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[1] Stevan MAKSIMOVIĆ, [2] Mirjana ĐURIĆ, [3] Mirko MAKSIMOVIĆ, [4] Ivana VASOVIĆ

FATIGUE LIFE ESTIMATION OF AIRCRAFT STRUCTURAL COMPONENTS WITH SURFACE CRACKS UNDER LOAD SPECTRUM

[1,2] Military Technical Institute, Belgrade, SERBIA
[3] Waterworks and Sewerage, Belgrade, SERBIA
[4] Institute GOSA, MilanaRakica 35, Belgrade, SERBIA

Abstract: Subject of this work is focused to developing computation procedure for residual fatigue life estimation of cracked structural componentsunder load spectrum. Finite element method is used for determination of the stress intensity factors (SIF`s) of structural element with surface cracks. These discrete values of the stress intensity factors of cracked structural componentsare used for derivation of analytic function for SIF that is necessary in crack growth analyses. To demonstrate efficient computation procedure in residual fatigue life estimation of damaged structural elements here numerical examples are included. For residual life estimation of cracked structural elements here Forman and Mettumethod is used. In this approach a low cyclic fatigue material properties are used. Computation procedure to strength analyze with respects to fracture mechanic and residual life estimations is applied to aircraft structural elements with surface cracks under load spectrum. Computation results are compared with correspond analytic experimental results.
Keywords: Fatigue, stress intensity factors, surface cracks, singular finite elements, fatigue life prediction

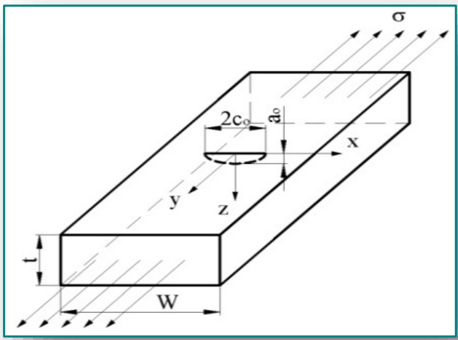
INTRODUCTION

Throughout their service life, aircraft are subjected to the combination of environmental attack and varying loads. The structural integrity of the vehicle can be impaired by surface degradation due to corrosive action or when crack damage is developed or aggravated by the environment. The requirement for lightweight aerospace structures leads to high design stresses [1]. High stresses can produce cracks early in the fatigue life of these structural components.Surface and corner cracks are encountered in engineering structures at locations where high stresses.Such cracks are present during a large percentage of the useful life of these components. Accurate stress intensity factors for such cracks are necessary for reliable prediction of fatigue crack growth rates or fracture. Three-dimensional (3-D) stress analysis of crack configurations have received considerable attention in the literature in the last three decades [2-4]. Various methods have been used to obtain stress-intensity factors for surface and corner cracks in plates: the alternating method [1,2], the finite-element method (FEM) with singularity elements [6], the finite element method with displacement hybrid elements and finite element alternating method. The slice synthesis method has also proved to be an accurate an inexpensive method to compute 3D stress intensity factor solutions [4-6]. The most accepted stress intensity factor solutions for surface cracks in finite thickness plates are obtained using FEM [3,4]; other methods are usually compared with FEM solutions to confirm their accuracy and convergence.

The methodology used here involves use the slice synthesis method that utilizes weight function technique.

STRESS INTENSITY FACTORS OF SEMI-ELIPTIC SURFACE CRACK

The slice synthesis approach used herein to computation of surface flaw stress intensities. The three dimensional surface flaw is idealized as a system of slices in the x-y plane, each containing a center crack whose length is determined by locations thru the thickness at which the slice was taken, Figure 2. Each slice is considered to react independently to the applied stress, σ, but are coupled through the introduction of pressure distribution, p^*, acting on the faces of the cracks. The pressure p^*, is determined by second system of slices in the z-y plane. Each of the z-y slices contains an edge crack of depth a(x) over which the pressure, p^*, acts in opposition to that applied to the center crack slices [5]. Thus there are two slice systems: center cracks, and edge cracks, Figure 2.



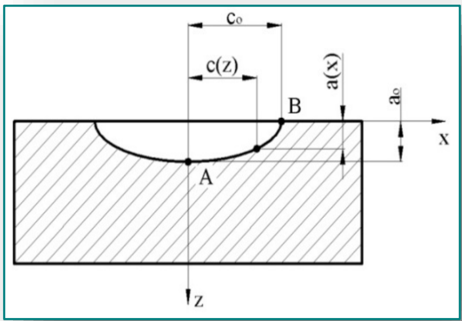


Figure 1. Surface crack idealization

The weight function in this case was formulated in the same manner as that of Fujimoto[5]. Using the crack face pressure distributions, stress intensity factors at A and B can be determined as

$$K_A = \sigma\sqrt{\pi a}\sum_{i=0}^{3}\sum_{j=0}^{3}A_{ij}\left(\frac{c}{a}\right)^{i/2}\left(\frac{a}{t}\right)^{i} \quad (1)$$

$$K_B = \sigma\sqrt{\pi a}\sum_{i=0}^{3}\sum_{j=0}^{3}B_{ij}\left(\frac{c}{a}\right)^{i/2}\left(\frac{a}{t}\right)^{i} \quad (2)$$

where: K_A is the stress intensity at depth; K_B is the stress intensity at surface, σ -applied stress,a - crack depth, c - half surface length, *t* -plate thicknes; A_{ij} and B_{ij} are the coefficients (represent the displacements over the entire crack face, the continuity expression is evaluated at 13 points).

To validate the analytic computation procedure, finite element method is used. Three-dimensional finite elements were used to model a plate containing a semi-elliptic surface crack. The finite element analyses were made using MSC/NASTRAN [8].

NUMERICAL EXAMPLES

Finite element analysis for surface cracks

To check validity of the above method for SIF evaluation by the semi-analytic slice synthesis approach, comparison between the calculated SIF results of surface cracks in plate and the solution obtained by finite elements are compared. For this purpose plate with semi-elliptic surface crack under tension σ=83.3 [N/mm2] is analyzed. Geometry properties of this plate are: w=60 mm, t=10 mm, c=10 mm, a=10 mm, Figure 2. Three-dimensional singular finite elements were used to model of a plate containing a semi-elliptic surface cracks under tensile load.

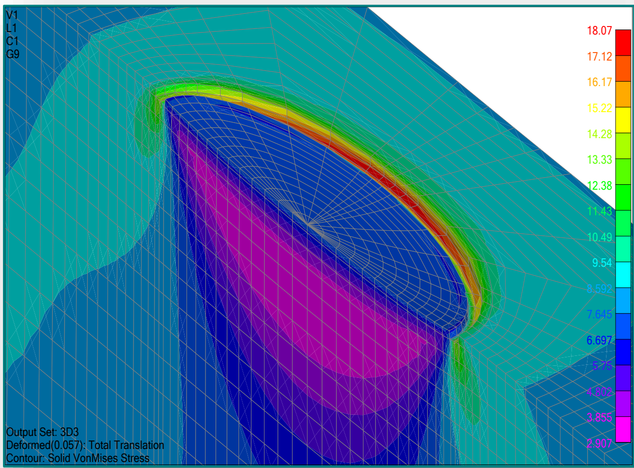


Figure 2. Detail finite element model of semi-elliptic crack

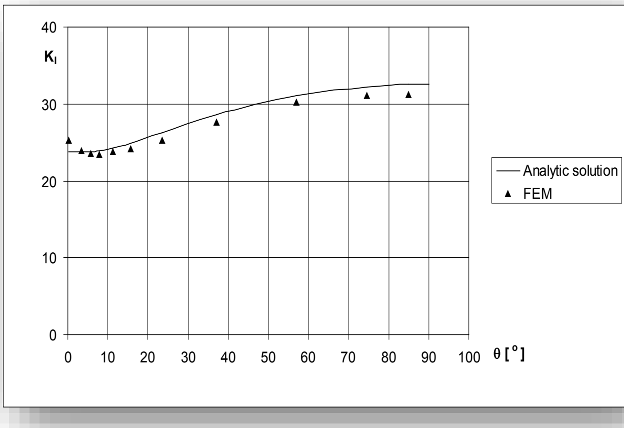


Figure 3. Comparisons between analytic and FE results for SIF calculations

Results presented in Figure 3 give good agreement between presented computation analytic and finite element results for the stress intensity factors. The difference was found to be less than 6%.

Fatigue crack growth

The stress-intensity factor equations (1) and (2) for surface cracks are used herein to predict fatigue-crack-growth patterns under load spectra, Figure 2. For this purpose Forman and Mettu equation [7] is used.

$$\frac{da}{dN} = C\left[\left(\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{max}}{K_c}\right)^q} \qquad (3)$$

where N is the number of applied fatigue cycles, a is the crack length, R is the stress ratio, ΔK is the stress intensity range, C, n, p and q are empirically derived constants, f is the crack opening function, ΔK_{th} is the threshold stress intensity factor and K_c is the fracture toughness.

Numerical validation

Crack growth analysis for the next geometric and material properties of structural component with semi-elliptic surface crack, Figure 2, are illustrated in Figure 4.

- depth of surface crack, a = .100E-02 [m],half-length of surface crack c = .100E-02 [m]
- plate thickness, t = .200E-01 [m], width of cracked plate w = .200E-01 [m]
- crack growth coef., C = .300E-10, exponent n= .250E+01
- fracture toughness, K_{IC} = .500E+02

Table 1. Load spectra

N_i	S_{min} [MPa]	S_{max} [MPa]
6000	0	500
6000	100	400

Figure 4 shows results of crack growth analysis under load spectra. Curves denoted as Anal-A and Anal-B represent crack growths of points A and B (Figure 2) for semi-elliptic surface cracked structural element under tension load using analytic expressions for (1) and (2) stress intensity factor calculations with one side and Forman and Mettu equation (3).

Curve denoted with MKE-B represents crack growth at point B where SIF determined using approximate finite element results. Procedure for approximations of SIF from finite elements are presented in paper [4]. This procedure is based on determination of SIF using special 3-D finite elements for several successive crack length and defining analytic expression for SIF in polynomial form from these values. This method based on using 3-D special singular quarter-point singular finite elements for determination of SIF is very reliable method. If we compare crack growth in point B using analytic approach derived in previous considerations with finite element results (FEM-B) good agreement is evident.Good agreement between analytic computation method based on slice synthesis method with finite element approximations of SIF confirmatequality of presented analytic method in crack growth analyses.

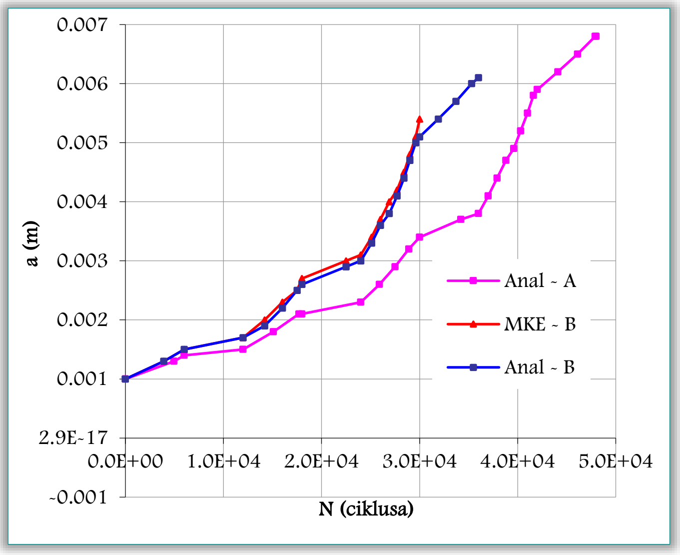


Figure 4. Surface crack growth under load spectra

4. CONCLUSION

Stress intensity factor solutions for semi-elliptical surface cracks were determined using analytic model and validation by comparisons with special singular finite element solutions. The slice synthesis approach is used herein to computation of surface flaw stress intensities. To validate the analytic derived stress intensity factors for semi-elliptic surface cracks, finite element method is used. The analytic results based on slice synthesis method were compared with finite element solutions and the difference was found to be less than 6% for surface points. Analytic model for the stress intensity factors, derived in this work, are used for crack growth analyses and fatigue life predictions.

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Note

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