Modeling of 3-D Fatigue Crack Growth in Real-Life Components

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ABSTRACT
Within the framework of the finite element method (FEM) and linear elastic fracture mechanics (LEFM), the development of a numerical tool for fatigue crack propagation computations is in progress. The method uses a combination of hexahedral and tetrahedral elements in order to achieve accurate singular FE-fields in the crack front neighborhood. The structured mesh at the crack front allows easy postprocessing of the computed FE-fields. Stress intensity factors (SIFs) and subsequently the equivalent SIF are determined at integration points directly ahead of the crack front. The crack growth rate is calculated from the equivalent SIF adopting a suitable crack growth law.

A brief description of the aims and underlying theory behind the approach is given. Results from an analysis of a gas turbine engine component illustrate how geometrical singularities may influence the crack growth rate and direction.

INTRODUCTION
The nature of gas turbine engines inherently involves complex loading conditions and environment factors. Environment factors such as pollution, combustion or even foreign objects impose the risk of surface damage and eventually crack nucleation. As a result, an important part of engine design and maintenance is the capacity to perform crack growth analyzes. At the design and development stage, crack growth predictions often bring the need for design improvements while during operation, engine maintenance and service may reveal crack initiation which necessitates crack growth risk analyzes.

Crack initiation can result from a range of factors including manufacturing flaws, mechanical damage, corrosion and creep. Once a crack is initiated, it is likely to undergo subsequent crack growth driven by a combination of e.g. temperature, gas, centrifugal and residual loads. Increasing challenges imposed by ecological requirements, cost efficiency and performance set higher demands for each new application. The increased demands are often reflected in the analysis in terms of more advanced structure geometries, loading scenarios and the increasing computational needs. These factors naturally inflict present crack propagation software and amplify the desire for versatile and powerful tools.

A number of crack propagation tools have been developed since the dawn of the finite element method (FEM) and the boundary element method (BEM). The earliest applications were based on libraries of a variety of crack configurations, e.g. NASA/FLAGRO [1] and NASCRAC [2]. However, most software today have abandoned the library based approach and instead determine crack growth for each unique crack growth state specifically. Examples of such FEM and BEM software are ADAPCRACK3D [3], BEASY [4], CRACKTRACER [5,6,7], FRANC3D [8] and ZENCRACK [9]. The choice of framework, either FEM or BEM, has been investigated in the past and show that both framework yield results that correspond well to experimental findings [10].

Within the industry, software is mainly adapted and intended for use within the FEM framework which therefore has gained more ground than any of the other methods. Not only is FEM widely known and practiced, a model created for the use with BEM can not be used directly in a FEM application. As a result, consideration of the conformity with the industry and previous investigations has led to the belief that a crack propagation tool within the framework of FEM should be pursued.

This paper describes the underlying method of the approach and presents an application of the method in order to demonstrate the challenges and potential for 3-D crack propagation computations.

AIMS OF THE METHOD

Since a number of crack propagation tools are already available, the development of new tools should introduce new means and possibilities. Three such very important requirements are 3-D crack growth, automation and mesh independence. An ability to treat non-planar crack growth, i.e. the crack front may bend or twist and the crack surface curve, becomes increasingly important. Crack growth computations are iterative processes involving a large number of crack front estimations which necessitates the automation of the tool. As the computational procedures tend towards tetrahedral meshes more often today than before meanwhile hexahedral meshes are still widely preferred, it is important that the tool is not bound to a specific type of mesh but rather independent of the supplied mesh type.

The crack growth rate and direction are determined by the state at the crack front. Therefore, the surrounding area must be appropriately modeled. A structured and focused tubular FE-mesh along the crack front is commonly advised for this purpose. Adopting an element type that provides suitable singular FE-fields allows these to be compared directly to available analytical solutions.

Elsewhere, the approach should be to introduce as few changes to the input data as much as possible. In most cases, any change introduces additional degrees of freedom (DOFs). One solution to reduce the additional DOFs is by manipulating only a limited domain of the given input mesh.

DESCRIPTION OF THE METHOD

The main objective of the method is to facilitate a well structured mesh that encloses the crack front region. A focused and structured mesh does not only yield accurate singular fields but also allows straight forward book-keeping of elements, nodes and integration points necessary for the crack growth rate computations. The program is composed of two modules; a preprocessor that generates the input for the FE-solver and a postprocessor that reads and makes use of the computed results.

Starting point is always the crack front. Based on the local crack front orientation, a tubular interface is generated by connecting piecewise linear concentric rings of nodes around the crack front. Boolean surface operations on the free boundary surface of elements included in the selected domain, the tubular interface and the crack face yields a boundary representation of what is referred to as the keyhole surface. The tubular hole is filled by the hexahedral mesh generated based on information from the interface nodes while the separated crack faces are represented by the gap. The volume enclosed by the boundary representation is filled with tetrahedral elements. Together, the hexahedral mesh, the tetrahedral mesh and the remaining intact initial mesh replace the supplied input mesh. All three separate meshes are connected by linear multiple point constraint (MPC) equations in order to hold the different parts together. The quality of the MPC connections between the tetrahedral mesh and the hexahedral mesh is secured by making the free faces of the hexahedral mesh as plane as possible. For the connection between the tetrahedral mesh and the intact input mesh, it is assumed that the faces of the input elements are sufficiently plane.

Initial conditions such as temperature and residual quantities are easily interpolated to the new replacement mesh, which is widely dissimilar to the input mesh. Boundary conditions such as MPCs and distributed loads, on the other hand, are less indulgent when it comes to interpolation and extrapolation. The solution has therefore been to avoid mesh manipulation in regions holding boundary conditions, which can therefore be directly transferred to the new input.

The postprocessing program calculates the stress intensity factors (SIFs) from the computed FE-fields at integration points directly ahead of the crack front. Due to the structured mesh and the simplified book-keeping this may be done by different methods. Here, SIFs are obtained from a direct comparison of the FE-stress field with the analytical solutions via a least squares-computation. An equivalent SIF and corresponding deflection angle are subsequently obtained from the computed SIFs and applied to the Paris' Law or equivalent. The transformation of the crack growth rates to crack growth increments rests on the assumption that the crack growth rate remains constant during the entire predefined cycle span or crack increment size. Each computed crack front is added to the previous crack configuration making the crack grow by each increment.

The above scheme is repeatedly executed until a stopping criterion is reached. A simple example input mesh consisting of three elements and the resulting cracked mesh are illustrated in Figure 1. The dark element in the input mesh represents the selection of elements to be manipulated and replaced. The method is further described in [11] and compared with an in-plane crack growth tool in [12].

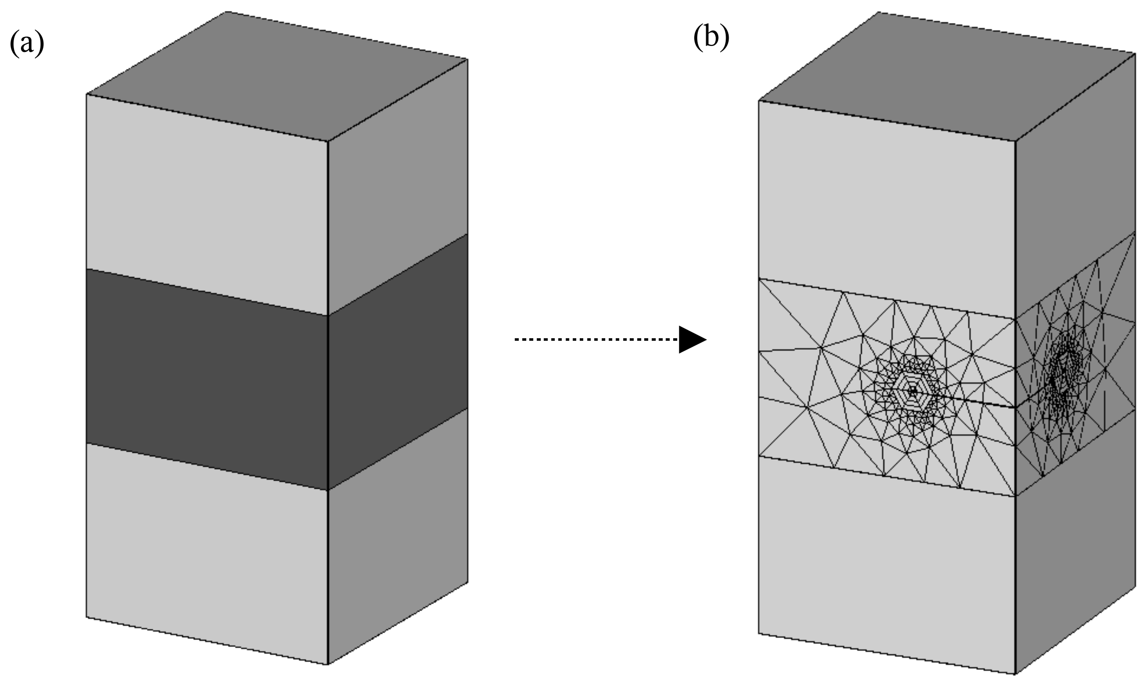

Fig. 1 *An illustration of the method applied to an input mesh (a) leading to the cracked mesh (b).*

MODELING OBSTACLES

Both the preprocessing and postprocessing steps involve challenging tasks concerning geometrical operations. Particularly demanding are the Boolean boundary operations between the tube interface and the free structure boundary involved in the preprocessing step. These tasks can quickly turn tremendously complicated if the free surface includes holes, corners, edges etc. Another equally difficult situation is when the tube interface becomes tangent to the free surface. The joint characteristic for these situations is that they require powerful enough methods that can treat such scenarios but at the same time function in the more common situation. During postprocessing, the challenge lies in computing the new crack front location. Simply moving the previous crack front in the growth direction by a distance determined from the crack growth rate does not make the new crack front match the structure geometry. Operations are needed to fit the new front to the boundary, without altering the accuracy of the new crack front location.

CRACK IN A GAS TURBINE ENGINE COMPONENT

The structure in Figure 2 is a part from a typical real-life gas turbine engine component. The mesh consists of 8120 hexahedral (quadratic) elements. A temperature field, distributed pressure load and residual stresses (all fictitious) account for the loading situation.

The area of interest is the front edge where a growing crack soon would reach the corners of the free surface. A selection of elements is chosen at the center of the front edge where an assumed part circular initial crack is inserted, see Figure 3. No boundary conditions prevail at the front edge or near the selected elements. However, both the temperature field and the residual stress grow stronger near the front edge center which bring the selected area even more attention.

Considering the loading situation and the resulting stress field of the uncracked structure, it is expected that a mode-I loading dominates with limited influence from mode-II and mode-III. The structure in general and the region of interest in particular hold a number of sharp edges and corners. It is believed that these corners have a considerable local effect on the crack growth rate distribution along the crack front. An additional aspect which influences the crack growth is the effect of increasing component thickness.

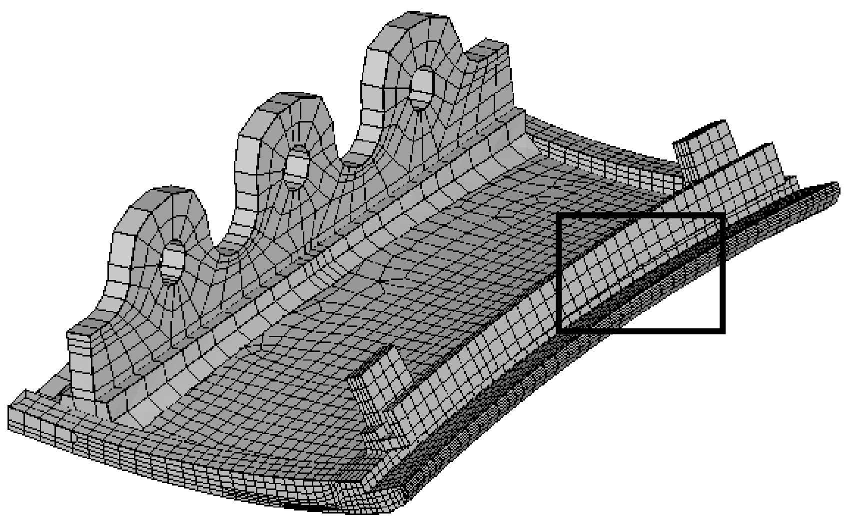

Fig. 2 *Part from a real-life component of a gas turbine engine with the front edge center framed.*

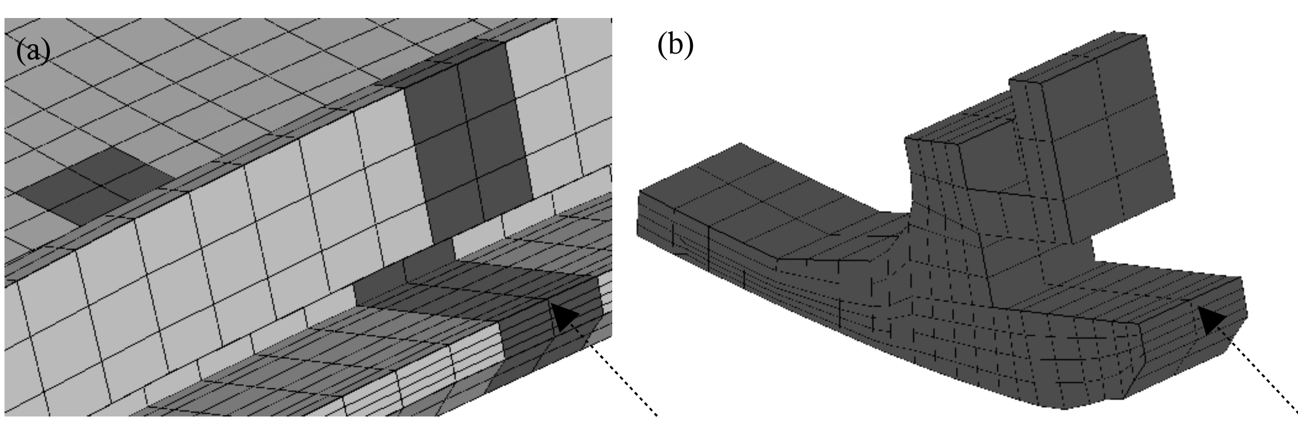

Fig 3. *The selected set of elements (dark) to be manipulated and replaced by the cracked mesh (a) and a cut out of the same (b). The arrows indicate the location of the part circular crack.*

RESULTS

A cross section of the cracked structure and the crack face are displayed in Figure 4a. It can be seen how the crack has grown from its initial location into the structure passing the two 270° corners and eventually divides into multiple crack fronts. It is emphasized the local effect the corners have on the crack growth rate, see Figure 4b. This interesting effect stands out by comparing the distance between consecutive crack fronts. The distance is in general of the same magnitude along each crack front but a pronounced reduction is noticed near the singularities and can be interpreted as a temporary reduction of the crack growth rate. That the reduction is temporary is supported by the distance between consecutive fronts beyond each corner, which again shows a relatively constant crack growth rate along the crack front.

It is also interesting to inspect the evolution of the minimum and maximum mode-I SIF as the crack grows. Figure 5a shows the minimum and maximum SIF for the first 80 iterations. The maximum SIF is found to be influenced mainly in the neighborhood of iteration 10 and 30. The peak effects of the maximum SIF are understood as an effect from the two relatively blunt edges at the bottom structure surface, see Figure 5b. As the crack front approaches the edges, the crack growth rate temporarily slows down but increases rapidly when an edge is passed. A third effect is a reduction of the minimum SIF as the crack front reached the first 270° corner at iteration 70. This singularity can be identified by the increasing difference between the maximum and minimum SIF. Again, the difference gradually fades as the crack front progresses beyond the corner.

A local reduction or increase in crack growth rate turns the direction of propagation in the next iteration. The change in crack growth rate therefore does not only influence the size of the crack, it also affects the shape of the crack front and the size of the crack.

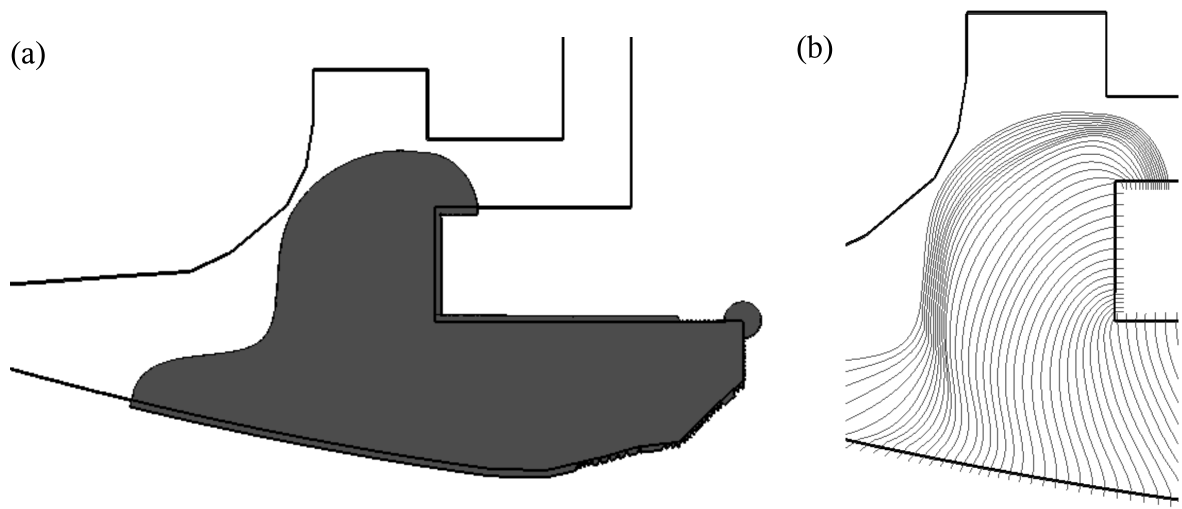

Fig. 4 *A cross section of the selected domain (a) shows the crack growth. Magnification of the two 270° corners (b) reveals the effect on crack growth rate distribution induced by geometrical singularities.*

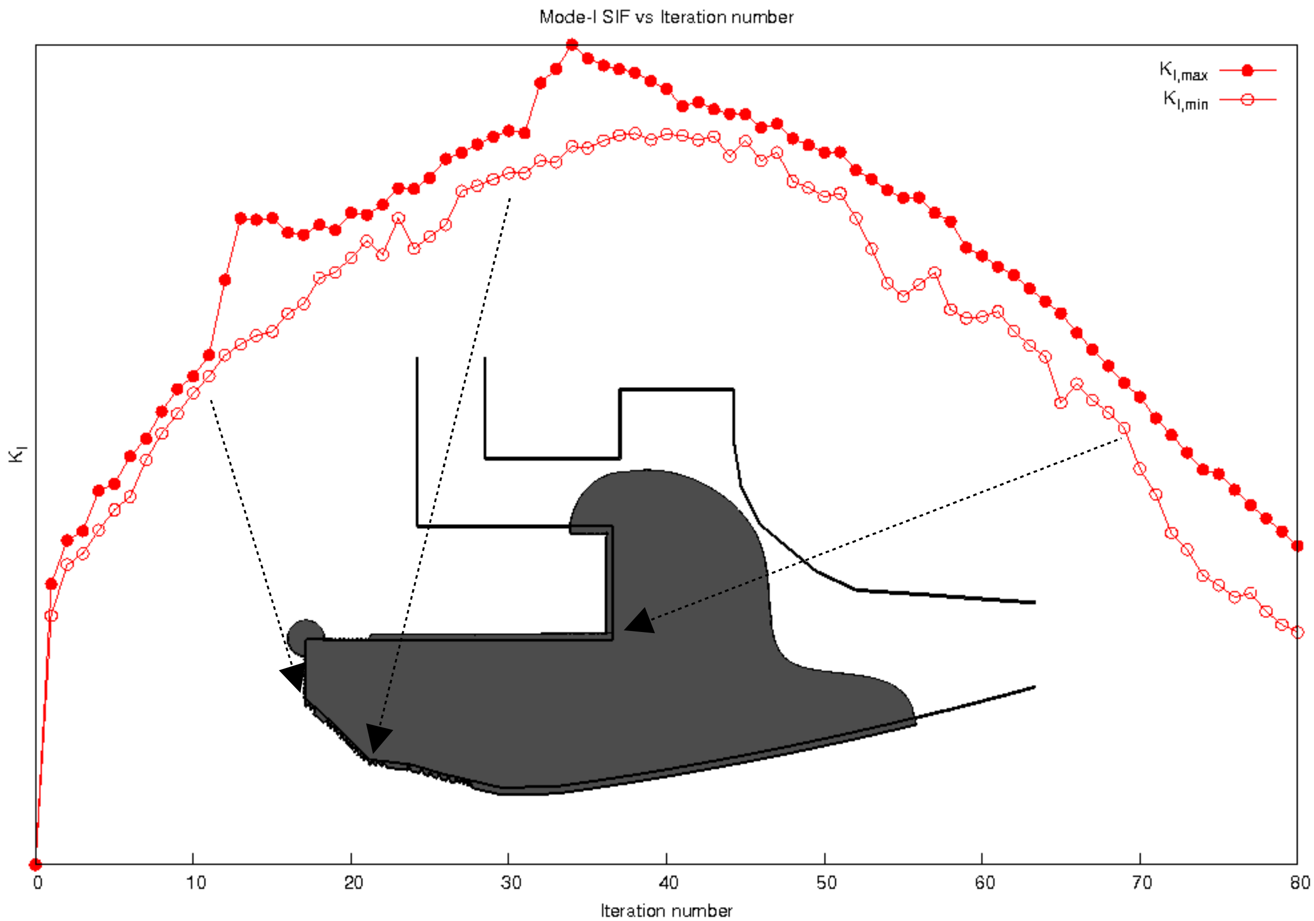

Fig. 5 *The mode-I SIF versus the accumulated number of load cycles. The arrows indicate geometrical singularities that locally influence the SIF.*

CONCLUSIONS

Results from this study of a real-life component emphasize the importance of access to numerical tools during crack propagation predictions. Particularly important is the ability to evaluate and account for the crack growth state in both a global and local sense. Temperature gradients, residual fields and tractions affect the crack growth rate and in most cases lead towards curved crack fronts as a result of the prevailing varying stress field in the component. Additionally, singularities such as edges and corners locally influence the crack growth rate and consequently the crack growth direction.

In this study, the above conclusion has been exemplified adopting a numerical tool with the principal aim of accurate modeling of the crack front region. The generation of the tubular hexahedral mesh along the crack front involves many challenging tasks. As a result, due to the current program structure, manual intervention occasionally becomes necessary. However, the above results favors future improvements and the continued development of a crack propagation tool based on a combination of tetrahedral and hexahedral elements.

ACKNOWLEDGMENTS

The authors gratefully acknowledge MTU Aero Engines GmbH for the permission to publish this work.

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