Automatic Cyclic Crack Propagation Calculations in Aircraft Engines

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Abstract. This document describes a mixed-element approach to perform mixed-mode crack propagation calculations in an arbitrary structure in a fully automatic way. In a preprocessing step a cylindrical volume about the crack front is meshed with hexahedral elements while the remaining parts of the structure at interest are filled with tetrahedrons. Subsequently, a finite element calculation is performed yielding the stress field at the crack tip. The postprocessor determines the stress intensity factors and the 3-dimensional crack growth, leading to a new crack front. This procedure is repeated until a user-defined criterion is reached. The method is illustrated by an aircraft casing component.

1. Introduction

Due to weight restrictions engine component designs are increasingly slender leading to crack propagation in high stress areas. Therefore, cyclic crack propagation calculations are becoming part of the standard calculations performed by the engineer. In order to take the actual load and temperature conditions into account automatic 3D crack propagation software is needed. To this end, a program with the name CURVEDCRACK was developed at MTU capable of calculating mixed-mode crack growth in arbitrary components by means of the Finite Element Method. In the past similar programs have been written such as ADAPCRACK3D [1], BEASY [2], CRACKTRACER [3], FRANC3D [4] and ZENCRACK [5]. CURVEDCRACK differs from the previous approaches by a series of very specific choices regarding the element types, the numerical method and the out-of-plane crack growth capability. Primary aim was the creation of a fast and robust tool to tackle crack propagation in parts with a difficult geometry such as aircraft engine components. In the authors' opinion this is best reached by using the Finite Element Method since this method is widely used in industry and well understood and accepted by the practicing engineer.

2. The preprocessing step

Starting point is often a component in which cracks were observed. Alternatively, a newly designed part may fail to reach the preset life requirements using the standard crack initiation considerations. In both cases crack propagation calculations are the proper choice to solve the problem. It is assumed that the engineer has already performed all kinds of calculations for the structure at stake, so a Finite Element input deck for the uncracked structure exists. For crack propagation calculations two additional files are needed: a file describing the geometry of the initial crack and a file with crack propagation data such as the Paris law constants for the appropriate material and temperature range. To reduce the computational cost the user can also isolate a region within the mesh the crack will not exceed during propagation. Using these four files, the preprocessor of CURVEDCRACK generates an input deck for the cracked structure in a fully automatic way. Although this does not sound very difficult, it is the most delicate step in the whole procedure, due to the high complexity of aircraft engine components.

The basic strategy is such that a cylindrical volume centered about the crack front is isolated and meshed with hexahedral elements, while the remaining part within the user-selected region is filled with tetrahedral elements. This is illustrated in Fig.1. On the left the complete structure is depicted, the region of interest in the middle has a dark grey color. On the right this region has been remeshed. The crack front, which takes a quarter circular shape, is surrounded by a cylindrical region filled with hexahedra. Note that the cross section of the cylinder is a hexagon in order to facilitate the hexahedral meshing. Furthermore, several layers of hexahedra were created about the crack front, with the innermost layer consisting of collapsed quarter point elements [6] in order to match the $1/r^{0.5}$ singularity typical for linear elastic fracture calculations. The remaining area is meshed with tetrahedrons. The connection of the hexahedrons with the tetrahedrons and the user-selected region with the rest of the component is taken care of by multiple point constraints. Notice that the nodes belonging to the crack shape are duplicated to allow the crack to open.

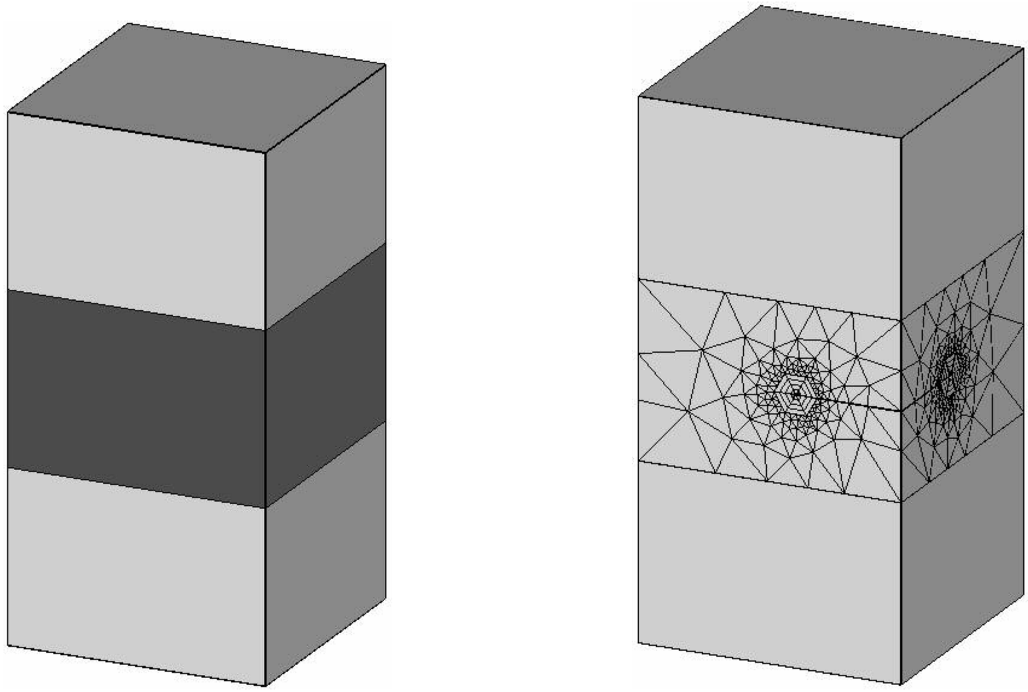

Figure 1: Insertion of the crack

Additional care is due in order to create a proper tetrahedral mesh. To this end the freeware program NETGEN [7] was used, which is able generate a tetrahedral mesh based on a triangulation of the surface. The sole purpose of this triangulation is the geometrical description of the body to mesh. Starting point is a triangulation of the uncracked structure based on the initial finite element mesh. In subsequent steps this triangulation is automatically modified to take the cylindrical volume at the crack front and the duplication of the crack shape into account [8].

3. The Finite Element calculation and postprocessing

In CURVEDCRACK the sole purpose of the finite element calculation is the determination of the stresses in the elements surrounding the crack tip. These are the collapsed quarter point elements. In the postprocessing step these stresses are used to determine the stress intensity factors.
To this end the two collapsed elements in front of the crack and adjacent to the crack shape at a given location along the crack front are focused on. For each of these elements the stresses in the integration point closest to the crack front are considered. This yields in each of both integration points a stress tensor with 6 stress components. To avoid the problem whether plane stress or plane strain conditions prevail the normal stress component on a plane perpendicular to the crack front is discarded. By comparing the remaining 5 stresses with the asymptotic stress field about the crack

front (which contains the stress intensity factors) one obtains 5 equations in three unknowns. Application of least squares yields a set of K-factors in each of the integration points. Finally, to conserve symmetry the mean of both sets is taken. This procedure has been explained in detail in [9].
Knowing the K-factors the asymptotic stress field can be determined. It is a function of the distance from the crack tip r and the angle with the crack shape φ. By multiplying the stress field with $r^{0.5}$ the dependence on r disappears and what is left will be called the self-similar stress field. It has the dimension of stress intensity factor. For each angle φ a self-similar stress tensor arises, for which the principal self-similar stresses can be derived. The planes on which these principal self-similar stresses act are characterized by an inclination angle φ_0 and a tilting angle ψ_0. A fundamental prerequisite for such a plane to be the crack propagation plane is that it contains the crack front, i.e. $\varphi = \varphi_0$. This leads to the correct crack propagation angle φ_0 and tilting angle ψ_0. Furthermore, the value of the corresponding principal self-similar stress is the equivalent K-factor. If more than one principal self-similar stress satisfies the above criterion, the largest of them all is taken. This procedure is applicable to isotropic as well as anisotropic materials and is discussed in [10].
To obtain a crack propagation increment the equivalent K-factor is substituted into a Paris-type crack propagation law yielding a crack propagation rate, i.e. a crack propagation increment per Low Cycle Fatigue cycle. Since performing a Finite Element calculation after each cycle is unfeasible (the required number of cycles is usually 20,000 to 30,000), a target increment size after which a new Finite Element calculation is to be performed can be specified by the user. Within this size the K-distribution along the crack front is assumed to remain constant. Typical increment sizes are about 50 to 200 µm. The postprocessor verifies where along the crack front the maximum equivalent stress intensity factor occurs, calculates the number of cycles to reach the target increment size at that location and applies this number to all positions along the crack front, taking the local inclination angle into account. This leads to a new crack front and the whole procedure can start over again.
In the case of missions the postprocessing becomes slightly more complicated. A mission is a set of load steps applied to the structure, for instance corresponding to a real flight of the aircraft: typically a few hundred loading points to simulate take-off, cruise, landing and thrust-reverse. For each position along the crack front each loading step leads to an equivalent K-factor and corresponding crack propagation plane. First, the time in the mission is identified leading to the maximum crack propagation rate for that position. Its inclination angle defines the crack propagation plane for that mission. Then, for all other times the principal self-similar stress is identified whose principal plane is closest to this crack propagation plane. The propagation crack propagation rates versus mission time is the curve on which the rainflow algorithm is applied. After cycle extraction the crack propagation due to each cycle is evaluated separately and summed.

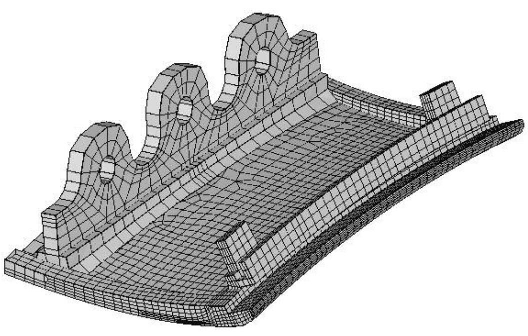
Figure 2a: Casing part

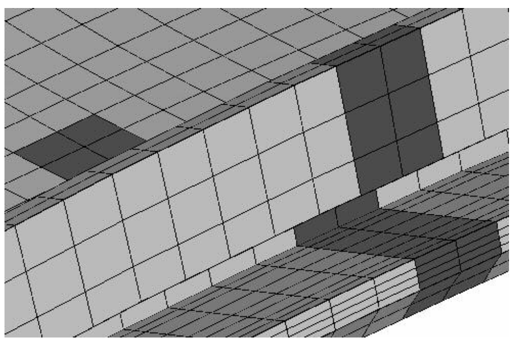
Figure 2b: Region of interest

The procedure is now illustrated using the casing part in Fig. 2a. The region of interest is the dark part in Fig. 2b. Fig. 3a shows a cross section and the location of the initial part circular crack, symbolized by a small circle.

Application of CURVEDCRACK led to the final crack shape in Fig 3a, whereas Fig. 3b shows a detail of the final crack fronts. For this application the crack propagation was forced to stay in-plane, i.e. the inclination angle φ was set to zero. One notices how the crack smoothly propagates, crossing several discontinuities at the free boundary.

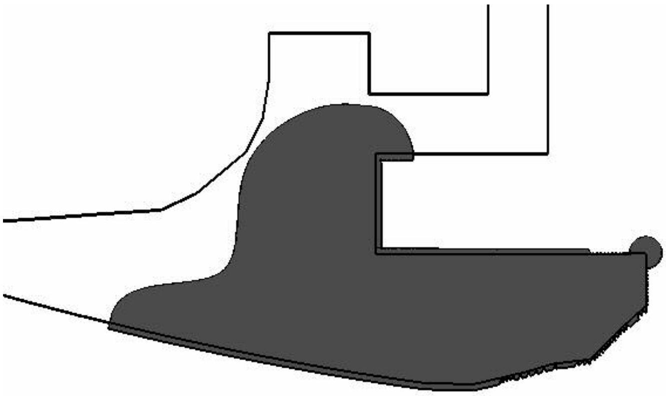

Figure 3a: Final crack shape

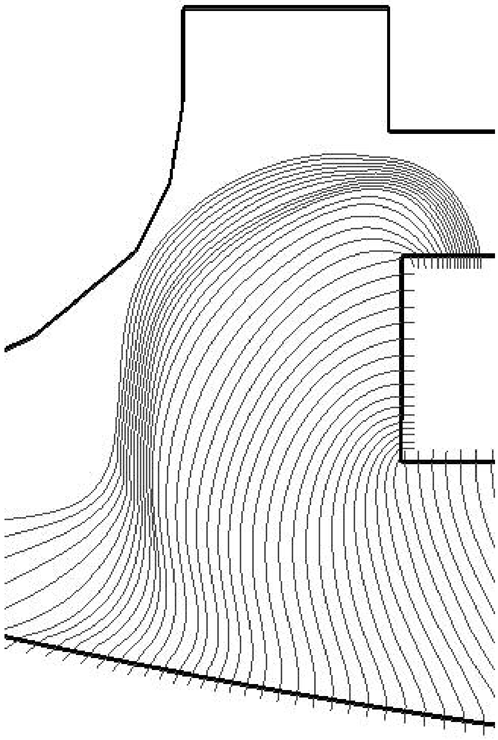

Figure 3b: Single Crack Fronts

4. Conclusions

A method has been developed to compute cyclic crack propagation in a fully automatic way. Due to the combination of hexahedrons at the crack front and tetrahedrons elsewhere, a very flexible procedure arises able to cope with the complex geometry one encounters in aircraft engine components.

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