Fatigue crack propagation in the frame of a hydraulic press

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ABSTRACT. Within this paper the fatigue crack growth in the frame of a hydraulic press will be discussed. The crack growth started at a shrink hole in a notch in the middle part of the frame. The state of stress of the crack is predominantly influenced by the notch, which induces a Mixed-Mode-loading during the crack growth. The propagation of the crack will be analyzed with the crack simulation program ADAPCRACK3D, which has been developed at the Institute of Applied Mechanics at Universität Paderborn. This program is able to calculate fully automatic the stress intensities along a 3D-crack front as well as the crack path and the lifetime of a structure.

INTRODUCTION

In the industrial practice the simulation of crack propagation processes by means of numerical methods, especially the Finite-Element-method, becomes more and more important. Responsible for this tendency on the one hand side is an increasing amount of damage caused by crack propagation, that can be found in all fields of mechanical engineering. Often the optimized exploit of the strength of a structure with respect to lightweight construction is a governing factor for this, since especially if materials with a worse crack resistance are used, the probability of crack growth increases with increasing stresses in a component. On the other hand side also a developing problem consciousness concerning fracture mechanical issues widely can be observed.

ADAPCRACK3D

For the investigations in this paper the three-dimensional crack growth simulation program ADAPCRACK3D has been used. The general functionality scheme of this program is given in Figure 1. ADAPCRACK3D consists of three independent modules, which in combination comprise a fully automatic fatigue crack growth simulation. The first module NETCRACK3D is responsible for all FE-mesh-adjustments, that are necessary during a simulation. This incorporates the geometry adaptation due to crack

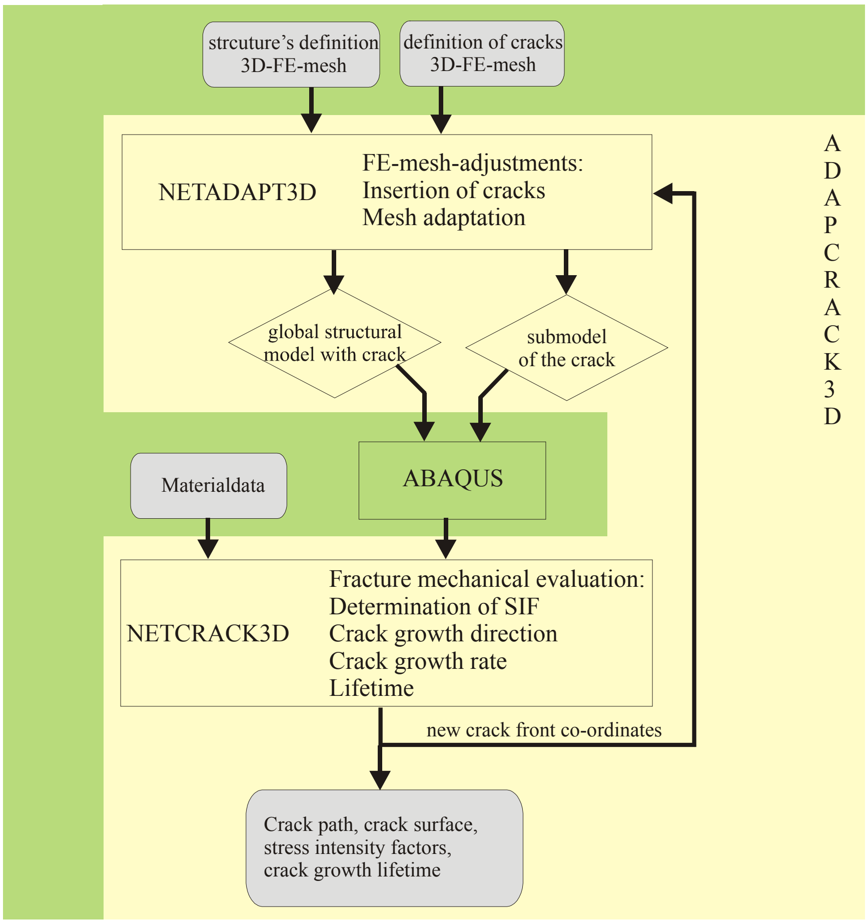


Figure 1. Functionality scheme of the program ADAPCRACK3D

growth as well as mesh improvement routines in order to guarantee a sufficient mesh quality throughout the simulation process. NETADAPT3D creates an FE-model of the structure containing the crack and a submodel of the crack front vicinity. Both models are solved by the commercial FE-code ABAQUS. On the basis of the submodel's solution a fracture mechanical evaluation is carried out by the third module NETCRACK3D. Besides the interesting fracture mechanical parameters such as the crack path or crack surface, stress intensity factors, crack growth lifetime etc. especially new crack front co-ordinates are calculated in case of stable fatigue crack growth, that are sent back to the first module in order to close the simulation circle. More details concerning this program can e.g. be gathered from [1,2].

NUMERICAL DESCRIPTION OF CRACK GROWTH IN THREE-DIMENSIONAL STRUCTURES

In order to reasonably describe crack growth in three-dimensional structures by means of a numerical simulation the knowledge of the direction as well as the crack growth rate at each discrete point of a crack front has to be provided. Those information necessarily needs to be of local character, since the local loading situations may substantially change along a 3D-crack front.

Crack growth direction

The direction of crack growth in ADAPCRACK3D is determined by the σ_1'-criterion [3]. This criterion assumes that crack growth will occur radial from the existing crack front in a direction, that is perpendicular to a maximum principle stress σ_1'. Thereby this stress σ_1' is evaluated on a curved cylinder with centre line along the crack front. This criterion yields two angles φ_0 and ψ_0, whereby φ_0 describes a local kinking of the crack front and ψ_0 a local twisting (Figure 2). Despite both angles are functions of all three fracture modes, there is a close correlation between on the one side Mode II and the kinking angle φ_0 and on the other side Mode III and the twisting angle ψ_0.

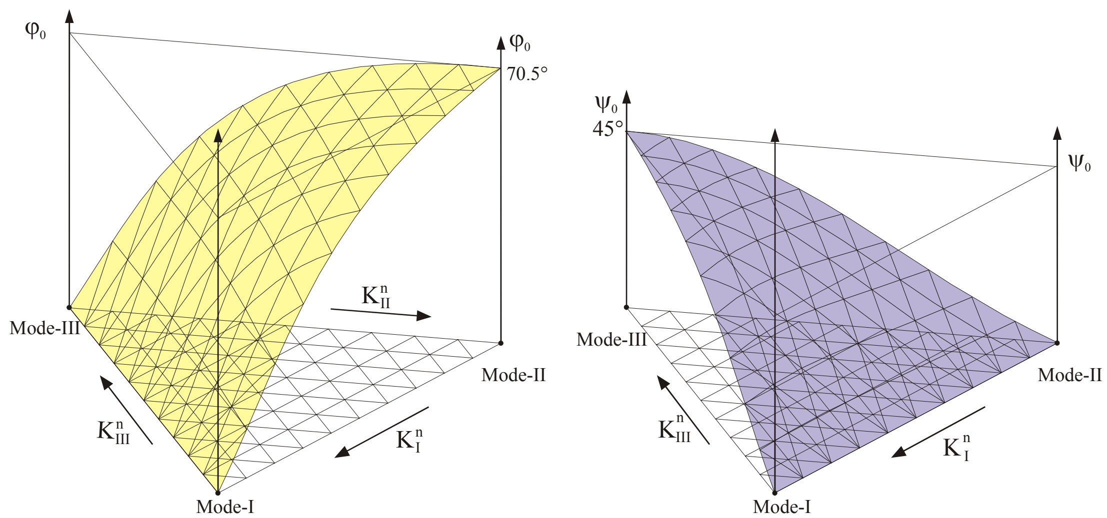


Figure 2. The crack deflection angles φ_0 and ψ_0 according to the σ_1'-criterion

Equivalent stress intensity factor

For an arbitrary Mixed-Mode-situation it is necessary to calculate an equivalent stress intensity factor from the single Mode components K_I, K_{II} and K_{III}. By the σ_1'-criterion this equivalent stress intensity factor K_{eq} is defined as

$$K_{eq} = \frac{1}{2}\cos\left(\frac{\varphi_0}{2}\right)\left\{K_I\cos^2\left(\frac{\varphi_0}{2}\right) - \frac{3}{2}K_{II}\sin(\varphi_0) + \sqrt{\left[K_I\cos^2\left(\frac{\varphi_0}{2}\right) - \frac{3}{2}K_{II}\sin(\varphi_0)\right]^2 + 4K_{III}^2}\right\}. \quad (1)$$

This definition enables to compare a Mixed-Mode-loading situation to the (Mode I-) fracture toughness K_{Ic}. Moreover this relation can be applied in fatigue crack growth calculations by replacing the ΔK_I by ΔK_{eq} in the usual crack growth rate equations like *Erdogan/Ratwani* [4] or *Forman/Mettu* [5]. More details concerning the σ_1'-criterion are e.g. given in [6].

CRACK GROWTH IN THE FRAME OF A HYDRAULIC PRESS

In a frame of a hydraulic press during service time a crack in the head part in a notched section originated. After an extensive fatigue crack growth this crack finally caused rupture of the whole structure (Figure 3). A shrink hole in the root of a notch finally was identified as reason for the fatigue crack growth. This shrink hole showed an almost semi-elliptical shape with a length at the surface of 28mm and a depth of 10mm. Consequently the initial crack for this simulation was chosen in that particular size.

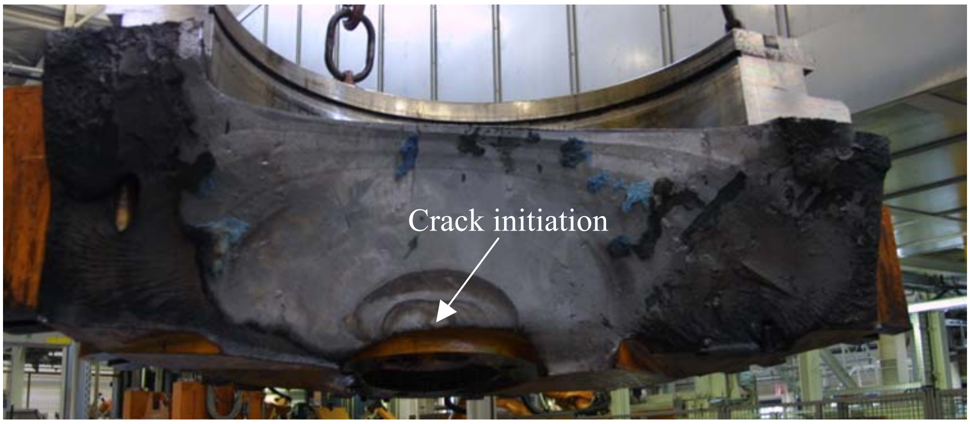


Figure 3: Fatigue crack growth in the frame of a hydraulic press

For reasons of numerical manageability (the overall diameter of the press frame is about 1800mm) only a half of the press frame was modelled in the simulation. The frame is loaded by distributed loads on the upper sides of the teeth (blue areas in Figure 4 with a load of 3.33MN each). This load is in balance with a membrane pressure at the inner part of the frame (red area) with p_0=53.6MPa.

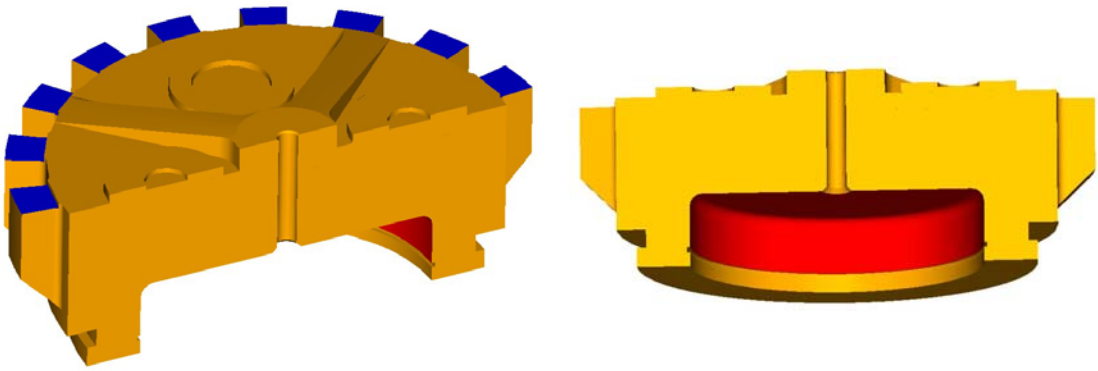
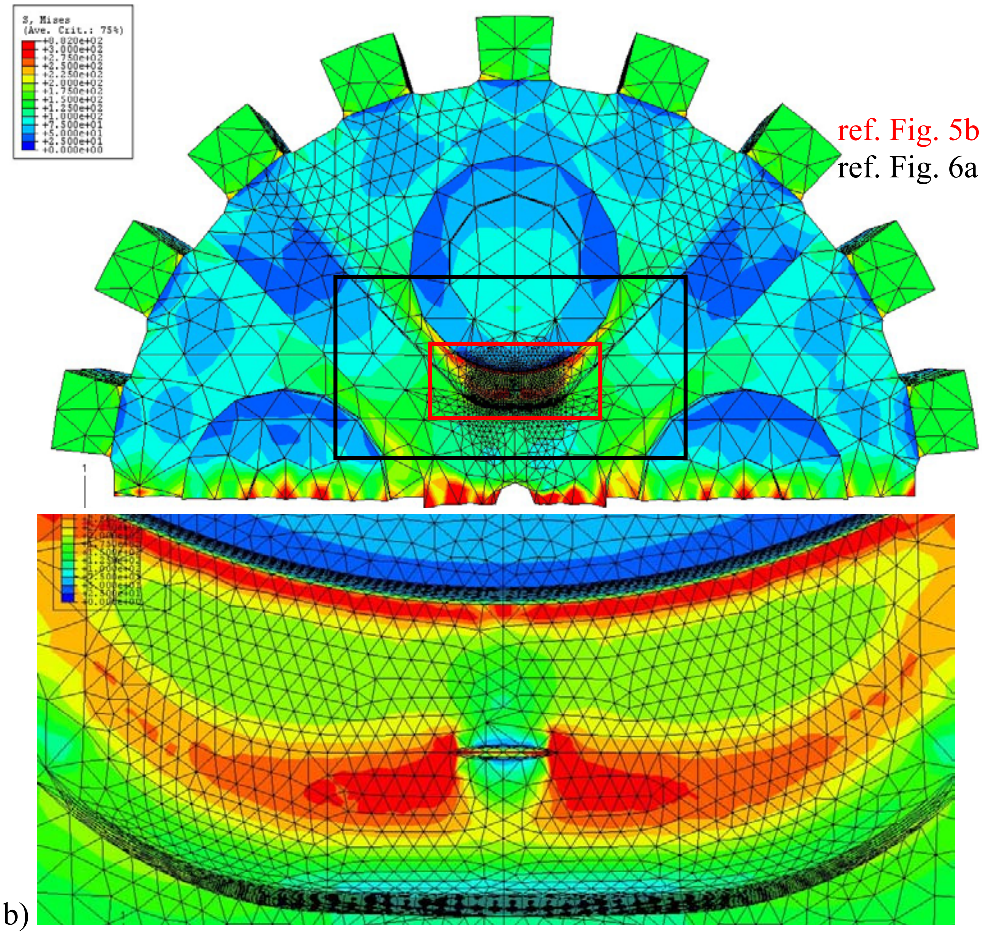


Figure 4. CAD-model of the press frame

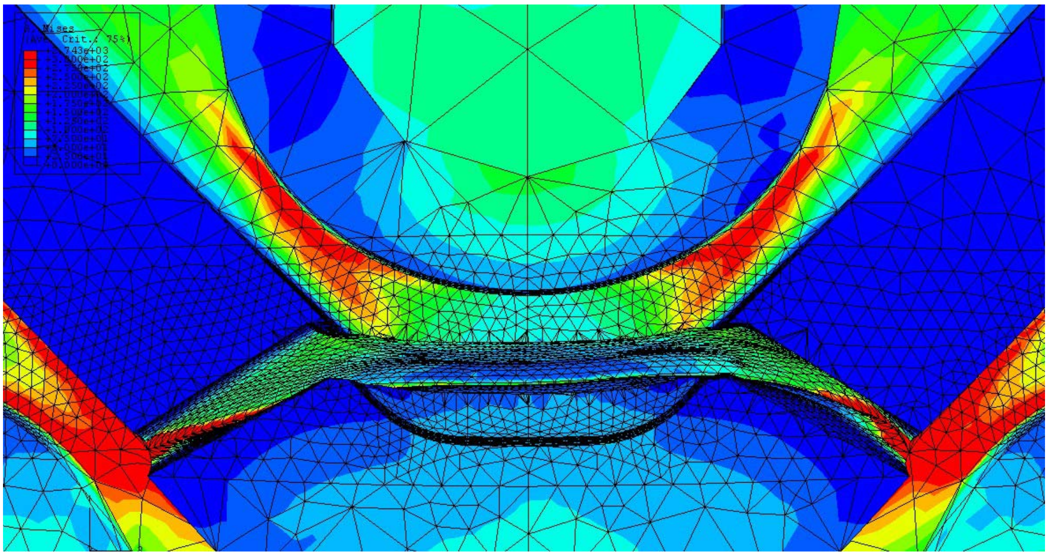


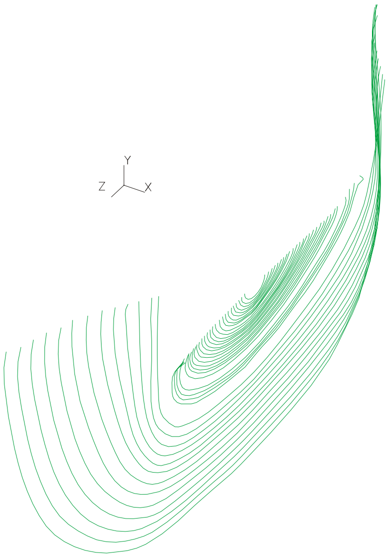
a)

b)

Figure 5. FE-model of the first simulation step
a) top view
b) zoom in to the area of the initial crack

Figure 5 shows the crack-containing FE-model of first simulation step with a displacement magnification factor of 100. This FE-mesh consists of approx. 114000 nodes and 78000 elements. Until the end of the simulation (step 43, Figure 6) those numbers increase up to 231000 nodes and 158000 elements, which results from the bigger parts of the model, that need a higher refinement level due to the crack growth. From Figure 6 it can be seen, that in the beginning the crack path along the surface is nearly straight forward according to the stress field of the notch. When reaching the side walls of the notch, the crack changes the overall direction and merely cuts perpendicular through the ribbing. The crack growth into the depth of the press frame is constantly influenced by different Mixed-Mode-loading situations along each crack front. This can be seen from Figure 6b, in which the isometric view on the developing crack fronts is given. As consequence of the changing Mixed-Mode-situations the crack surface is far from being flat, but shows a lot of inner twisting (comp. Figure 8).

a) 



b)

Figure 6. crack development after 43 simulation steps
a) FE-model, zoom into the cracked area
b) isometric view on the calculated crack fronts

At the beginning of the simulation in the stress intensity factor development only a slight increase for both directions a and c (Figure 7) can be observed. When reaching the “wall” of the notch (c≈130mm–150mm), the crack even exhibits a temporary decrease in the stress intensity factors. In the following the stress intensity factors in the root of the crack (crack depth a) remain nearly constant, while along the surface the stress intensity increases rapidly.

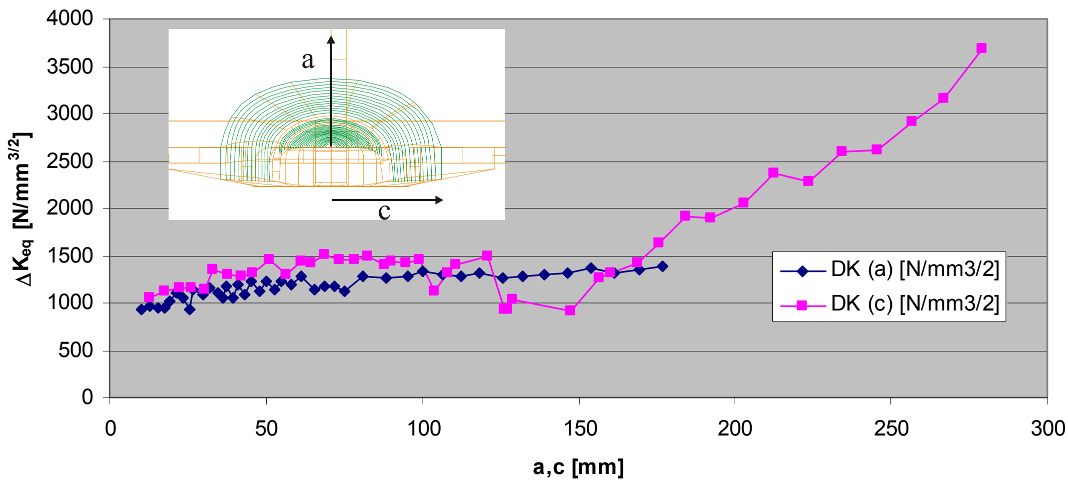


Figure 7. Development of the equivalent stress intensity factor during the crack growth

a)

b)

Figure 8. Comparison of the calculated crack fronts with the real crack surface

a) global view

b) detailed view on the initial crack growth area

The comparison of the calculated crack fronts with the real fracture surface shows an excellent agreement (Figure 8). This is true for both the overall direction (the "inner twisting" of the fracture surface, which has already been discussed) and the calculated crack fronts themselves, which can be compared at least at the beginning of the crack growth to the arrest lines of the fracture surface. The lifetime estimated for the calculated crack growth is about 390000 loading cycles, which is in good agreement with the real number of loading cycles. Those were estimated as 860000, but of course also include the crack initiation phase from the shrink hole. Further examples concerning the applicability of the program ADAPCRACK3D i.a. can be gathered from [7,8]

CONCLUSIONS

In this paper an analysis of the crack growth in the frame of a hydraulic press has been shown. Therefore the 3D crack simulation program ADAPCRACK3D has been applied, that was developed at the Institute of Applied Mechanics at Universität Paderborn. This program is able to calculate crack growth in arbitrary 3D structures under complex loading conditions. The fracture mechanical evaluation of this program is based on the σ_1'-criterion. Besides the crack growth direction this criterion also defines an equivalent stress intensity factor for Mixed Mode situations, that can be used for determination of the fatigue crack growth limits (ΔK_{th} and ΔK_c) as well as for the calculation of the crack growth rate and thus for the lifetime of a structure. The comparison of the simulated crack propagation showed excellent agreement with the observed crack growth in the real structure.

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