

Automatic 3-D Crack Propagation Calculations in Industrial Components: a pure Hexahedral versus a combined Hexahedral-Tetrahedral Approach

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Abstract. In recent years, increased loading and low weight requirements have led to the need for automatic crack tracing software. At MTU a purely hexahedral code has been developed in the nineties for Mode-I applications. It has been used extensively for all kinds of components and has proven to be very flexible and reliable. Nevertheless, in transition regions between complex components curved cracks have been observed, necessitating the development of mixed-mode software. Due to the curvature of the crack faces, purely hexahedral meshes are not feasible, and therefore a mixture of hexahedral elements at the crack tip, combined with tetrahedral in the remaining structure has been selected. The intention of the present paper is to compare both methods and to point out the strength and weaknesses of each regarding accuracy, complexity, flexibility and computing time. Furthermore, difficulties arising from the out-of-plane growth of the crack such as the determination of the crack propagation direction are discussed.

1. Introduction

Fully automatic mixed-mode crack propagation calculations are gaining importance in high technology fields such as aero engine manufacturing. The key problem on the numerical side is the automatic creation of arbitrarily shaped and oriented cracks in the model of the structure. This especially applies to the finite element method, since it requires the structure do be split in relatively nicely shaped finite elements, including the crack tip region. Therefore, people have tried to come up with methods bypassing this difficulty. This has led to the use of the boundary element method and meshless methods. The boundary element method reduces the complexity of remeshing by limiting the extent of the mesh to the surface of the structure. It has been implemented in commercial codes [1] and is quite successful. More recent efforts were invested in meshless methods [2], removing the need to deal with a mesh at all. These methods, however, have several disadvantages:

- they are not compatible with the classical finite element method. This means that the model for the cracked structure cannot be used in a classical finite element calculation. Only those calculations are feasible, which are provided by the boundary element method or meshless method, respectively.
- The underlying theory is more difficult to grasp and not so intuitive as the finite element method.
- They require the purchase of the appropriate code. This means that more codes have to be maintained and more people have to be trained in different codes thus increasing the cost.

These considerations have led to the believe that performing crack propagation calculations with the finite element code is a goal worth pursuing. First efforts have been undertaken quite a long time ago in the mid-nineties. Crack propagation problems in an existing engine led to the conviction that a crack propagation tool would be a valuable asset. Therefore, a scheme was developed to insert an existing plane crack in between existing layers of hexahedral finite elements. An algorithm was developed to split the bricks at the crack front into new hexahedral elements in a fully automatic way [3-4]. This method, however, only works for Mode-I calculations. In Mixed-Mode calculations the crack can take an arbitrary shape and does not necessarily remain plane. Cutting a hexahedral mesh with this arbitrary shape usually deteriorates the element quality substantially. Therefore, for Mixed-Mode calculations a combined hexahedral-tetrahedral approach has been selected.

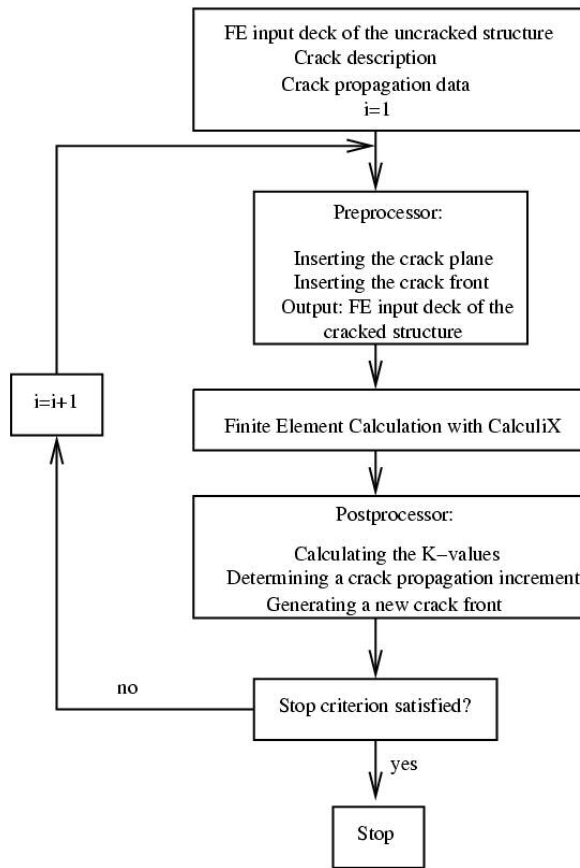


Figure 1: Flow chart for the hexahedral approach

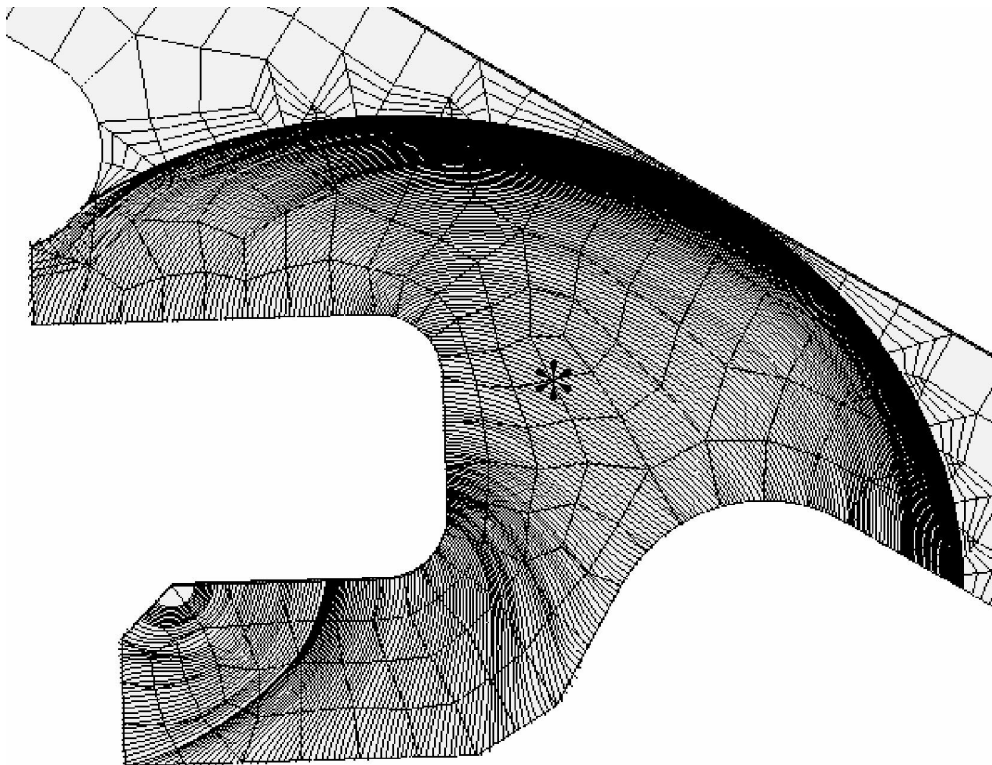


Figure 2: Crack fronts in the hexahedral approach

2. The pure hexahedral approach.

The flow chart for the hexahedral approach is shown in Figure 1. In each iteration the program starts from a CalculiX [5] input deck for the uncracked structure. The task of the preprocessor is the insertion of the actual crack plane and front into the mesh and to create a CalculiX input deck for the cracked structure. This also includes the automatic modification of the boundary conditions and loads. With the finite element program CalculiX the stresses at the crack front are determined. These are used in the postprocessor to calculate the stress intensity factors and the number of cycles leading to a given crack propagation increment (by means of an appropriate crack propagation law such as the Paris law). The new crack front is determined and the procedure can start over again, unless the stopping criterion is satisfied. The algorithm has by now been used for over 10 years and has proven to be very reliable. It has been applied to a variety of engine components. Figure 2 shows the crack propagation results in a casing part. In particular, the cracks smoothly propagate across corners of the structure, a feature which is rarely mastered by commercial crack propagation tools. The main disadvantage of the method is its limitation to planar crack growth in between element layers. Especially this latter point frequently requires either additional cutting by a plane, which deteriorates the element quality, or tedious mesh modifications by the user. Therefore, an alternative strategy is being developed.

3. The combined hexahedral-tetrahedral method.

The primary aim of the combined approach is the complete removal of any constraints on the crack propagation, i.e. the crack should be completely free to choose its propagation path in agreement with the prevailing stress fields. This requires a substantial amount of mesh flexibility, which is generally only feasible by using (quadratic) tetrahedral elements. This type of element, however, is not very suited to model the stress field at the crack tip. Indeed, due to its irregular shape one frequently observes local stress maxima which can only be avoided by an exceedingly fine mesh. Furthermore, this type of element does not exhibit the very handsome $1/\sqrt{r}$ singularity provided by the collapsed quarter-point brick element. Therefore, a cylindrical region about the crack front is created and filled with hexahedral elements to take advantage of their excellent crack tip properties. To handle this task, the flow chart in Figure 3 is used. Based on the mesh of the uncracked structure a triangulation of the surface is created. This triangulation is used to generate the tetrahedral mesh, after modifying it in two ways: first, the cylindrical region about the crack front is subtracted, and subsequently the slit in between the crack faces (which are geometrically described by a triangulation on their own) is removed. This leaves us with a triangulation of the cracked structure minus the cylinder. Now, based on this triangulation the volume is filled with tetrahedra using an automatic tetrahedral meshing code. The cylinder at the crack front, however, is filled with regular hexahedra. Both meshes are connected using multiple point constraints. The resulting mesh is shown in Figure 4. Finally, the boundary conditions and loads are mapped on this new mesh and a finite element calculation can be performed yielding the stress field at the crack tip. The postprocessor calculates the stress intensity factors based on these stresses and a crack propagation increment. Since we deal with mixed-mode, this also involves the determination of a crack propagation direction [6]. The triangulation of the crack is updated and a new iteration can start. Presently, the smoothing of the K-factors and the determination of the crack propagation increment is worked on. The code is scheduled to be ready (first version) by the end of 2007.

References

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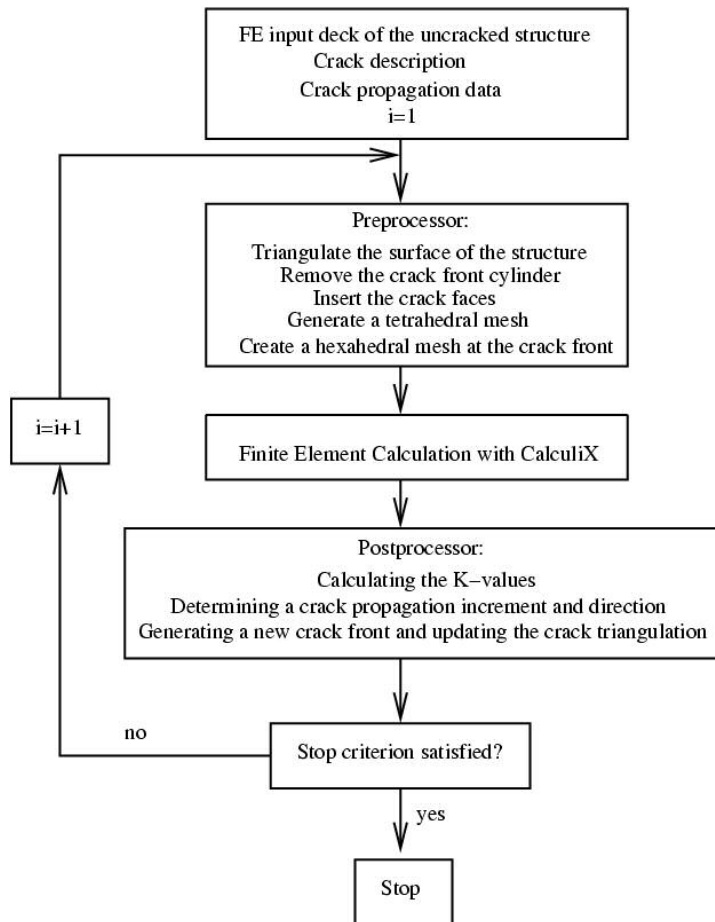


Figure 3: Flow chart for the hexahedral-tetrahedral approach

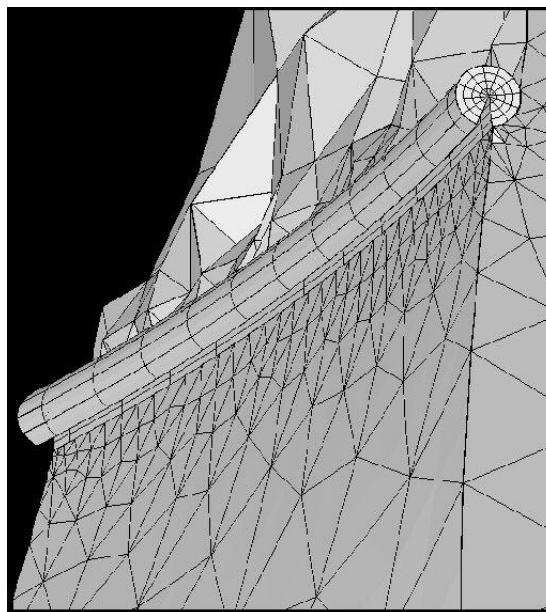


Figure 4: Mesh at the crack front in the hexahedral-tetrahedral approach