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Simulation of fatigue crack propagation processes in arbitrary three-dimensional structures with the program system ADAPCRACK3D

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ABSTRACT

The following paper provides both an overview on the abilities and general functionality of the three-dimensional crack simulation program ADAPCRACK3D and introduces a new three dimensional concept for the prediction of crack growth processes, that also takes the effects of Mode-III into consideration. ADAPCRACK3D, which has been developed at the Institute of Applied Mechanics at the University of Paderborn, is a finite element based code, that is able to perform crack propagation simulations in arbitrary structures under arbitrary loading conditions. Therefore, on the one hand an adaption of the existing FE-mesh to the change of geometry due to crack growth is needed in every single step of the simulation. As generally the manipulation of a FE-mesh causes a deterioration of the mesh quality, many algorithms especially adjusted to a crack growth simulation have been implemented to improve the quality of the FE-mesh. On the other hand an automatic fracture mechanical evaluation of the crack front is performed, that results in the computation of crack propagation. This procedure also includes the new concept, that – different from the rare existing three-dimensional simulation tools – also calculates the effect of the stress intensity factor K_{III} on crack growth direction and rate. This new concept is described in detail. The outcome of the simulation shows good agreement with experimental results.

KEYWORDS
crack simulation, Mixed-Mode, ADAPCRACK3D, mesh-adaption, crack growth concept, 3D fracture criterion

INTRODUCTION
In the last years lightweight construction has become more and more important in all fields of mechanical engineering. This development can be seen as a consequence both of ecological (resource conserving) and economical (saving of material) considerations. However, lightweight construction generally shows a greater liability to the initiation of cracks during its proposed lifetime. So the damage tolerant design is of increasing importance in relation to safe life design. Nevertheless failure especially of critical structures such as power plants, aircraft, ships etc. must not be tolerated, so the urgent need for simulation tools for the prediction of three-dimensional crack growth processes is obvious. These simulations then can be used to determine the appropriate point of time to substitute a crack damaged component and to find suitable inspection intervals for them. ADAPCRACK3D is a new program, that can be used to perform this necessary simulations in arbitrary three-dimensional components. In conjunction with the implemented new three dimensional crack

propagation concept it is a powerful tool for damage tolerant design of components in all fields of engineering practice.

THE CRACK SIMULATION PROGRAM ADAPCRACK3D

ADAPCRACK3D consists of three independent modules, the mesh-adaption NETADAPT3D, that provides all necessary manipulations of the FE-mesh, the well known commercial FE-solver ABAQUS and the module NETCRACK3D performing the fracture mechanical evaluation. Figure 1 shows the simplified functionality scheme of ADAPCRACK3D with its three modules. As major input objects a description of the uncracked object in terms of a three-dimensional FE-mesh consisting of tetrahedrons and a description of the crack (2D triangular elements) are requested.

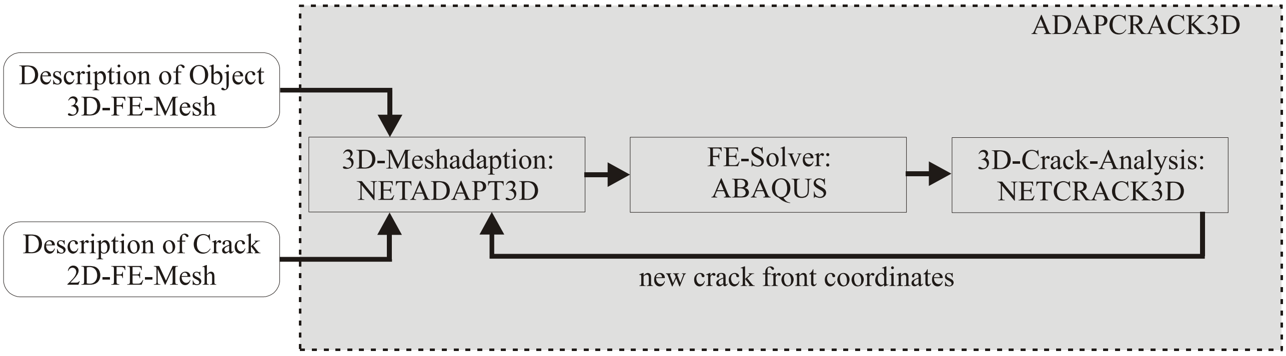

Figure 1: Simplified functionality scheme of ADAPCRACK3D

In the first simulation step both input files are composed to a description of the cracked object. The resulting FE-model is solved by the finite element code ABAQUS. Afterwards NETCRACK3D uses the results of the FE-calculation to compute new crack front coordinates. These new coordinates are sent back to the module NETADAPT3D and define the necessary geometry modification for the next simulation step. In the following some important aspects of the modules of ADAPCRACK3D will be discussed including the presentation of the new crack propagation concept already implemented in NETCRACK3D.

The module NETADAPT3D

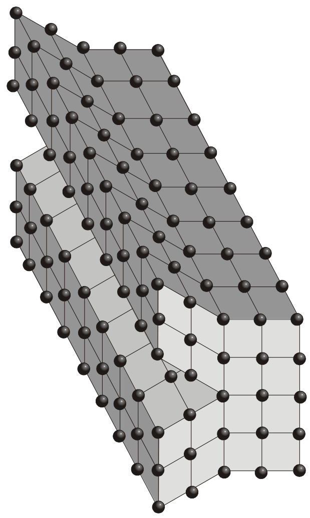

Figure 2: Submodel for straight crack front

The module NETADAPT3D has two major tasks within ADAPCRACK3D. First of all it has to realize the geometry changes due to crack growth in the describing FE-model. Beyond this it has to assure a sufficiently good mesh quality during the whole simulation procedure especially in regions near the crack front. The good mesh quality can be obtained by the use of ABAQUS submodeling technique [1] by defining a hexahedral submodel along the crack front as can be seen in Figure 2. Besides the obviously good mesh quality the main advantage of this submodel can be found in its regular structure, which allows an easy automatic evaluation of the fracture mechanical parameters at the crack front. Moreover, this technique simplifies the manipulation of the (global) FE-model, that is necessary to adjust it to the changing geometry, as it is no longer essential to guarantee an extra high mesh quality at the crack front of the global model. All model-manipulation work regarding the realization of the initial crack (first simulation step) and the crack propagation (all further steps) is performed by inserting additional nodes into the existing model. By choosing appropriate locations for these nodes a global FE-model can be created, that contains all necessary crack describing objects (nodes, edges, faces) [2]. If this is done, the correct crack description consisting of two crack surfaces lying directly at one another can then easily be obtained by doubling those nodes, edges and faces and unstitching the FE-Model along the crack face. The node insertion itself can – by user's choice – either be performed with a Delaunay-algorithm [4] or a more direct approach minimizing the influenced region of the node insertion within the model [3]. The main advantage of the direct method in comparison to the Delaunay technique is the fact, that this algorithms never destroys already existing edges and faces, which simplifies the algorithmic implementation, as only one iteration for the insertion procedure in each simulation step is necessary. Its greatest disadvantage can be found in the generally worse mesh quality obtained by this method. Nevertheless both methods generate a mesh quality that needs to be improved in order to obtain reliable results. Therefore improvement algorithms especially adapted to the requirements of a crack simulation of different classes (Table 1) have been implemented.

TABLE 1

CLASSES OF IMPROVEMENT ALGORITHMS IMPLEMENTED IN ADAPCRACK3D

	Number of nodes changed	**Number of nodes unchanged**
during insertion process	Bisection algorithm	Flip algorithm
after insertion process is finished	Melting of nodes Local domain decomposition	Laplacian algorithm Controlled displacement

The Bisection algorithm originally presented by Rivara [5] is used as a rule to subdivide elements without quality deterioration. The Flip algorithm changes the connectivity of 5 nodes at a time and is applied within ADAPCRACK3D for the Delaunay Method of node insertion. After the insertion process is finished, the mesh quality can – depending on the local situation – be improved either by adding nodes (Local domain decomposition) or removing nodes by melting them. Another also implemented improvement strategy, in which the number of nodes remains unchanged, is to reposition the existing nodes for the purpose of a better node distribution in the model. Therefore both the well known and very easy Laplacian algorithm and another algorithm controlling the displacement by calculating the reposition effect on the quality are implemented [2,3].

The module NETCRACK3D

The module NETCRACK3D provides all fracture mechanical evaluations within ADAPCRACK3D. At first the energy release rates are calculated for all nodes of the crack front. This is performed under utilization of the special structure of the submodel (Figure 2) with use of the modified virtual crack closure integral (MVCCI) method [7,8]. The energy release rates are converted afterwards into cyclic stress intensity factors ΔK_I, ΔK_{II} and ΔK_{III} for all three crack opening modes. By user's choice this can be done either under plane strain or plain stress conditions. The calculated stress intensity factors are then used by the new three-dimensional concept discussed in the next chapter to compute the cyclic comparative stress intensity factor ΔK_V as well as the direction of crack growth for each node of the crack front. The cyclic stress intensity factor ΔK_V can be compared to the limiting values ΔK_{th} and ΔK_c for stable crack growth. Moreover it is the determining factor for the computation of the crack growth rate according to the law of Erdogan and Ratwani [6]. With the knowledge of crack growth direction and rate the new coordinate for each crack front node is uniquely defined.

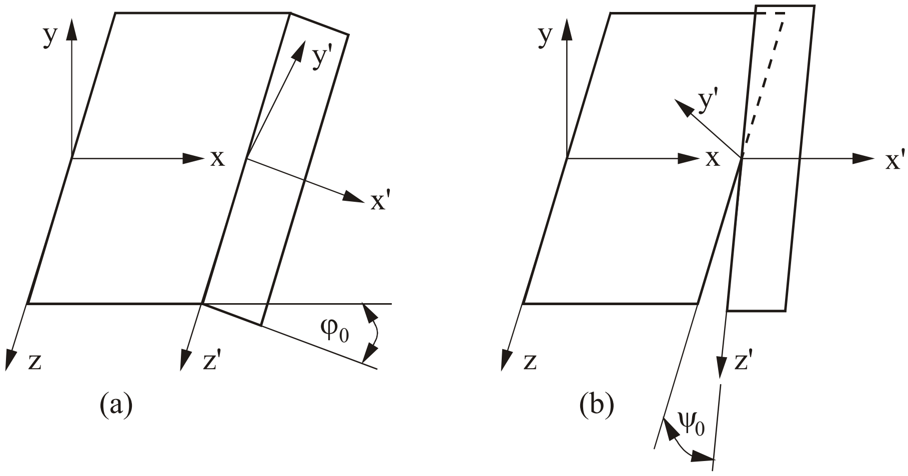

Figure 3: The definition of the angles φ_0 and ψ_0

For the simulation of superimposed Mode-I/ Mode-II loading it is sufficient to compute one angle φ_0 for the description of crack growth. As soon as Mode-III is also under consideration, it is essential to define a second angle ψ_0 describing the rotation around the x-axis (see Figure 3). The new criterion is based on the assumption, that crack propagation occurs perpendicular to the direction of the biggest principal normal stress $\sigma_{1'}$ which can be found on a cylindrical sphere around the crack front (Figure 4). For planar mixed-mode situations this definition is equivalent to the MTS-criterion of Erdogan and Sih [9], where $\sigma_{\varphi\,max}$ also is the maximum normal stress on the same cylindrical sphere. In three-dimensional loading cases the crack propagation is no more perpendicular to the maximum tangential stress σ_φ, but perpendicular to $\sigma_{1'}$ which is given by

$$\sigma_{1'} = \frac{\sigma_\varphi + \sigma_z}{2} + \frac{1}{2}\sqrt{(\sigma_\varphi - \sigma_z)^2 + 4\tau_{\varphi z}^2}\,, \tag{1}$$

with

$$\begin{aligned}
\sigma_\varphi &= \frac{K_I}{4\sqrt{2\pi r}}\left\{3\cos\left(\frac{\varphi}{2}\right) + \cos\left(\frac{3\varphi}{2}\right)\right\} - \frac{K_{II}}{4\sqrt{2\pi r}}\left\{3\sin\left(\frac{\varphi}{2}\right) + 3\sin\left(\frac{3\varphi}{2}\right)\right\}\\
\sigma_z &= \nu\left(\sigma_r + \sigma_\varphi\right) = \frac{8\nu}{4\sqrt{2\pi r}}\left\{K_I\cos\left(\frac{\varphi}{2}\right) - K_{II}\sin\left(\frac{\varphi}{2}\right)\right\}\\
\tau_{\varphi z} &= \frac{K_{III}}{\sqrt{2\pi r}}\cos\left(\frac{\varphi}{2}\right)
\end{aligned} \quad . \tag{2}$$

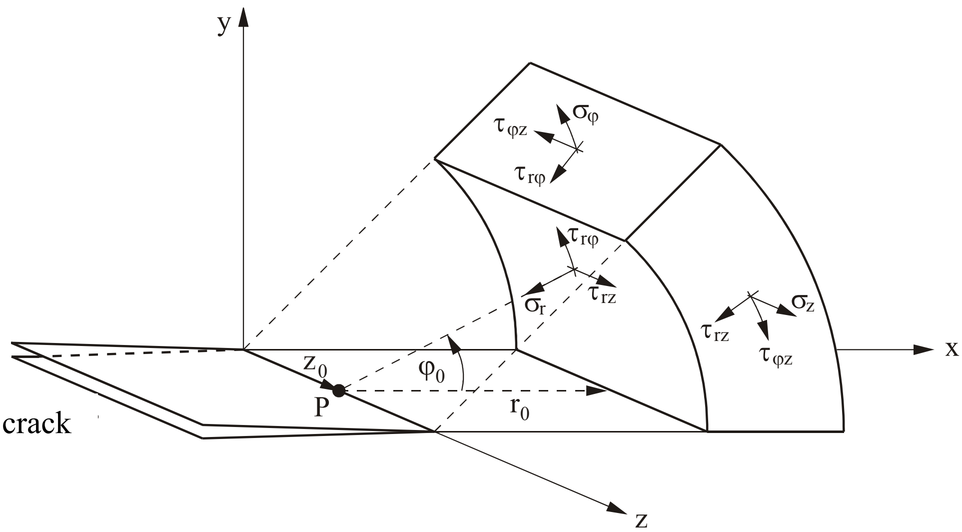

Figure 4 : Cylindrical coordinate system at a three-dimensional crack front

So the kinking angle φ_0 can be calculated by the partial derivatives

$$\frac{\partial \sigma_{1'}}{\partial \varphi} = 0 \quad \text{and} \quad \frac{\partial^2 \sigma_{1'}}{\partial \varphi^2} < 0 . \tag{3}$$

The second angle ψ_0 can then easily be found by the calculation of the angle of the principal normal stress given by

$$\tan(2\psi_0) = \frac{2\tau_{\varphi z}(\varphi_0)}{\sigma_\varphi(\varphi_0) - \sigma_z(\varphi_0)} . \tag{4}$$

Equations 3 and 4 obviously present a formulation for the determination of the two kinking angles for three dimensional crack growth, that take all stress intensity factors K_I, K_{II} and K_{III} into consideration, which makes them suitable for arbitrary mixed-mode-combinations. The solution of Eqn. 3 can be found in [10]. It can not be solved in a close form, but Figure 5 shows the visualization of the numerical results for a grid of different K_I-K_{II}-K_{III}-ratios.

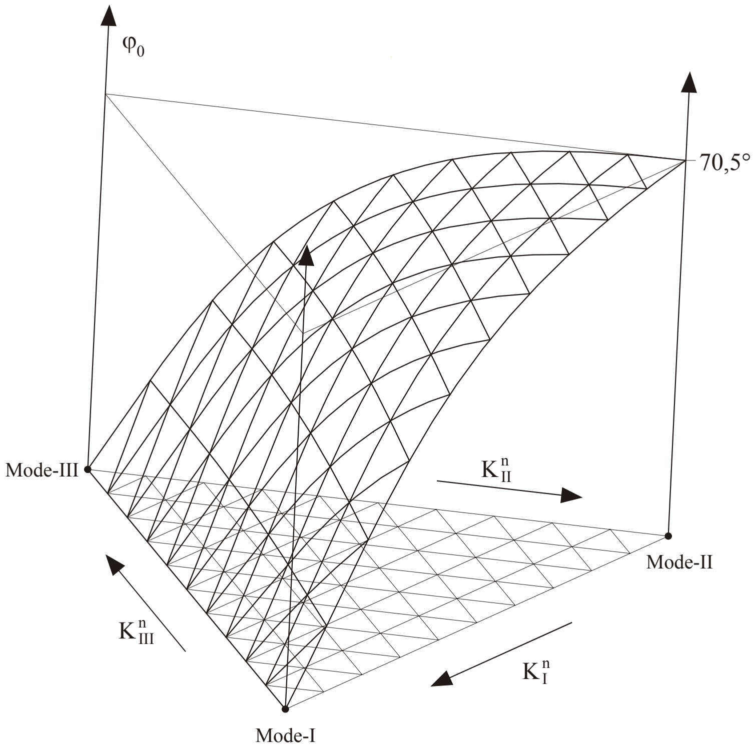

Figure 5 : The angle φ_0 depending on the mixed-mode ratio

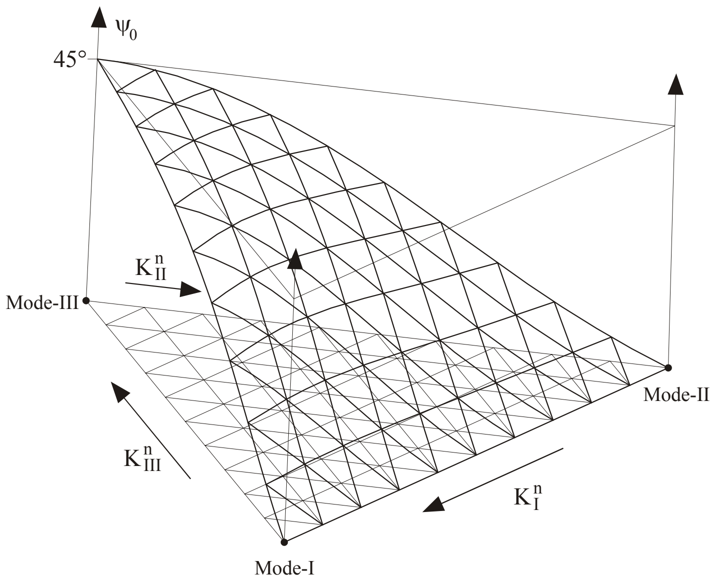

Figure 6 : The angle ψ_0 depending on the mixed-mode ratio

Figure 6 presents the angle ψ_0 according to Eqn. 4. In both figures the stress intensity factors are normalized by

$$K_I^n = \frac{K_I}{K_I + |K_{II}| + |K_{III}|}, \quad K_{II}^n = \frac{K_{II}}{K_I + |K_{II}| + |K_{III}|} \text{ and } K_{III}^n = \frac{K_{III}}{K_I + |K_{II}| + |K_{III}|}, \quad (5)$$

which results in a barycentric coordinate system. The front line of Figure 5 (between Mode-I and Mode-II) redelivers the MTS criterion for planar loading situations. With the use of the calculated φ_0 the comparative stress intensity factor can be obtained by $K_v = \sigma_{1'}\sqrt{2\pi r}$ as

$$K_V = \frac{1}{2}\cos\left(\frac{\varphi_0}{2}\right)\left\{K_I\cos^2\left(\frac{\varphi_0}{2}\right) - \frac{3}{2}K_{II}\sin(\varphi_0) + \sqrt{\left[K_I\cos^2\left(\frac{\varphi_0}{2}\right) - \frac{3}{2}K_{II}\sin(\varphi_0)\right]^2 + 4K_{III}^2}\right\}. \quad (6)$$

CONCLUSIONS

The presented program ADAPCRACK3D is a powerful tool for the simulation of three-dimensional crack propagation processes. Due to its modular structure the three general simulation functions *Meshadaption*, *FE-solving* and *Crack Analysis* can be modified and adapted to new investigations independent of each other. The module 3D-Meshadaption provides the insertion of a crack into a former uncracked FE-model and asserts the necessary good mesh quality The crack analysis module performs all fracture mechanical evaluations. Its special purpose is the computation of new crack front coordinates for the next simulation step in order to run a fully automatic crack growth analysis. The new three-dimensional criterion introduced above is implemented in this module and used for both the calculation of the kinking angles and the determination of ΔK_v . First numerical simulations are extraordinarily encouraging in comparison to experimental and analytical results known so far. Examples can be found in [2, 10]. Nevertheless a lot of experimental review is still to be done in order to verify this new theoretically found criterion.

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