behaviour according to the cyclic curve of steel EA4T (σ_Y = 611 MPa and σ_{UTS} = 727 MPa, σ_{YC} = 470 MPa). Specimen was cyclically loaded with constant stress intensity factor range ΔK = 20 MPa$\sqrt{\text{m}}$ and load range $R = 0$. Crack growth was simulated by debonding nodes of the crack front when maximum load was reached, specimen was subjected in total to 10 cycles with 10 crack increments in order to reach final crack length 2a = 15 mm.

Contact elements were required in order to simulate premature crack faces contact. Therefore contact elements were prescribed on the crack face, while the opposite stationary crack face was substituted by creating horizontal line or surface and meshed with target elements. Crack closure determination was performed by monitoring of displacement of the 1st node behind the crack tip. Change of the displacement u_y to a negative value signalized that crack was closed and corresponding K_{cl} was determined.

3D numerical model was assumed with straight crack front only in order to compare 2D and 3D results. Crack closure values, determined after the 10 cycles of loading, agree very well between 2D and 3D. In the middle of the body, where plain strain conditions prevails, closure values correspond to the 2D model assuming plane strain conditions and furthermore, it agrees also with Newman+Wanhill empirical equation and Pokorny [4] experimental results. Crack closure values at the free surface are also very similar with 2D results, assuming plane stress conditions.

Since the effect of residual plastic strains is the deciding factor on crack closure appearance, it would be appropriate to take a look at plastic zones (Fig. 2a). Thick lines reffers to the plastic zone shapes through the 3D crack front. It can be found that plastic zone shape is moreless constant from the middle of the body almost the the free surface (Fig. 2b). There can be found a pop-up inside the body close to free surface, but it goes back to stabilized cylindrical shape . Plane strain result is very similar to the plastic zone at the middle of the body. In contrary, plane stress assumption provides significantly different shape of plastic zone than the plastic zone \at the free surface of 3D body.

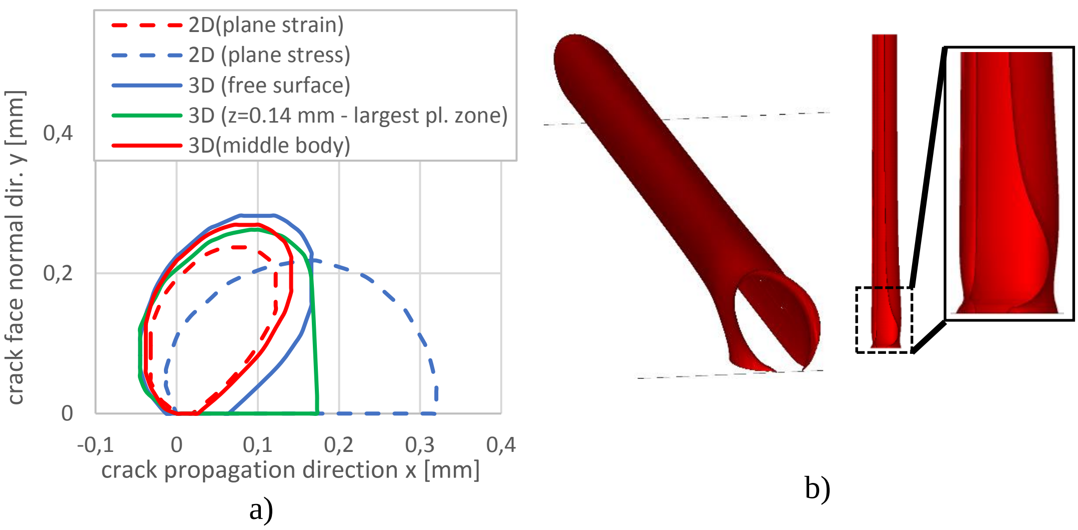

Fig. 2. Plastic zone shapes comparison between 2D and 3D model after monotonic loading a) and 3D plastic zone shape envelope b)

It is generally assumed that when the crack closure is present, the determinitive factor in the crack growth is not whole range of the loading cycle ΔK, but only its effective part ΔK without the rest of the cycle where the crack has been already closed

$$\Delta K_{eff} = \Delta K - K_{cl} \tag{1}$$

Fig. 3 presents plotted distributions of elastic K_{max}, closure value K_{cl} and determined effective part of the cycle ΔK_{eff} through the specimen thickness for case of the straight crack. At the free surface, elastic K_{max} decreases due to the vertex point singularity. In the paper [2] was presented that the crack front curvature caused due to the free surface effect is found when constant horizontal Kmax distribution is obtained. For the MT specimen, horizontal K_{max} distribution was found for crack front curvature with angle 7.5°. However, crack closure values K_{cl} didn't decrease, but increase. Finally, the effective part of the loading ΔK_{eff} remains more or less similar as for the straight crack front.

It seems that curvature of the crack front doesn't affect ΔK_{eff} distribution in numerical model, although in experimental results there is a difference between pure free surface effect and cyclic loading with plasticity induced crack closure involved. Therefore, further research must be devoted to this topic in order to prove or disprove the validity of effective stress intensity factor range ΔK_{eff}.

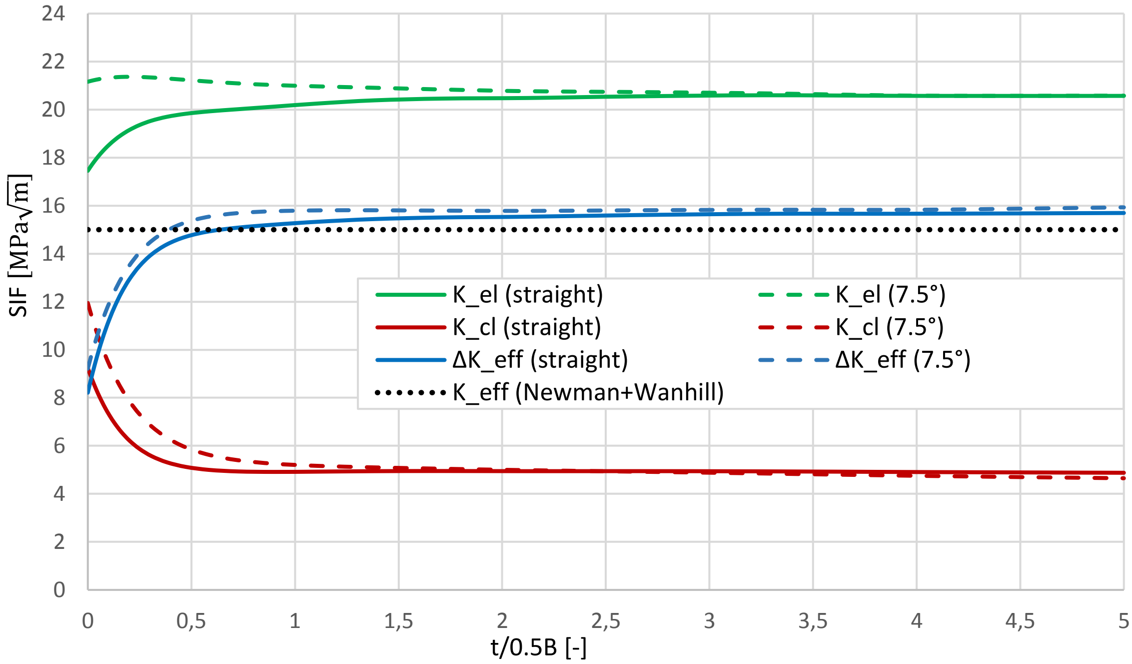

Fig. 3. Elastic SIF (Kmax), closure SIF (Kcl) and effective SIF (Keff) for the specimen with straight crack front

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