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Stress intensity factor for multiple cracks on curved panels

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Abstract

The aim of this paper is to explore and to demonstrate the capacity, performances and difficulties of stress intensity factors (SIFs) calculations in a case of multiple cracks on curved panels analyzed by means of different computational methods. So-called bulging effect, which is occurring in cracked curved panels, increases the effective stress-intensity factor, making the SIFs assessment in case of multiple cracks more challenging. Here, the stress intensity factors are considered by using two different computational methods: extended finite element method (XFEM) and the approximate method based on superposition, which has been adjusted for curved panel application. The SIFs determination was carried out for aircraft fuselage model: unstiffened panel with three cracked fastener holes, for four different curvature diameters, subjected to uniform internal pressurization. The comparison of the results showed that conducted analyses delivered the data which can be useful in evaluation of crack-growth rate, residual strength and fatigue life of curved aircraft structures with multi-site damage.

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Keywords: Multi-site damage; Stress intensity factor; Extended Finite Element Method; curved panels;

1. Introduction

Over the recent years, problem of extended exploitation of aging aircraft structures is becoming more pressing, because of their diminishing structural integrity. This diminishing is largely caused by multiple site damage (MSD), which often occurs in longitudinal and circumferential riveted lap joints, starting when the fuselage pressure cycling fatigue loads lead to crack initiation and propagation at multiple rivet locations. Those multiple cracks may interact

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and, according to Labeas G. et al. (2005) sudden crack link-up may occur, reducing the overall structural integrity of the structure, which may lead even to catastrophic failure. Prediction of residual strength of the structure, as well as the crack growth rate, requires an accurate calculation of stress intensity factor (SIF), since it is one of the most important parameters in fracture mechanics analysis. It sufficiently defines the stress field near the crack tip and provides fundamental information on how the crack is going to propagate. In most of the real situations, it is almost impossible to find an exact solution for SIFs. This is especially true in case of multiple cracks on curved panel, which basically represent the aircraft fuselage. The additional problem in SIFs determination in case of cracked curved panels is so called bulging effect. This effect represents in-plane and out-of-plane deformations of the crack faces of longitudinal cracks in curved panels subjected to internal overpressure, due to loss of hoop tension reaction to pressure loading (Koolloos J. et al (2006), Broek D., et al. (1994) and Swift T., (1979)). This causes local bending at the crack tips, which increases the effective stress-intensity factor. According to available literature, and to the best knowledge of the authors of this paper, there is a lack of SIFs determination methods, as well as the SIFs solutions in case of multiple cracks on curved panels. The SIFs calculations in these configurations imply the usage of numerical methods.

Over the years, many numerical techniques and methods have been used to simulate the fracture mechanics problems, among which the finite element method (FEM) is the most popular one. But recently, relatively new extended finite element method (XFEM) has becoming more employed in these kind of analyses, because its major advantage is that it allows crack growth within the existing mesh, making the finite element mesh update obsolete. The XFEM has already been used to calculate SIFs for problems involving multiple, interacting cracks, resulting from MSD in Aldarwish M., et al. (2017, 2018), as well as for the fatigue life estimation of the integral skin-stringer panel in Sghayer, A., et al. (2017, 2018) or even for simulating crack paths development in more complex models like in Hojjati-Talemi R., and Waha M. A., (2012), Curà F., et al. (2015) and Taheri S., et al. (2015).

In this paper capacities, performances and difficulties of computational methods used in SIFs calculations in a case of multiple cracks on curved panels are demonstrated.

2. Numerical evaluation of stress intensity factors for curved panels

2.1. Adjusted approximation method

In an engineering analysis, according to Koolloos J. et al (2006), the SIFs for a curved panel can be assessed by adjusting the SIF for a flat panel with an appropriate bulging factor (β_B). There are several empirical equations for determining this factor (Koolloos J. et al (2006), Broek D., et al. (1994), and Chen, D. and Schijve, J., (1991)) but the most frequently used, especially in the aerospace industry is the bulging effect assessed by Swift T., (1979):

$$\beta = 1 + \frac{10a}{R} \tag{1}$$

where a is half crack length, and R is the radius of curved panel.

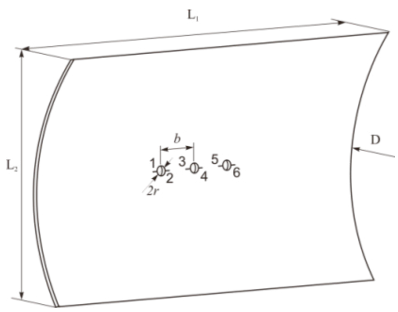

Fig. 1. Analyzed configuration with multiple cracks (not to scale).

Equation (1) was used for adjusting the flat panel results for SIFs, obtained by approximation method by Kastratović G., et al. (2015), which is based on superposition and SIFs solutions for the configuration with two unequal cracks in an infinite plate subjected to remote uniform stress.

Here, the SIFs determination was carried out for aircraft fuselage model: unstiffened curved panel (dimensions L1×L2=600×400 mm, thickness=1.6 mm), with three cracked fastener holes (radii=2.4 mm, at distance b=25 mm), for four different curvature diameters (D=1.6 m, 2.4 m, 3.2 m, and 4 m). Each hole in the panel had two radial cracks, numbered from 1 to 6 and positioned as shown in Fig. 1.

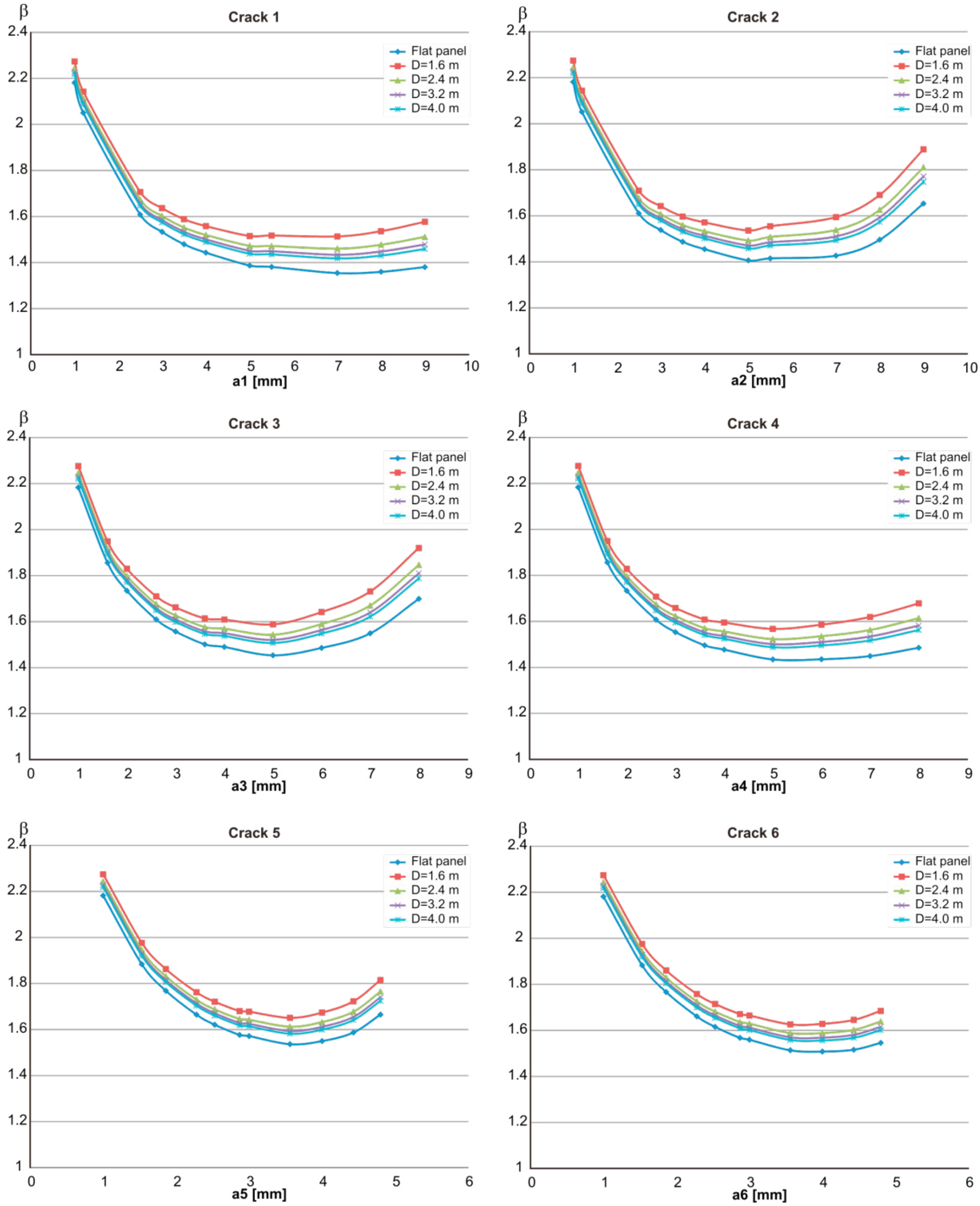

Fig. 2. Normalized stress intensity factors for all cracks - Adjusted approximation method.

The mode I SIF results (K_I) for analyzed curved models, along with the results for corresponding flat panel are shown in Fig. 2. The results are presented through normalized stress intensity factors (geometry factors β) for all cracks in analyzed configuration denoted as in Fig.1. As it can be seen, there is a steady increase of normalized SIFs with increase of radius of panel, which is expected. This increase goes from around 5% for the largest radius of 2 m to 14% for the radius of 0.8 m, regarding the solutions for flat panel.

2.2. XFEM analysis

The mode I SIFs (K_I), for the same geometrical configurations, were also considered by using XFEM.

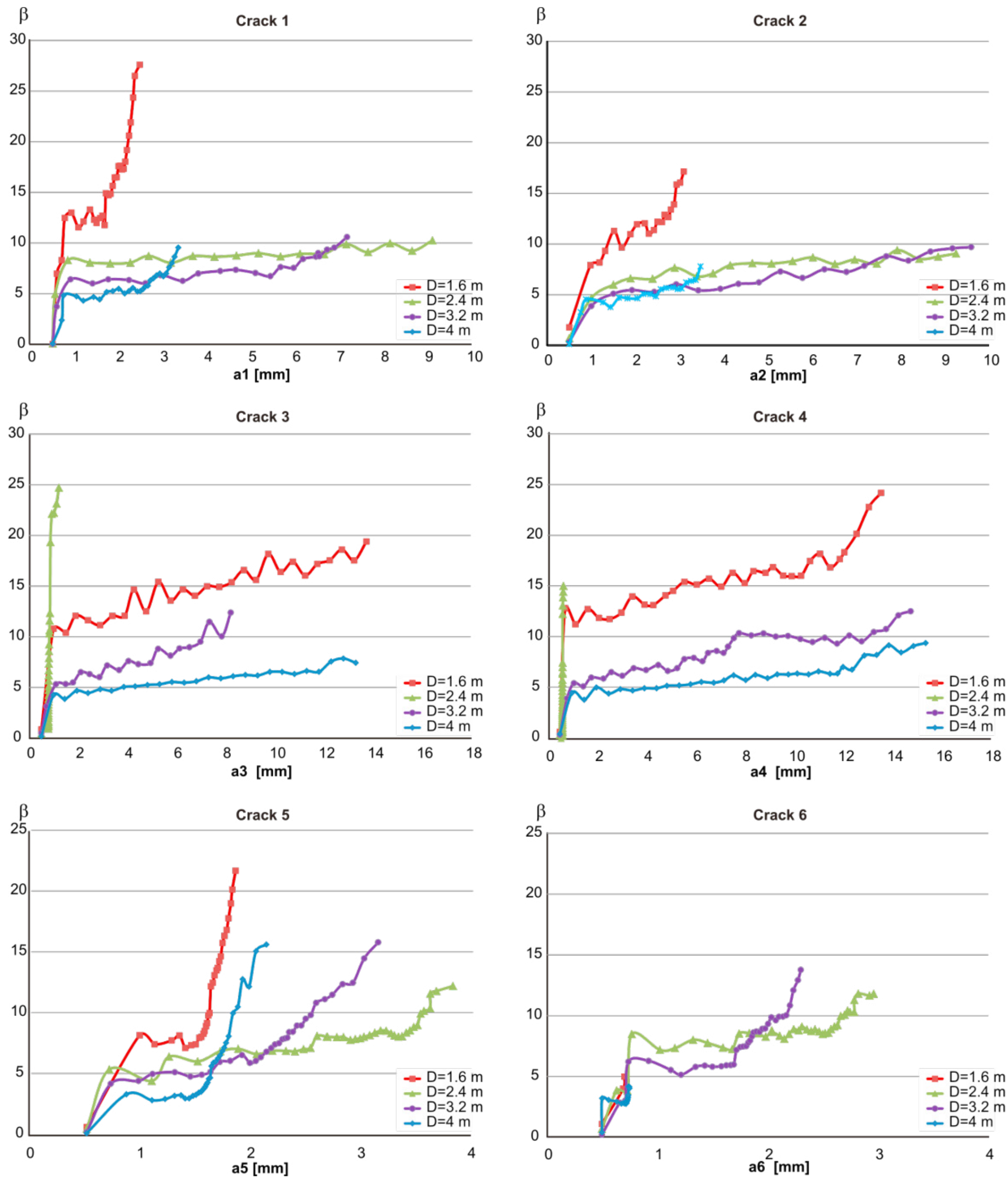

Fig. 3. Normalized stress intensity factors for all cracks - XFEM analysis.

This method was implemented thru *Morfeo/Crack for Abaqus* software. For this purpose, the curved panels were subjected to uniform pressure of 0.054 MPa (characteristic value of the fuselage pressure differential) and material of the panels was aluminum (Young's modulus of 73000 MPa, Poisson's ratio of 0.33). The results are presented in Fig. 3 thru normalized stress intensity factors. As it can be seen, the values of normalized SIFs also show increase with increase of curvature radii. On the other hand, in this case SIFs values are significantly higher than values obtained by implementing bulging factor on a flat panel. This was expected considering the fact that boundary conditions and loads applied in XFEM analysis were different from those applied in the case of flat panel (uniform stress on the edges). It has to be noted that *Morfeo/Crack for Abaqus* showed significant differences in cracks' lengths in analyzed cases. For example, for D=2.4 m, the cracks' lengths after 15th step of growth were 6.60 mm, 6.97mm, 0.79 mm, 0.60 mm, 2.67 mm and 2.04 mm for cracks 1 to 6, respectively (Fig. 4).

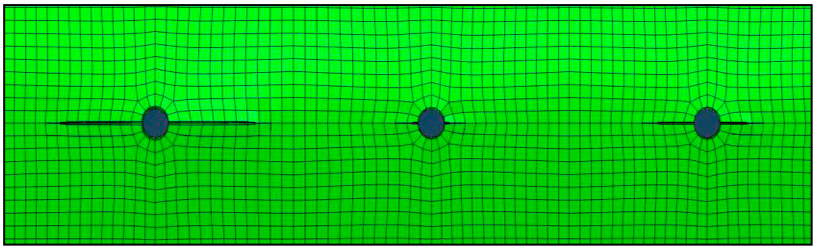

Fig. 4. XFEM model after cracks opening (step 15), D=2.4 m

With further cracks propagation, after step 36 (Fig. 5), link-up between crack 2 and 3 occurs. After link-up, cracks 1 and 4 continue to propagate faster than cracks 5 and 6.

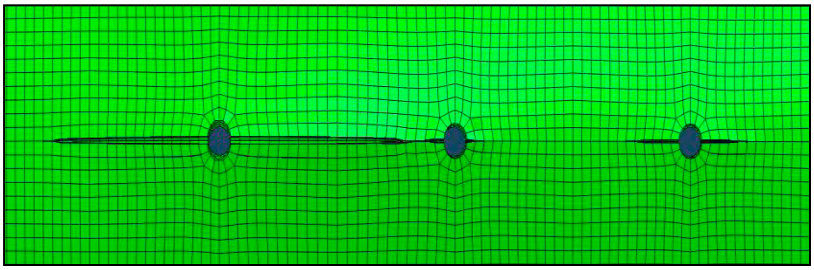

Fig. 5. XFEM model after cracks opening (step 36), D=2.4 m

It's also worth mentioning that *Morfeo/Crack for Abaqus* calculates other SIFs modes and that significant values of K_{III} (tearing mode, Fig. 6) appeared during simulations, influencing the values of equivalent SIFs (K_{eq}) used in Paris law for estimation of the number of cycles to fatigue failure.

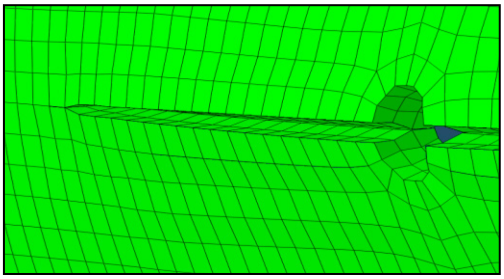

Fig. 6. XFEM model – occurrence of tearing mode (step 36), D=2.4 m

3. Conclusion

In this paper, SIFs calculations – based on implementation of XFEM in *Morfeo/Crack for Abaqus* software – were presented for three-dimensional unstiffened panels of different curvatures with three cracked fastener holes subjected to pressure differential of 0.054 MPa. Values of SIFs obtained in XFEM analysis, due to the absence of experimental and numerical data for this configuration in the literature, were compared to SIFs estimated by the approximate method efficaciously used for flat panels and to some extent adjusted for curved panel applications. The main disadvantage of this method is impossibility of the load application different from uniform tensile stress and this is why difference between obtained SIFs was significant.

Analysis of XFEM results showed considerable influence of unstiffened panel geometry (i.e. radius of the curvature) and applied boundary conditions on cracks' paths and their shapes. High SIFs values obtained in these calculations were compared to values obtained by empirical equations for circumferential crack in thin cylinder subjected to internal pressure (Aldarwish M., (2018)). The comparisons revealed much better agreement in SIFs values than in the case of approximate method based on superposition. But, the challenges and difficulties that XFEM implementation imposes are something that should be paid attention to in the next studies.

Although the presented research is in preliminary stage and a lot of work is yet to be done (particularly experimental work), it showed why researchers must try to introduce new computational methods and techniques in their work when complex geometries with multiple cracks are in the focus of investigation.

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