Computational Simulation and Experimental Results on 3D Crack Growth in a SEN-Specimen under Torsion Loading

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ABSTRACT. *In this paper the rather complex 3D fatigue crack growth behaviour in a SEN-specimen with an inclined plane of the initial crack under torsion loading is investigated by the aid of the programme ADAPCRACK3D and by application of a recently developed 3D fracture criterion. It will be shown that the computationally simulated results of fatigue crack growth in the FE-model of the specimen are in good agreement with experimental findings for the development of the spatially twisted and warped crack faces in the real laboratory test-specimen. Consequently, also for this case with a rather complex 3D crack growth behaviour, the functionality of the ADAPCRACK3D-programme and the validity of the proposed 3D fracture criterion can be stated.*

INTRODUCTION

The understanding and analysis of mixed-mode fracture is an important subject in fracture mechanics because material flaws or pre-cracks, which may have been introduced unintentionally during the manufacturing process, can have an arbitrary orientation with respect to any service loading that may act on a component of a machine or structure.

In the past, 2D crack extension problems under mixed-mode I and II loading conditions have attracted much attention and through many investigations the problem is now well understood. A number of fracture criteria for predicting the initiation and the direction of fatigue crack growth under mixed-mode I and II crack tip loading conditions are well established. But for the corresponding 3D case this can not be stated, because only a few 3D fracture criteria have been proposed so far and furthermore there is a lack of experimental work on which they could be based and proved.

In this paper detailed results of a computational 3D crack growth simulation will be presented. The simulation is based on the FE-programme ADAPCRACK3D and a maximum principal stress s_1'-criterion, which both have been developed and proposed recently at the Institute of Applied Mechanics of the University of Paderborn [1,2]. The specimen under investigation is a SEN-specimen which has an inclined plane of the initial crack or notch and is subject to torsion loading (see Fig. 1). The computational

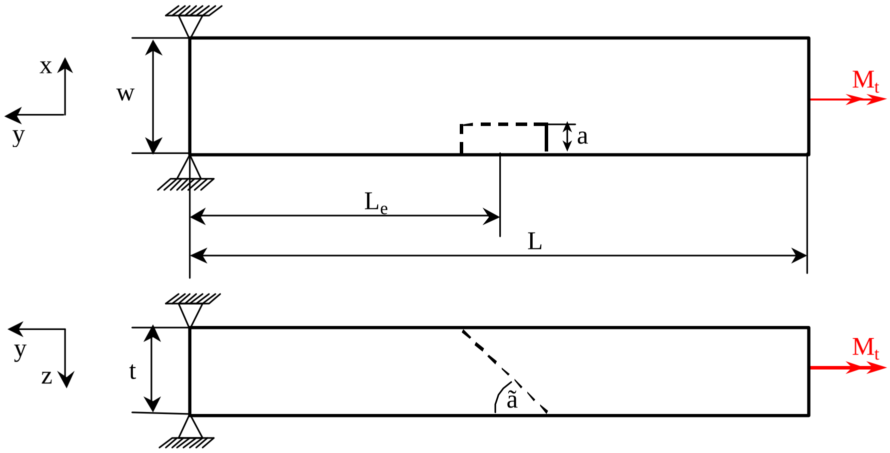


Figure 1. SEN-specimen with an inclined plane (*g* =45°) of the initial crack or notch subject to torsion loading

results are found to be in good agreement with experimental findings which show a rather complex 3D crack growth behaviour. The crack initiates under general and variable mixed-mode loading conditions along the initial crack or notch front and finally exhibits crack faces which are spatially twisted and warped and which intersect the free surface of the specimen opposite of the initial notch in a kind of S-shaped curve.

The following investigation is focussed on the complex 3D shape or geometry of the developing crack faces, because the maximum value of the cyclic torsion loading moment has to be reduced for several times as well during the computational simulation of fatigue crack growth as during the experimental test procedure in order to avoid reaching the critical crack length between stable fatigue crack growth and unstable crack growth. The correlated retardation effects on local fatigue crack growth rates along a 3D crack front are not yet known in detail and thus not implemented in the Erdogan/Ratwani relation [3] which here is used optionally in ADAPCRACK3D. Only in that case a computationally based assessment or prediction of service life could be achieved also for this case of complex 3D fatigue crack growth in this very special specimen. Further more a reliable experimental crack front marking and measurement technique has to be available before in the experiment a number of load cycles can be correlated to a specific, spatially curved crack front in the test specimen and this finding could be compared quantitatively with corresponding results of the computationally simulated fatigue crack growth.

FE-MODEL OF THE SPECIMEN; ADAPCRACK3D AND s_{1}´ 3D FRACTURE CRITERION

The geometrical and material parameters of the SEN-specimen (Fig. 1) are as follows: length L=2Le=160mm, thickness t=15mm, width w=20mm, normalised crack length

a)

b)

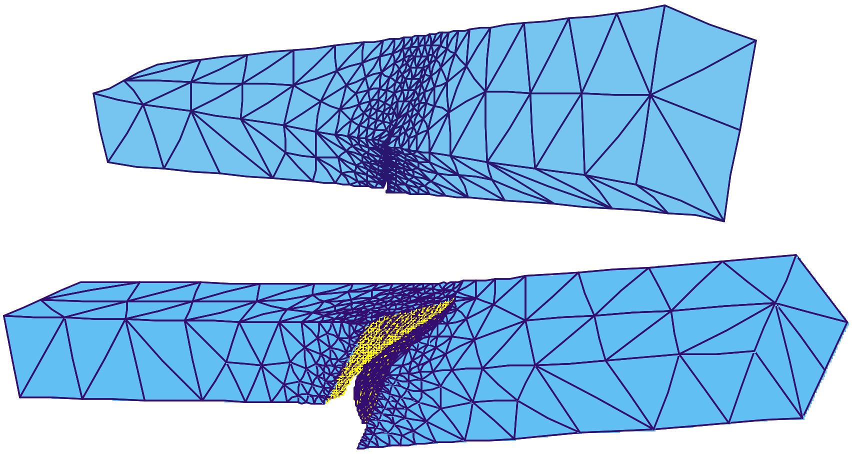


Figure 2. Deformed FE-model of the twisted SEN-specimen a) with initial crack ($a=a_1$=5mm, g =45°), b) with twisted and warped crack after 14 steps of simulated incremental fatigue crack growth (Δa_{max}=1mm, a_{max}=19mm, displ. magn. DMF=50)

a/w=1/4, angle of the inclined plane of the initial crack g = 45deg.; Young's modulus $E=2.1*10^5$ N/mm^2 , Poisson's ratio ν=0.3, threshold-value ΔK_{th}=685 N/mm$^{3/2}$and fracture toughness K_{IC}=5091 N/mm$^{3/2}$. The specimen is subject to a cyclic torsion moment of initially M_{tmax}=200Nmm which is acting around the y-axis of the specimen and the stress ratio of the cyclic loading is and R=0.1.

In Fig. 2a the deformed 3D FE-model of the specimen is shown for the initial crack (crack front 1). It is generated automatically by the ADAPCRACK3D-programme and is assembled from 4287 simple 4-node Tetrahedron elements and has about 2900 degrees of freedoms. Adjacent to the initial crack plane a moderate mesh refinement can be noticed. In order to calculate the parameters of fracture mechanics, which are required as input for the computational fatigue crack growth simulation, the sub-modelling technique is utilised by the ADAPCRACK3D-programme.

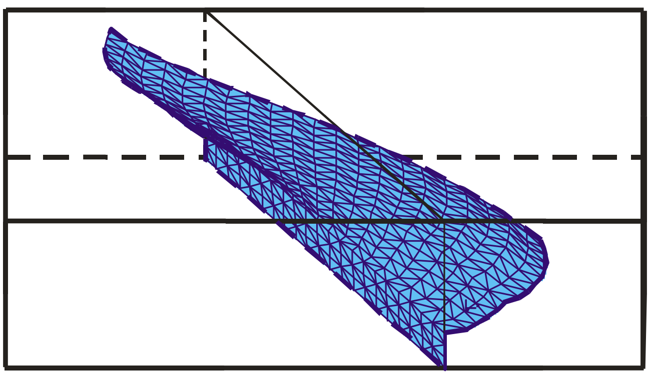


Figure 3. SEN-specimen with FE-mesh of the S-shaped crack after 14 steps of simulated incremental fatigue crack growth (Δa_{max}=1mm, a_{max}=19mm)

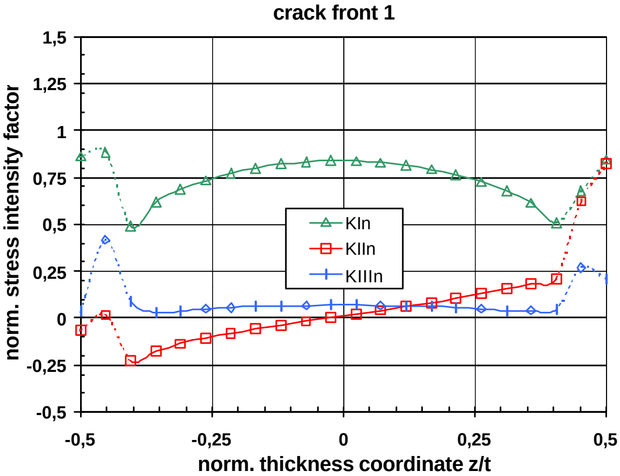


Figure 4. Norm. SIFs along the crack front for the initial inclined crack (crack front 1)

The loading of the sub-model is achieved through prescribed displacements interpolated from relevant nodal point displacements of the global model. Within the sub-model of variable and adjustable size, the calculation of the strain energy release rates (SERRs) along the crack front is performed by the numerically very accurate and reliable modified virtual crack closure integral (MVCCI) method [4-6]. Subsequently the stress intensity factors (SIFs) are calculated by using Irwin´s equations relating SERRs and SIFs. Here plane strain conditions along the crack front are assumed generally, but also plane stress conditions can be used optionally. For further details on the computational simulation of fatigue crack growth by the aid of the ADAPCRACK3D-programme here reference is given to [1]. The only exception is the

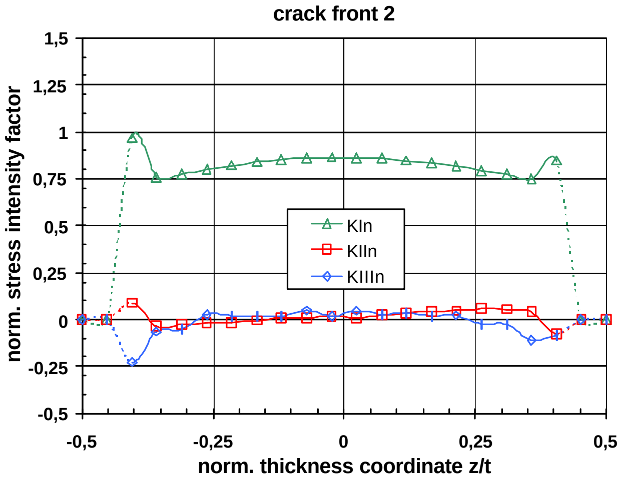


Figure 5. Norm. SIFs along the crack front after the 1st increment of computationally simulated fatigue crack growth ($\Delta\ a_{max}$=1mm, crack front 2, a_{max}=6mm,)

3D fracture criterion used in ADAPCRACK3D on which along the crack front the decision has to be made with which size of local crack increment and in which direction the crack growth has to be modelled for the next step of fatigue crack growth simulation. For this in ADAPCRACK3D a recently developed and proposed 3D fracture criterion is utilised, which can take into account all three basic fracture modes I, II and III and namely as well for the size of the next crack increment as for its new direction in space [2]. This so called maximum principal stress s_1'-criterion reduces to the well established MTS-criterion, in case of plane mixed mode I and II loading conditions along the crack front, and thus can be taken as its 3D generalisation.

DISCUSSION OF RESULTS

In Fig. 2b the deformed FE-model of the twisted SEN-specimen is shown after the last step of simulated fatigue crack growth and clearly an opened crack and the spatially twisted and warped crack faces can be seen (displacement magnification factor DMF=50).

A better impression of the global S-shape of the final crack one can get through Fig. 3, in which the FE-mesh of the final crack is shown in a sketch of the undeformed specimen. A distinct anti-symmetric crack kinking can be noticed along the straight

a) **b)**

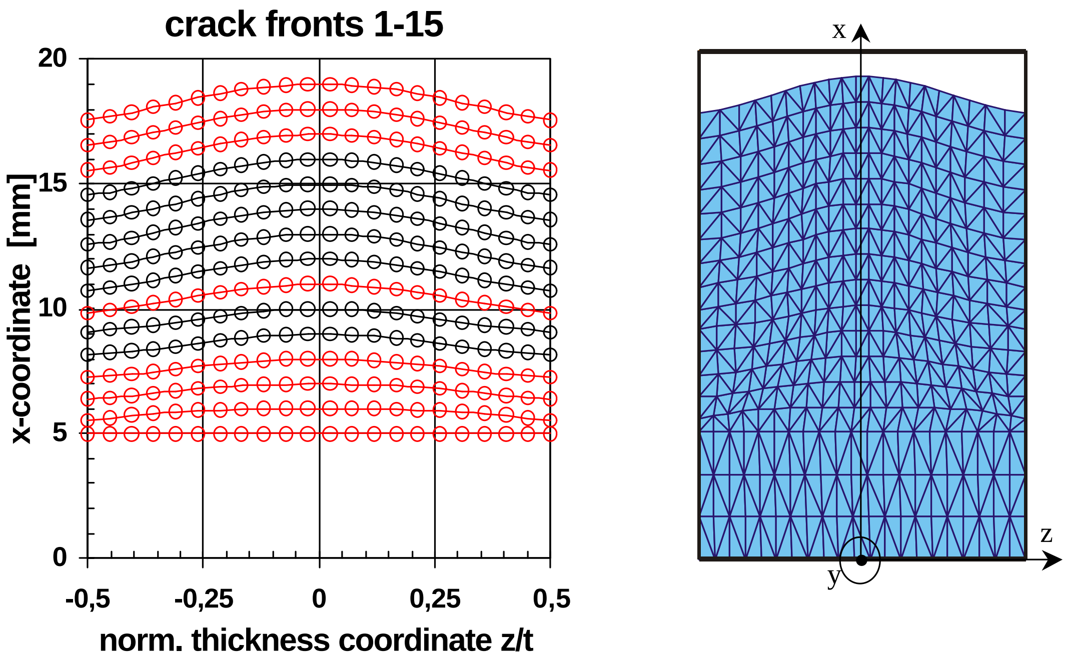


Figure 6. Development of crack fronts for simulated fatigue crack growth from initial crack (crack front 1) to final crack (crack front 15)
a) individual crack fronts, b) FE-mesh of final crack (view against y-axis)

crack front of the inclined initial crack, with kink angles $\varphi_0<0$ for $z/t>0$ and $\varphi_0>0$ for $z/t<0$. This obviously is caused by the combination of the mode I and the anti-symmetric mode II loading conditions along the initial crack front (crack front 1), which are analysed by the MVCCI-method and given quantitatively in form of the normalised $K_I(z/t)$ and $K_{II}(z/t)$-curves in Fig. 4. Due to the torsion loading of the specimen also mode III loading conditions are generated along the initial crack front and analysed in form of $K_{III}(z/t)$.The course of the $K_{III}(z/t)$-curve is about constant and its values are rather small, in particular compared to the predominant $K_I(z/t)$-values, which are responsible for the pronounced crack opening that already was to be noticed in Fig. 2b. The distinct oscillations to be observed in all SIF-curves for $z/t \rightarrow \pm 0.5$ are artificial and should be ignored. They are related to a minor problem with the sub-modelling technique that arises if the intersection of the embedded crack front with a free surface of the specimen or body is not about perpendicular ($75 \leq g \leq 105$) but at angles of e.g. g =45 deg. or less, as it is the case here and which had not been solved at the time of this investigation.

The corresponding SIF-curves after the first increment of computationally simulated fatigue crack growth are given in Fig. 5 (crack front 2). The differences compared to Fig. 4 are remarkable because it is analysed that the mode II and mode III loading conditions along the new crack front already have disappeared (besides the discussed numerical oscillations). This obviously is due to the variable crack kinking with $\varphi_0(z/t)$ along crack front 1 as a result of its considerable variable mixed mode I and II loading

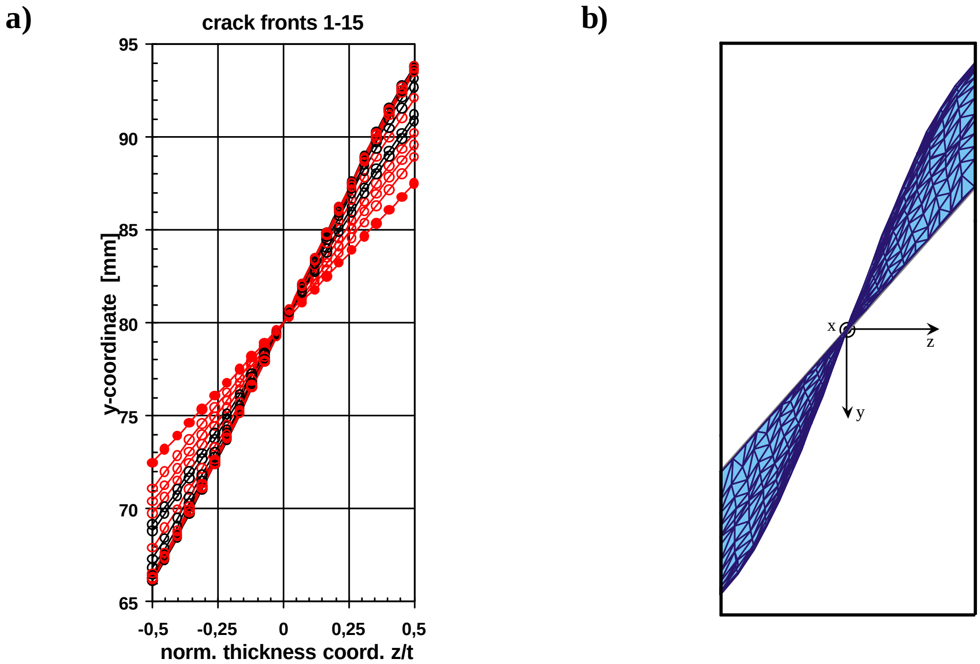
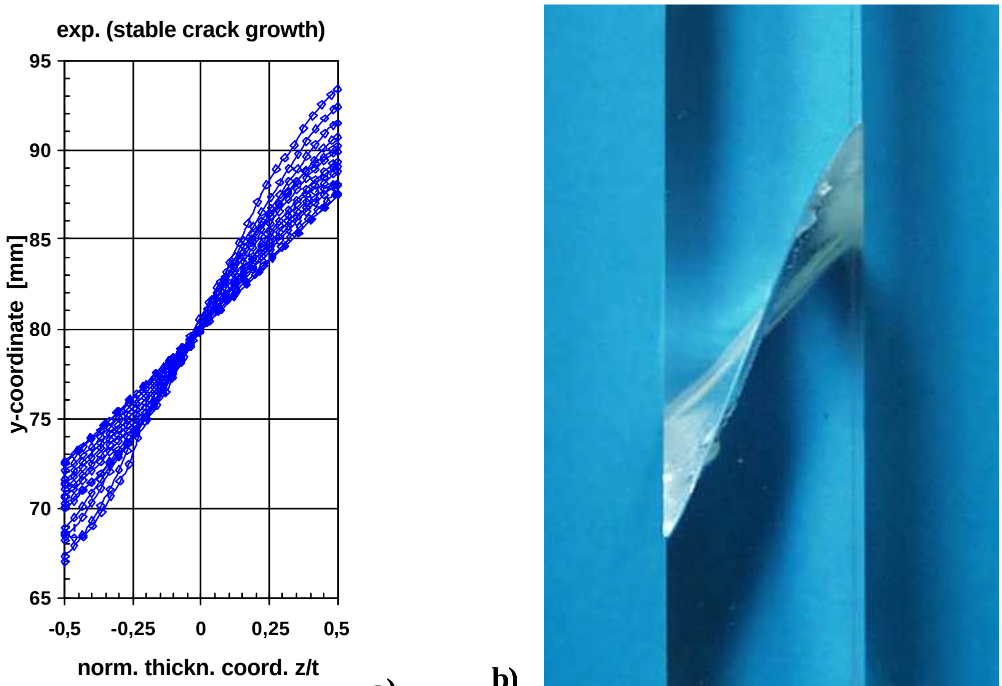


Figure 7. Development of crack fronts for simulated fatigue crack growth from initial crack (crack front 1) to final crack (crack front 15)
a) individual crack fronts, b) FE-mesh of final crack (view against x-axis)



a) b)

Figure 8. Development of crack fronts for stable crack growth in the experimental test specimen
a) individual crack fronts performed by processing of the specimen
b) digital photo of the cracked experimental specimen (view against y-axis)

conditions, as discussed in conjunction with the previous Figs. 3 and 4, and the correlated input to the $s_1{}'$-criterion implemented in ADAPCRACK3D.

The corresponding Figures related to further steps of incremental fatigue crack growth are skipped here, because they all look rather similar. They all show about vanishing values for $K_{II}(z/t)$ and only small values for $K_{III}(z/t)$, compared with the permanently rising values for $K_I(z/t)$ which indicate further increasing mode I loading conditions along the corresponding crack fronts, respectively. Their more and more spatially curved properties are illustrated in Figs. 6 and 7 by a view against the y-axis (Fig. 6) of the specimen and against the x-axis (Fig. 7), respectively. In particular from Fig. 6a a practically self-similar propagation of the mainly convexly curved crack fronts can be noticed, after the first few steps of simulated fatigue crack growth and in Fig. 7a the incremental development of the additional slight S-shape of the crack fronts is to be seen in more detail.

In Fig. 8 the corresponding experimental findings for a test specimen from PMMA are presented. Especially in Fig. 8a experimentally obtained curves are shown which are defined through the intersection of the crack with y-z-planes at different levels x (Δx=1mm) and which are obtained through subsequent processing of an experimentally cracked test specimen. Figure 8b shows by a digital photo a top view of the cracked specimen (before processing) directly corresponding to the top view onto the FE-mesh of the simulated crack in Fig. 7b In both cases a good qualitative agreement is found, which confirms that also for this case of rather complex 3D fatigue crack growth the functionality of the ADAPCRACK3D-programme and the validity of the proposed s_1'-criterion can be stated.

SUMMARY AND CONCLUSIONS

In this paper detailed results of a computational 3D fatigue crack growth simulation have been presented. The simulation is based on a maximum principal stress s_1'-criterion and the FE-programme ADAPCRACK3D, which both have been developed and proposed recently at the Institute of Applied Mechanics of the University of Paderborn. The specimen under investigation was a SEN-specimen, which has an inclined plane of the initial crack or notch and is subject to torsion loading. The computational results are found to be in good qualitative agreement with experimental findings which show a rather complex 3D crack growth behaviour. Consequently, also for this case the functionality of the ADAPCRACK3D-programme and the validity of the proposed 3D fracture criterion can be stated. By their aid also other cases of 3D fatigue crack growth in solids under any kind of loading can be investigated and based on the correlated experimental results the proposed s_1'-criterion can further be tested and proved or adapted or dismissed.

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