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APPLICATION OF EXTENDED FINITE ELEMENT METHOD FOR FATIGUE LIFE PREDICTIONS OF MULTIPLE SITE DAMAGE IN AIRCRAFT STRUCTURE

PRIMENA PROŠIRENE METODE KONAČNIH ELEMENATA NA PROCENU ZAMORNOG VEKA VIŠESTRUKO OŠTEĆENE VAZDUHOPLOVNE KONSTRUKCIJE

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Abstract

This paper presents an application of the extended finite element method (XFEM) to the modelling of the propagation of four cracks in a typical aircraft structural configuration. It is a thin plate with three holes subjected to uniform uniaxial tensile stress. Material of the plate is aluminium alloy Al-2024 T3. Short theoretical background information is provided on the XFEM as well as the representation of cracks and the stress intensity factors computation. The accuracy of these computations is verified through superposition based approximate procedure and through finite element method (FEM) with singularity elements. The numerical results illustrate that XFEM is efficient for the simulation of crack propagation in MSD (Multiple Site Damage) without the need to re-mesh during the propagation if the finite element mesh is well defined.

Izvod

U ovom radu je predstavljena primena proširene metode konačnih elemenata (XFEM) na modelovanje širenja četiri prsline u tipičnoj aerostrukturi. U pitanju je tanka ploča sa tri otvora, podvrgnuta jednoosnom naponu na zatezanje, pri čemu je materijal ploče legura aluminijuma Al-2024 T3. U radu su ukratko date teorijske postavke metode, kao i položaji prslina i proračun odgovarajućih faktora intenziteta napona. Tačnost ovih proračuna je potvrđena i proverena najpre aproksimativnom metodom baziranom na superpoziciji. a zatim metodom konačnih elemenata (FEM) sa singularnim elementima. Numerički rezultati su pokazali da je XFEM odlična metoda za simulaciju rasta prslina u slučaju višestrukih oštećenja (MSD), bez potrebe kreiranja nove mreže konačnih elemenata pri svakom koraku širenja prsline, pod uslovom da je početna mreža dobro definisana.

INTRODUCTION

The loss of strength in an aircraft structure as a result of cyclic loads is an important phenomenon for life-cycle analysis. Service loads are accentuated at areas of stress concentration such as lap joints in the aircraft fuselage. Rivet holes or fastener holes are shown to have an important effect on the fatigue life of structural components by promoting crack initiation sites, /1/. Rivet holes are usually very close to each other, so the possibility of multiple site damage (MSD) appearance is very high. MSD represents simultaneous development of fatigue cracks at multiple sites in the same structural element. Those cracks are close enough to influence each other and to affect the overall structural integrity. MSD often occurs in longitudinal and circumferential riveted lap joints. It can be very serious, because of possible link-up of adjacent cracks creating one large crack that can cause catastrophic failure due to the reduction in residual strength of the structural element.

MSD is one of the sources of widespread fatigue damage (the other is the multiple-element damage). Compared with the case of a single crack, MSD is much more dangerous to the structure because it reduces the critical crack size and shortens the crack propagation life remarkably.

The prediction of the crack growth rate and the residual strength of the structure with MSD demands an accurate calculation of stress intensity factors (SIFs) /2, 3/. As technology and computer sciences are developing and have become widely available, numerical analyses is frequently used for SIF assessment /4-7/. The use of these analyses came as a need, since it was required to conduct various tests during exploitation to detect fatigue damage resulting from the repeated working load and to evaluate residual strength and structural integrity of the structural elements.

The level set method allows for treatment of internal boundaries and interfaces without any explicit treatment of the interface geometry, /9/. This provides a convenient and an appealing means for tracking moving interfaces.
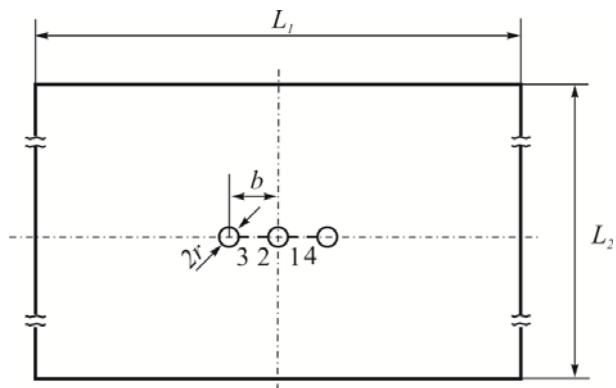
Figure 1. Analysed configuration with multiple cracks.

Knowing that these kinds of tests require specific and expensive testing devices, numerical analysis as a non-distractive method is the logical next step in the evaluation of the stress intensity factor.

EXTENDED FINITE ELEMENT METHOD

The Finite Element Method (FEM) and the Boundary Element Method (BEM) have been used for decades to solve numerous problems, but there are a number of instances where these methods pose restrictions in efficient applications (such as problems involving interior boundaries, discontinuities or singularities) because of the need for re-meshing or very high mesh densities.
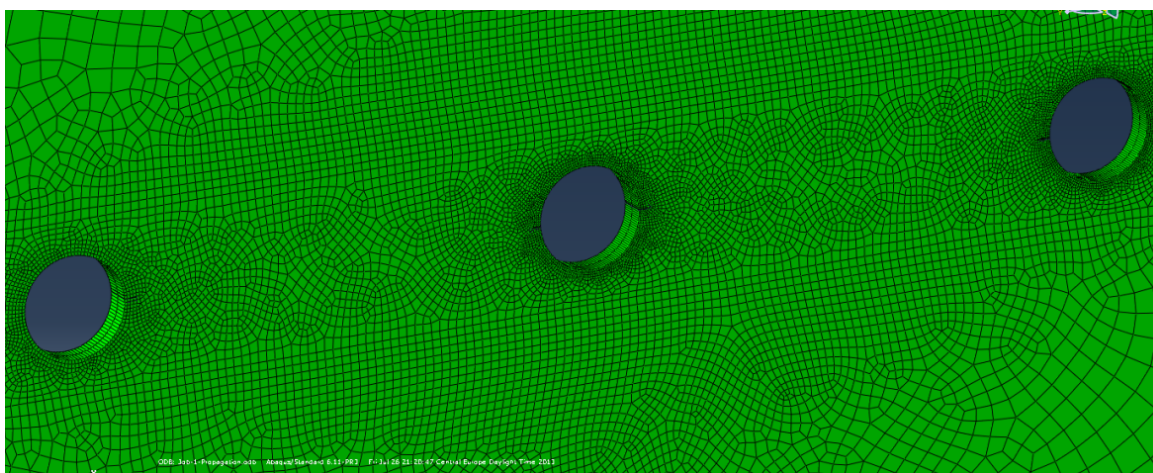

Figure 2. Finite element model of the MSD panel (Abaqus software).

The Extended Finite Element Method (XFEM) was implemented for modelling arbitrary discontinuities in 1D, 2D and 3D domains. XFEM is a local partition of unity based method where the key idea is to paste together special functions into the finite element approximation space to capture desired features in the solution. Recently, XFEM and its coupling with level set method was intensively studied and discussed in detail for geometric representation of discontinuities, /8/.
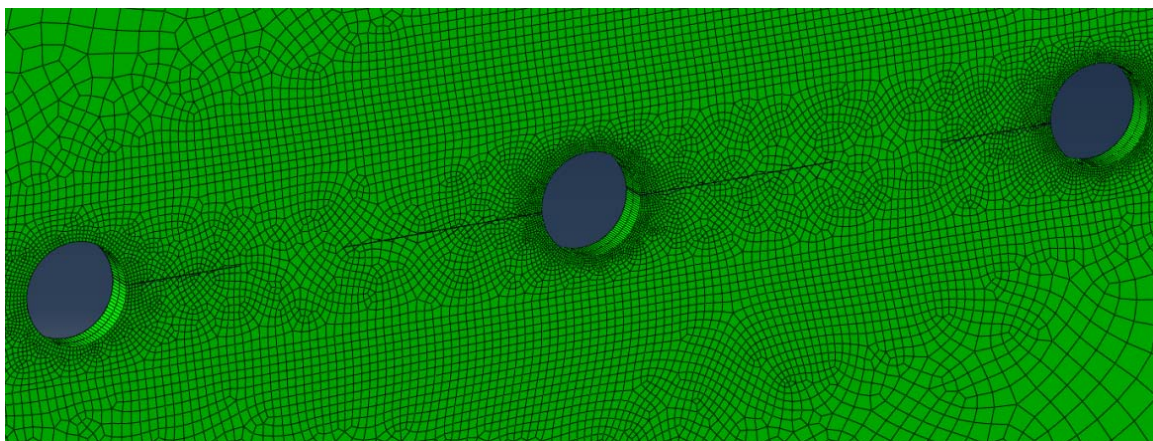

Figure 3. FEM model of the MSD panel after 50 steps of crack propagation.

Problems involving static cracks in structures, evolving cracks, cracks emanating from voids, had been numerically studied and the results are compared with analytical and experimental results to demonstrate the robustness of the method, /10/.

NUMERICAL EXAMPLE

The prediction of crack growth rate and residual strength of structure with MSD demands accurate calculation of stress intensity factors (SIFs). In this paper a finite element model (FEM) of a representative panel (dimensions of

$L_1 \times L_2 = 600 \times 400$ mm, Fig. 1) with 3 holes (radii $r = 2.4$ mm at distances $b = 25$ mm) subjected to uniform uniaxial tensile stress (value 100 MPa) is created.

Material of the plate is aluminium alloy Al-2024 T3, /11/. The middle hole has two radial cracks (numbered 1 and 2 in Fig. 1) and other two holes have one radial crack each (numbered 3 and 4 in Fig. 1). The finite element model is presented in Fig. 2.

A finite element model of the MSD panel is created using Abaqus software. The mesh is refined around the

cracks at the edges of each hole, and a uniform template of elements around each hole is used (Fig. 2). SIFs are calculated for each crack tip as a function of crack length, and these are used to predict relative rate-of-growth of each crack as well as the direction of growth. The FEM naturally includes the effects of crack interaction, and comparisons are made between the growth rates of the cracks, and between these rates and those that would occur under the simplified assumption of no-interaction.
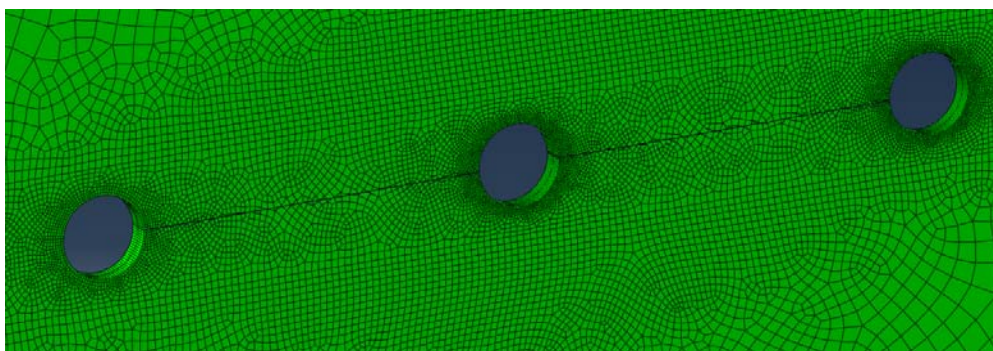

Figure 4. FEM model of the MSD panel at the end of the simulation (true scale).
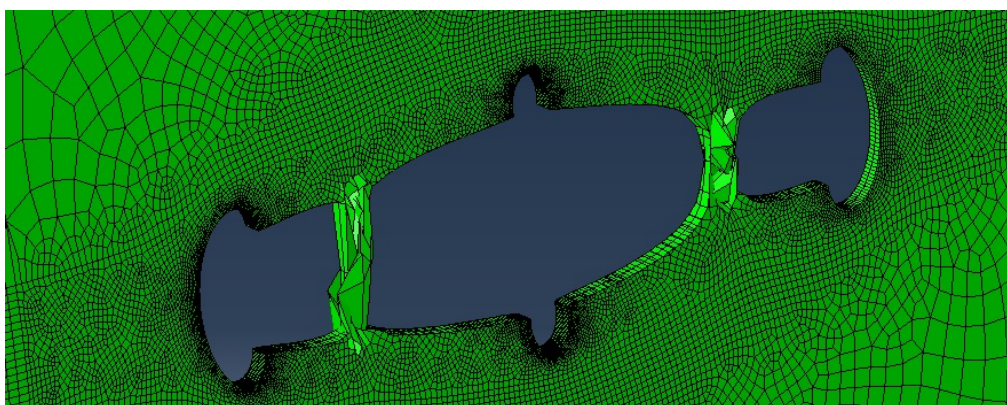

Figure 5. FEM model of the MSD panel at the end of the simulation (deformed view).

The crack growth simulation capability of Morfeo/Crack for Abaqus software, /12/, was used for this purpose. Morfeo/Crack for Abaqus relies on the implementation of the extended finite element (XFEM). Morfeo/Crack for Abaqus is capable of performing crack propagation simulations in complex geometries. It calls Abaqus at each propagation step and between each step, then reads the Abaqus solution, recovers a richer, improved XFEM solution in a small area surrounding the crack and computes the SIFs. SIF values at each crack tip, determine the appropriate crack growth increment for each crack. This procedure was performed 62 times in order to simulate incremental crack growth. The initial crack length used in the analysis was 0.5 mm. The fastest growing cracks (numbered 1 and 2 in Fig. 1) are incremented at steps of 0.2 mm, while other crack growth increments are automatically calculated at each step using crack tip SIFs. Figure 3 shows all 4 cracks after 50 steps of propagation, while Fig. 4 shows the MSD panel at the end of XFEM simulation (step number 62).

ANALYSIS OF THE RESULTS

Figure 3 shows that the length of each crack varied with its stress intensity factor history. The lengths of middle cracks (1 and 2) are longer than for other two cracks (3 and 4) which is the fact previously confirmed by many experiments. The analysis was arbitrarily stopped after the 62nd step, since after that step the cracks would form one large crack (Figs. 4 and 5).

The accuracy of the calculated SIFs is verified using a simple and easy to use approximation procedure, developed on an existing solution for SIFs in the case of two unequal cracks in an infinite plate subjected to remote uniform stress /13, 14/. The solution for this configuration was used in order to obtain the interaction effect coefficients which take into consideration the increase of SIFs of analysed crack tip due to the interaction with an existing adjacent crack tip. The comparison of the results has shown very good agreement between solutions (Fig. 6), verifying that XFEM can be successfully used in SIFs calculations as well as fatigue life predictions of MSD in aircraft structures.

SIF histories of crack propagation are generated for each crack tip. As it can be seen on Figs. 6 and 7, histories for cracks 1 and 2 are in very good agreement, but the histories for cracks 3 and 4, are almost identical (Figs. 8 and 9). Obtained stress intensity factor histories can be used to predict fatigue crack growth rates by using them as input data for AFGROW of NASGRO software.
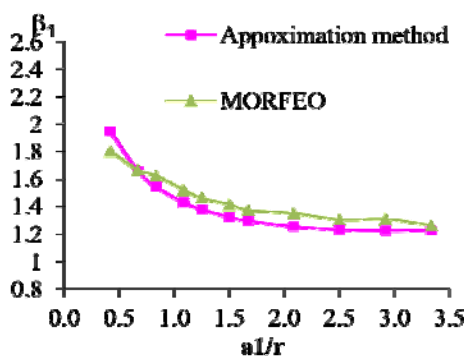

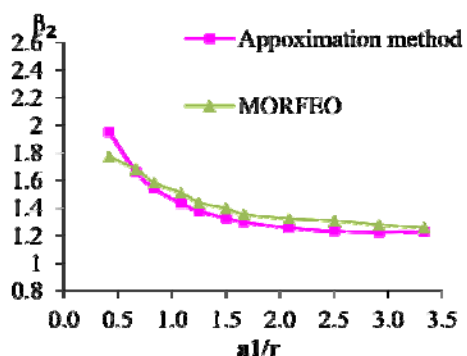Figure 6. Normalized stress intensity factors for crack tip 1.

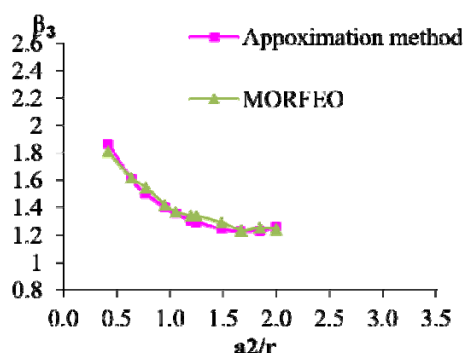Figure 7. Normalized stress intensity factors for crack tip 2.

Figure 8. Normalized stress intensity factors for crack tip 3.
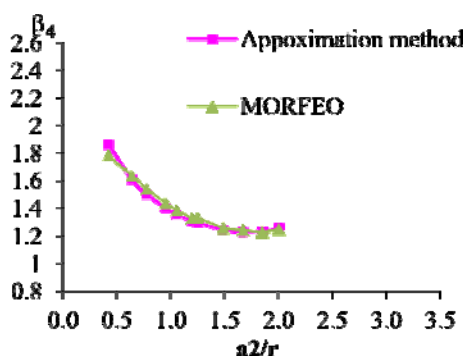

Figure 9. Normalized stress intensity factors for crack tip 4.

CONCLUSION

The SIF calculations by MorfeoCrack software for Abaqus, based on XFEM are conducted for a typical aero structural configuration with MSD. These factors are also obtained by approximate procedure. The analysis of the results has shown that the obtained solutions can be used for the prediction of SIFs of analysed configuration with acceptable accuracy, from the engineering point of view. Although, XFEM is time consuming and requires substantial computer resources, especially when multiple cracks are involved, this example showed that with a well-defined mesh, and well-set boundary conditions, 3D simulation of a typical 2D problem by using the XFEM gives very good results. It also showed that for three-dimensional cracked structures, this kind of analysis can be fully acknowledged.

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