Prediction of three-dimensional crack propagation paths taking high cycle fatigue into account

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ABSTRACT. Engine components are usually subject to complex loading patterns such as mixed-mode Low Cycle Fatigue Loading due to maneuvering. In practice, this LCF Loading has to be superimposed by High Cyclic Fatigue Loading caused by vibrations. The changes brought along by HCF are twofold: first, the vibrational cycles which are superposed on the LCF mission increase the maximum loading of the mission and may alter the principal stress planes. Secondly, the HCF cycles themselves have to be evaluated on their own, assuring that no crack propagation occurs. Indeed, the vibrational frequency is usually so high that propagation leads to immediate failure. In the present paper it is explained how these two effects can be taken care of in a standard LCF crack propagation procedure. The method is illustrated by applying the Finite Element based crack propagation software CRACKTRACER3D on an engine blade.

KEYWORDS. Crack propagation; Mixed-mode; High cycle fatigue; Mission; Vibrations.

INTRODUCTION

Crack propagation calculations have become standard in aircraft engine applications. Frequently, crack initiation life is not sufficient and has to be augmented by crack propagation life in order to obtain the envisaged component life. This requires crack propagation calculations in the design phase of the engine. However, also later on in the life of the engine fracture mechanics calculations may be necessary to analyze damage observed in-service. By now, three-dimensional fully automatic mixed-mode crack propagation calculations are state-of-the-art [1-3]. They generally consist of a pre-processing module which automatically inserts an arbitrary crack into a given mesh, a call to a Finite Element Program to determine the stress field and a post-processing module taking care of the calculation of the stress intensity factors, cycle extraction [4] and the calculation of the new crack front based on a crack propagation law [5-7]. Notice that, since the K-factor concept is used, all calculations are linear elastic. In order to take HCF due to vibrations into account all these modules have to be modified. In essence, additional frequency calculations have to be performed for the cracked structure, the results must be scaled based on experimental evidence and the mission containing the mixed-mode K-values at different positions along the crack fronts has to be augmented by the HCF K-values. In addition, the HCF cycles have to be evaluated on their own to check that no propagation occurs. The following sections explain in detail the necessary modifications. Finally, an example based on a simplified blade shows a practical application.

MODIFICATIONS TO THE PREPROCESSOR AND THE FINITE ELEMENT CALCULATIONS

The preprocessing unit takes the finite element input deck for the uncracked structure, inserts the crack (or cracks) and generates an input deck for the cracked structure. Without HCF this input deck usually contains a complete flight mission, i.e. a collection of maybe 100 to 200 loading points along the mission. Taking HCF due to vibrations into account requires a careful analysis of the mission. First, the user must identify those loading steps prone to resonances, and for each of these determine due to which eigenmode the resonance arises. Indeed, vibrations usually occur selectively at certain engine speeds at which they are triggered. A bending mode may be active at a different engine speed than a torsional mode. This means that the user must be able to specify at the start of the preprocessing step which eigenmode should be superimposed on which loading step in the mission. Based on this information, the preprocessing unit will create input decks for frequency calculations consisting of an appropriate static pre-loading step followed by a frequency calculation up to and including the mode of interest.
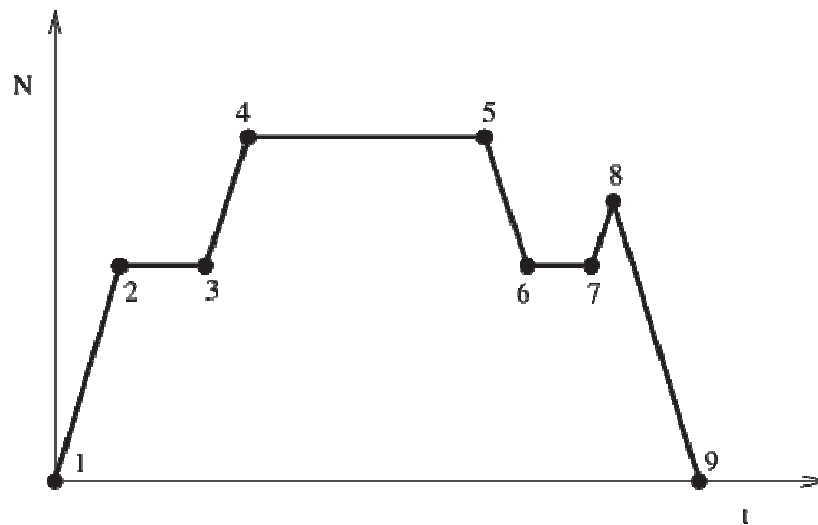

Figure 1: LCF-mission.

For instance, the mission in Fig. 1 contains 9 loading points. Suppose that a preliminary analysis has revealed that mode 1, which happens to be a bending mode, is resonant near loading point 2 and mode 4, which happens to be a torsion mode, is resonant near loading point 4. Then, the preprocessor has to generate three input decks for the finite element program: a static calculation of the mission (9 loading points), a static step corresponding to loading point 2 followed by a perturbation frequency step for at least the first eigenmode and a static step corresponding to loading point 4 followed by a perturbation frequency step for at least the lowest four eigenmodes. Since these calculations can be performed in parallel, this should not significantly increase the overall computation time. Notice that these calculations have to be performed for the cracked structure in each iteration of the crack propagation software.

MODIFICATIONS TO THE POSTPROCESSOR

In the postprocessor of CRACKTRACER3D the stress intensity factors are determined by comparing the stress tensor at the integrations points of the collapsed quarter point elements immediately ahead of the crack tip with the asymptotic stress field [1]. A frequency calculation, however, does not yield absolute stress values since it is the solution of a homogeneous set of equations: the results can be freely scaled by a constant. To get absolute values, a scaling has to take place by comparing the engineering strain at a certain location and direction with experimental evidence. This evidence is usually gathered for the uncracked structure, and it is assumed that the experimental reference point is far enough away from the crack location, so that the interaction with the crack is minimal. After scaling the eigenmodes, the mixed-mode stress intensity factors can be determined for the mission and for each of the selected eigenmodes. Then, referring to the example in Fig. 1, three crack propagation calculations are performed.
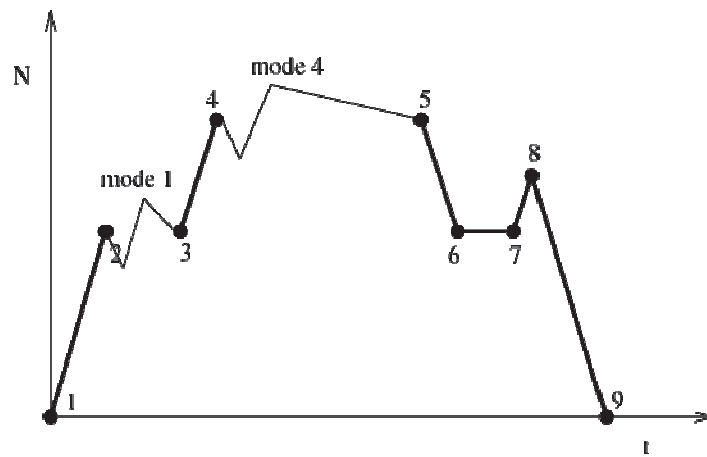
Figure 2: LCF-Mission augmented by HCF-cycles

The first one is for the mission augmented by the eigenmodes at the specified locations (Fig. 2). This corresponds to a LCF calculation for an extended mission. The usual procedure is followed involving the determination of a dominant loading point to determine the crack propagation direction, the reduction of the mixed-mode K-values to an equivalent K-factor, calculation of the crack propagation of each loading point separately, cycle extraction on the resulting curve and evaluation of the crack propagation of each extracted cycle based on the maximum cycle temperature (for details the reader is referred to [8]). The crack propagation increments from each extracted cycle are summed. Including HCF will frequently lead to more crack propagation, since a HCF cycle at a maximum point of a mission will increase the equivalent K-factor. The second and third calculation concerns the eigenmode itself, centered at the appropriate loading point (Fig. 3). Also here, the usual cycle extraction routines are applied to short missions consisting of the loading point plus the eigenmode and the loading point minus the eigenmodes. Since the calculations are linear the K-factors can be summed appropriately. For the pure HCF-evaluation the criterion is that no propagation should occur. Indeed, the HCF frequency is usually so high that propagation results in immediate failure.
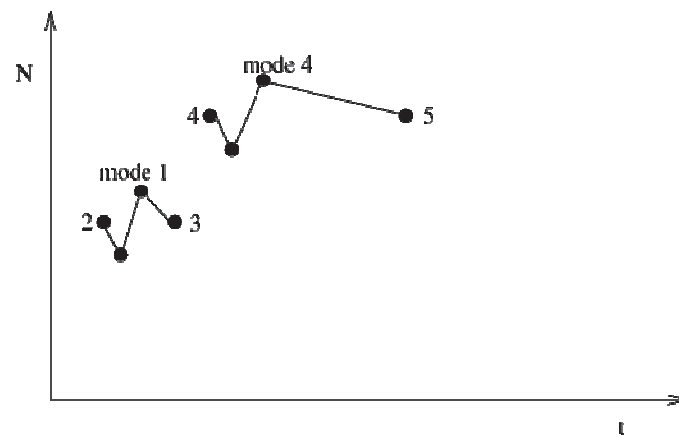

Figure 3: HCF cycles.

EXAMPLE

A simple example is presented in the form of an imaginary blade (Fig. 4) subject to centrifugal loading. Only two loading points are considered, full power and zero loading. An initial quarter circular crack of with radius 0.4 mm is inserted at the location of maximum principal stress about 25 mm above the disk. The orientation of the crack plane was orthogonal to the maximum principal stress, acting in radial direction. At first a calculation consisting of 50 iterations of CRACKTRACER3D was performed without HCF. The mesh in the last calculation is shown in Fig. 5. One can clearly see the domain in which the mesh was modified in order to accommodate the crack. At the crack tip a focused

20-node reduced integration hexahedral mesh with collapsed quarter point elements was generated, whereas the remaining domain was automatically meshed with quadratic (10-node) tetrahedral elements.
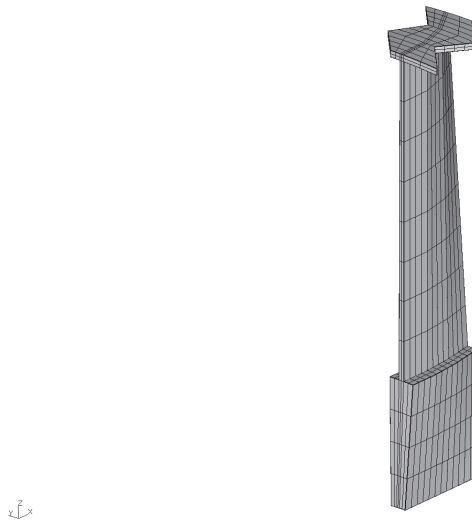
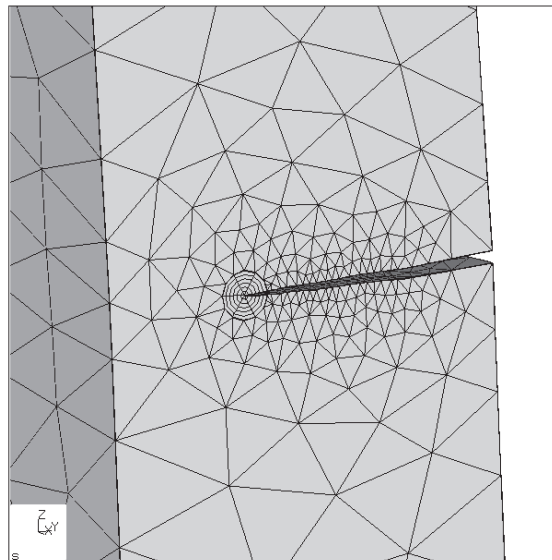

Figure 4: Mesh of the engine blade.

Figure 5: Mesh at the crack tip.

In a subsequent calculation the eigenmodes of the blade were determined. The first eigenmode, which is a bending mode (Fig. 6) was, taking fictitious experimental data in to account, judged most critical. This mode was appended to the full power loading point. The crack length versus the number of cycles for the original LCF mission and the LCF-mission augmented by the HCF-mode is shown in Fig. 7. The superimposed HCF vibration clearly decreased the life of the blade substantially. The shape of the crack, however, did not change. This is illustrated in Figs. 8a and 8b. Although the crack in Fig. 8b is somewhat more rough, the overall shape is the same. This was to be expected since both the centrifugal force and the bending mode lead to a predominantly mode-I loading of the initial crack. This, however, may be different for other missions and vibrational modes.

Taking the HCF-cycle on its own revealed that no HCF crack propagation takes place, i.e. all equivalent K-values along the crack front in each iteration are below threshold.
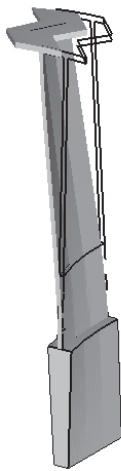
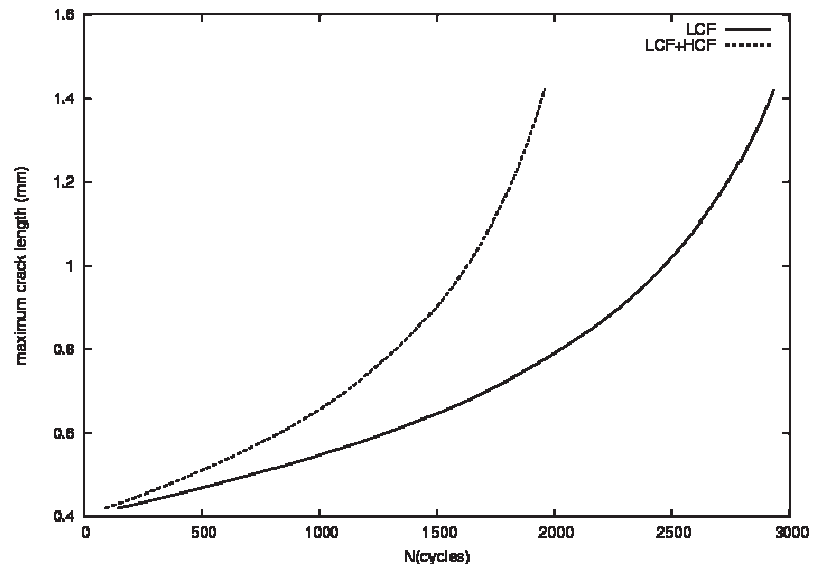Figure 6: First eigenmode (bending mode).

Figure 7: Crack propagation due to LCF and due to combined LCF+HCF.
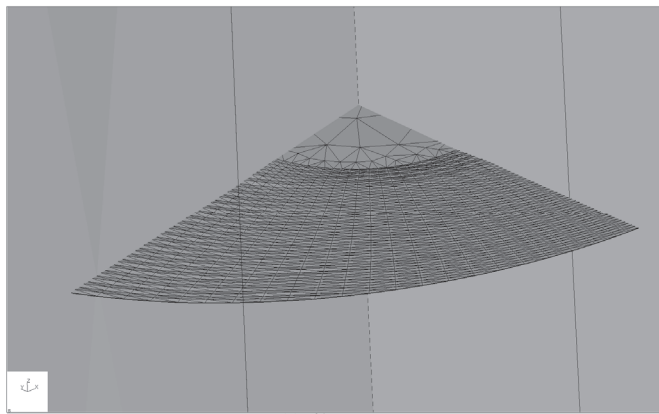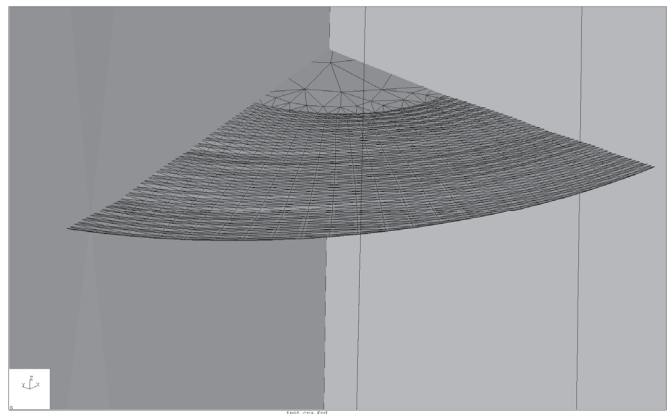

Figure 8a: Crack propagation due to LCF.

Figure 8b: Crack propagation due to LCF+HCF.

CONCLUSIONS

A method was presented how to alter a procedure capable of calculating LCF crack propagation in order to take HCF due to superimposed vibrations into account. Two aspects were looked into: the augmentation of the LCF-mission by interspersed HCF-cycles and the evaluation of HCF cycles alone. The modifications needed in the code are little, provided the program is capable of treating arbitrary mixed-mode loading in three-dimensional structures. It was shown that the augmented LCF-mission usually leads to a decreased life. The HCF evaluation itself is usually reduced to a check whether the threshold value is not exceeded and no HCF-propagation occurs.

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