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Application of the Finite Element Method to mixed-mode cyclic crack propagation calculations in specimens

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ABSTRACT

Cracks in real applications frequently exhibit mixed-mode characteristics. At MTU a software tool CRACKTRACER3D was developed to predict mixed-mode cyclic crack propagation in a fully automatic way. It consists of a preprocessor, inserting the actual crack into a finite element input deck for the uncracked structure, a call to the free software finite element program CalculiX and a postprocessor evaluating the stress intensity factors and calculating the new crack front. This loop is repeated until some predefined criterion has been reached. In order to verify the code, mixed-mode fracture in several specimens has been simulated and compared with the experimental results. This includes the propagation of a slanted crack in a 4-point bending specimen, a Compact Tension Shear Rotation Specimen under nominal Mode-III loading and a biaxial test of a square specimen with holes. Qualitatively the crack shapes are well predicted, quantitatively the numerical results are frequently on the conservative side due to the neglect of friction and interlocking in between the crack faces.

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1. Introduction

Optimization of industrial structures frequently leads to smaller cross sections and reduced safety margins. Therefore, crack initiation considerations do not always guarantee the required component life and crack propagation has to be taken into account. Indeed, the need for reliable 3-dimensional cyclic crack propagation calculations has significantly increased over the years, especially in high-technology applications such as aircraft engines. The need for automatic crack propagation tools using advanced numerical techniques has long been recognized and some of the tools have been on the market for over a decade. The geometrical aspects of crack propagation, however, are very complex and progress has been slow though albeit constant. Most of the tools such as ZENCRACK [1], FRANC3D [2] and ADAPCRACK3D [3] use the Finite Element Method. They start from a Finite Element input deck for the uncracked structure and insert the actual crack shape. In ZENCRACK the neighborhood of the crack is replaced by a premeshed building block with built-in crack. This clearly puts constraints on the uncracked mesh. FRANC3D and ADAPCRACK3D both use the submodeling technique. In FRANC3D a submodel without crack is defined. In this submodel the crack is subsequently inserted and a global remeshing of the submodel is performed. This mesh consists of a focused hexahedral mesh at the crack front and a tetrahedral mesh elsewhere. Both are connected using pyramid elements. In ADAPCRACK3D a tetrahedral mesh for the uncracked structure is automatically modified in order to include the actual crack shape. This global model is in a subsequent step used to create the displacement boundary conditions for a submodel consisting of a regular focused hexahedral mesh at the crack front. The crack propagation parameters are determined based on the submodel. A quite different approach is taken by BEASY [4–6]. This program uses the Boundary Element Method to determine the crack propagation parameters. This has the advantage that only the boundary of the structure has to be meshed, the resulting matrices, however, are asymmetric and fully populated.

The code CRACKTRACER3D developed at MTU [7,8] combines several aspects of the previously discussed codes. Starting from a mesh for the uncracked structure, a subset of elements (the so-called domain) is remeshed using a regular focused hexahedral mesh along the crack front combined with a tetrahedral mesh elsewhere. Unlike ZENCRACK and ADAPCRACK3D the resulting mesh in the domain does not depend on the mesh for the uncracked structure, provided the latter describes the geometry of the structure well enough. Also the element type of the uncracked mesh can be freely chosen, it does not have to be hexahedral (ZENCRACK) or tetrahedral (ADAPCRACK3D). Unlike FRANC3D or ADAPCRACK3D the complete structure is kept in the crack propagation calculation with complete feed-back of the effects of the crack on the global structure. Contrary to BEASY the Finite Element Method is used throughout. This is largely because this method has proven

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to be very efficient in a large range of applications and it is basically the standard numerical technique in industry.

It is worthwile to note that in the last decade a lot of other approaches have been published which have not yet found application in commercial software. These include meshless Galerkin methods [9], algebraic multigrid approaches [10], partitioned model order reduction approaches [11] and many others. The most critical aspect for the use of these methods in calculations of industrial components remains the 3-dimensional applicability.

In order to validate a general mixed-mode cyclic crack propagation code, well-documented mixed-mode crack propagation experiments are needed, which are rare. At MTU a total of 15 four-point bending (4PB) specimens wich slanted cracks were tested and described in [12,13]. At the university of Paderborn a Compact Tension Shear Rotation (CTSR) Specimen was tested under Mode-III [14]. Finally, biaxial tests on a plate with holes were reported in [15,16]. Mixed-mode crack propagation for the initial cracks in these specimens was simulated using CRACKTRACER3D and the propagation was compared qualitatively, and, if appropriate, quantitively with the experimental results.

2. Inserting the actual crack shape

CRACKTRACER3D is a fully automatic tool for mixed-mode cyclic crack propagation based on the stress intensity factor concept. It consists of a preprocessor inserting the crack into the uncracked mesh, a call to the Finite Element program CalculiX and a postprocessor calculating the crack propagation increment (Fig. 1).

2.1. Input data

Data which have to be provided include:

- a Finite Element input deck for the uncracked structure,
- a description of the initial crack,
- crack propagation data,
- an element set defining the crack propagation domain.

The numerical tool being used is the Finite Element Method. Therefore, it is assumed that an input deck for the uncracked structure is available, containing all boundary conditions and loads the user wishes to apply. This input deck should be able to run on its own. The resulting stress distributions frequently point to the position at which to insert an initial crack. This initial crack must be provided by the user. Right now, two ideal types of geometry are available: a crack with a straight front and a part-elliptical crack. They are described by simple geometrical data such as the center, location of the major axis and length of the major and minor axis for a part-elliptical crack. Internally, these initial cracks are triangulated with 3-node triangles. Any crack propagation increment calculated within CRACKTRACER3D is also triangulated and appended to the previous crack shape. The third file needed contains the crack propagation data. This will be discussed at length in Section 4. Finally, a crack propagation domain has to be defined.

2.2. Selection of the domain

The crack propagation domain is an element set in the uncracked structure in which crack propagation will be analyzed. The reason for limiting the crack propagation to a subset of the structure is twofold. First, the domain will be remeshed using an automatic tetrahedral mesher. This usually leads to a lot more elements than in the uncracked structure. Therefore, if the user knows that the crack propagation will be limited to some parts of the structure, it saves computational time to define an appropriate small domain. Secondly, due to remeshing all boundary conditions defined in the domain have to be remapped. This has not been implemented yet, so right now the user should define his domain in such a way, that no loadings or constraints are included. This

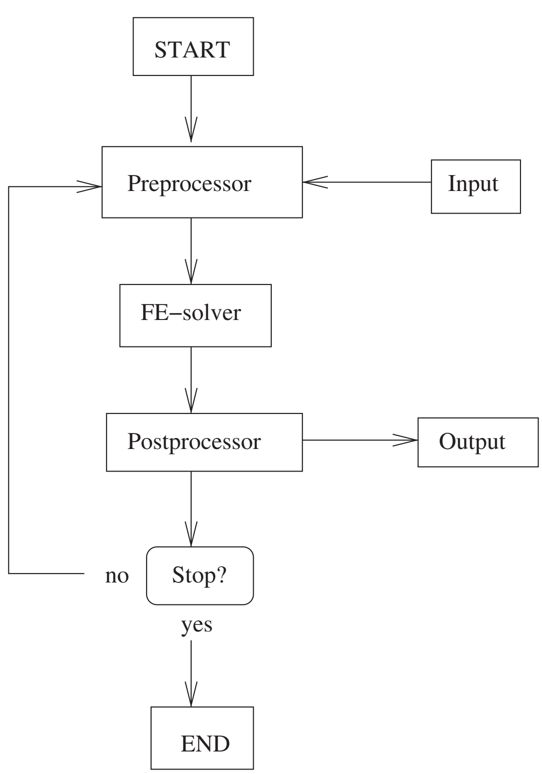

Fig. 1. Organigram of CRACKTRACER3D.

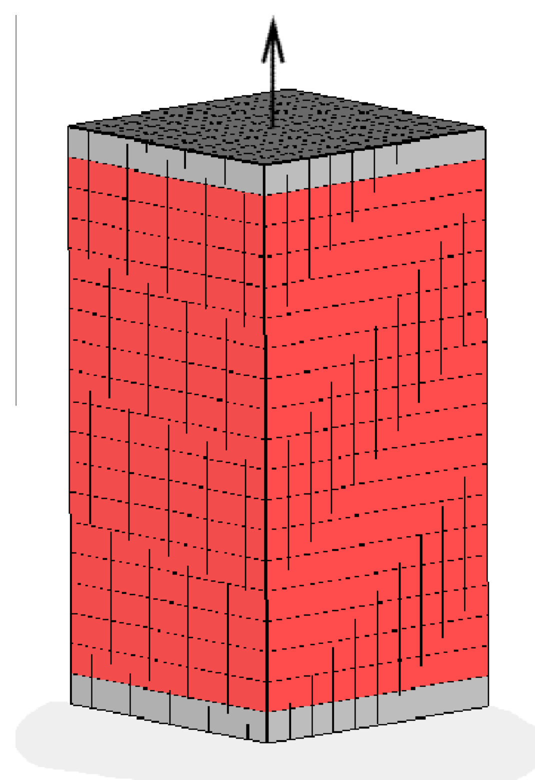

Fig. 2. Definition of the domain.

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