UDK: 620.178.3
COSATI: 11-13

Fatigue Crack Growth Analysis of Damaged Structural Components Under Mode-I and Mixed Modes

Katarina Maksimović, MSc (Eng)[1)]

The work presents a life prediction methodology of damaged structural components under the interspersed mode-I and the mixed-mode (I and II). This work considers the numerical computation methods and procedures for predicting the fatigue crack growth life for cracks at notched structural components. A special attention is focused on notched structural components under mixed modes. Stress intensity factor (SIF) solutions are required for assessing fracture strength and residual fatigue life for defects in structures, or for damage tolerance analysis recommended to be performed at the stage of the aerospace structure design. A variety of methods has been used to estimate the SIF values, such as approximate analytical methods, finite element (FE), finite element alternating, weight function, photo elasticity and fatigue tests. In this work the analytic/numerical methods and procedures were used to determine SIFs and predict the fatigue crack growth life of damaged structural components with notched cracks. For this purpose the finite element method (FEM) is used to derive analytic expressions for SIFs of cracked structural components. To obtain the stress intensity factors of cracked structural components, singular finite elements are used. The strain energy density and MTS criteria are used to determine the crack trajectory or the angle of crack growth in thin-walled structures with cracks emanating from holes. Computation results are compared with experiments.

Key words: **fracture mechanics, crack growth, fatigue life, finite elements, mixed modes, crack growth trajectory.**

Introduction

NOTCHES in structural components are places where stresses concentrate and, because of that, can trigger cracks leading to catastrophic failures or to a shortening of the assessed structural life. For this reason different criteria have been proposed for evaluating the maximum load a notched component can withstand.

When the stress concentrators are cracks, the tools of linear elastic fracture mechanics (LEFM) are applicable. As soon as the notch is blunted, i.e. the notch root radius is not zero, the stress singularity disappears and LEFM, in rigueur, is no longer applicable. The problem becomes more involved if the loading symmetry is lost, i.e. when the notched structural component is subjected to mixed mode loading.

Methods for design against fatigue failure are under constant improvement. Fracture mechanics has developed into a useful discipline for predicting strength and life of cracked structures. Surface and through-thickness cracks frequently initiate and grow at notches, holes in structural components. Such cracks are present during a large percentage of the useful life of these components. Hence, understanding the severity of cracks is important in the development of life prediction methodologies [9]. Current methodologies use the stress intensity factor of (SIF) to quantify the severity of cracks and the development SIF solutions for notched structural components using analytical, numerical and semi-analytical methods has continued for the last three decades.

The adoption of the damage tolerance design concept [1] along with an increased demand for accurate residual structure and notched component life predictions have provided growing demand for the study of fatigue crack growth in aircraft mechanical components. The damage tolerance approach assumes that the structure contains an initial crack or defect that will grow under service usage. The crack propagation is investigated to ensure that the time for crack growth to a critical size takes much longer than the required service life of notched structural components. For a damage tolerance program to be effective it is essential that fracture data can be evaluated in a quantitative manner. Since the establishment of this requirement not only the understanding of fracture mechanics has greatly improved, but also a variety of numerical tools have become available to the analyst. These tools include Computer Aided Design (CAD), Finite Element Modeling (FEM) and Computation Fluid Dynamics (CFD). A fracture mechanics software provides the engineering community with this capability. Computer codes can be used to predict fatigue crack growth and residual strength in aircraft structures. They can also be useful to determine in-service inspection intervals, time-to-onset of widespread fatigue damage and to design and certify structural repairs. Used in conjunction with damage tolerance programs fracture analysis codes can play an important role in extending the life of “high-time” aircraft. Traditional applications of fracture mechanics have been concerned on cracks growing under an opening or mode I mechanism. However, many service failures occur from cracks subjected to mixed mode loadings. A characteristic of mixed mode fatigue cracks is that they usually propagate in a non-self similar manner. Therefore, under mixed mode loading conditions, not only the fatigue crack growth rate is of importance, but also the crack growth direction. Several

[1)] Secretariat for Comunal and Housing Affairs, Office of Water management, 11000 Belgrade, SERBIA

criteria have been proposed regarding the crack growth direction under mixed mode loadings. In this work the maximum strain energy density criterion [5, 6] and the maximum tangential stress criterion [14] are considered. This S-criterion allows stable and unstable crack growth in a mixed mode. The application of this criterion can be found in the works by several authors [7, 8]. The aim of this work is to investigate the strength behavior of important aircraft notched structural elements such as cracked lugs and riveted skin. The attention is focused on crack growth behavior of cracked structural components under mode I and the mixed mode.

Numerical simulation of crack growth

Numerical simulation of crack growth provides a powerful predictive tool to use during the design phase as well as for evaluating the behavior of existing cracks. These simulations can be used to compliment experimental results and allow engineers to economically evaluate a large number of damage scenarios. Numerical methods are the most efficient way to simulate fatigue crack growth because crack growth is an incremental process where stress intensity factor (SIF) values are needed at each increment as an input to crack growth equations.

In order to simulate mixed-mode crack growth an incremental type analysis is used where knowledge of both the direction and the size of the crack increment extension are necessary. For each increment of the crack extension, a stress analysis is performed using the quarter-point singular finite elements (Q-E) [4] and SIFs are evaluated. The incremental direction and size along the crack front for the next extension are determined by fracture mechanics criteria involving SIFs as the prime parameters. The crack front is re-meshed and the next stress analysis is carried out for a new configuration.

Stress intensity factor solution of cracked lugs

In general geometry of notched structural components and loading it is too complex for the stress intensity factor (SIF) to be solved analytically. The SIF calculation is further complicated because it is a function of the position along the crack front, crack size and shape, type loading and geometry of the structure. In this work analytic and FEM were used to perform a linear fracture mechanics analysis of the pin-lug assembly. The analytic results are obtained using the relations derived in this paper. Good agreement between finite element and analytic results is obtained. It is very important because we can use analytic derived expresions in crack growth analyses. Lugs are essential components of an aircraft for which a proof of damage tolerance has to be undertaken. Since the literature does not contain the stress intensity solution for lugs which are required for proofs of damage tolerance, the problem posed in the following investigation are: selection of a suitable method of determining SIF, determination of SIF as a function of crack length for various forms of lugs and setting up a complete formula for calculating the SIF for lug, allowing essential parameters. The stress intensity factors are the key parameters to estimate the characteristics of the cracked structure. Based on the stress intensity factors, fatigue crack growth and structural life predictions have been investigated. The lug dimensions are defined in Fig.1.

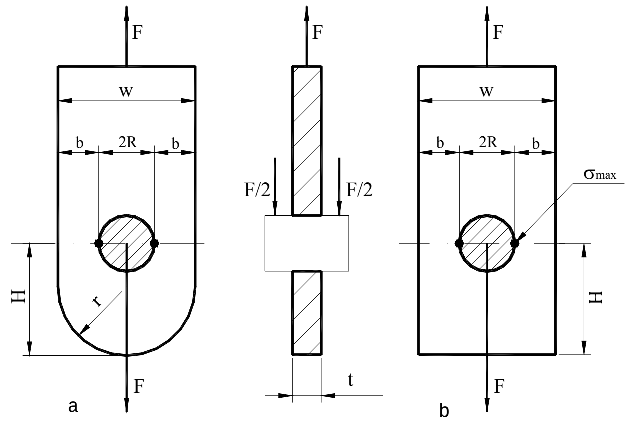

Figure 1. Geometry and loading of lugs

To obtain the stress intensity factor for the lugs it is possible to start with the general expression for the SIF in the next form

$$K = Y_{SUM}\, \sigma \sqrt{\pi a} \tag{1}$$

where: Y – the correction function, a- the crack length. This function is essential in determining the the stress intensity factor. Primary, this function depends on the stress concentration factor, k_t and the geometric ratio a/b. The correction function is defined using experimental and numerical investigations. This function can be defined in the next form [11, 12]:

$$Y_{SUM} = \frac{1.12 \cdot k_t \cdot A}{A + \frac{a}{b}} \cdot k \cdot Q \tag{2}$$

$$k = e^{r\sqrt{a/b}} \tag{3}$$

$$b = \frac{w - 2 \cdot R}{2} \tag{4}$$

$$r = -3.22 + 10.39 \cdot \left[\frac{2 \cdot R}{w}\right] - 7.67 \cdot \left[\frac{2 \cdot R}{w}\right]^2 \tag{5}$$

$$Q = \frac{U \cdot \frac{a}{b} + 10^{-3}}{\frac{a}{b} + 10^{-3}} \tag{6}$$

$$U = 0.72 + 0.52 \cdot \left[\frac{2 \cdot R}{H}\right] - 0.23 \cdot \left[\frac{2 \cdot R}{H}\right]^2 \tag{7}$$

$$A = 0.026 \cdot e^{1.895 \cdot \left(1 + \frac{a}{b}\right)} \tag{8}$$

The stress concentration factor k_t is very important in the calculation of the correction function, eq.2. In this investigation a contact finite element stress analysis was used to analyze the load transfer between the pin and the lug.

Incremental direction growth criteria

Several criteria have been considered to describe the direction of crack propagation for mixed mode crack growth.

Strain energy density criterion

The minimum strain energy density criterion [5, 6] is discussed in this work. The strain energy density criterion is based on the postulate that the direction of crack propagation at any point along the crack front toward the region where the strain energy density factor is minimum. The strain energy density factor, *S*, is given as

$$S(\theta) = a_{11}K_I^2 + a_{12}K_I K_{II} + a_{33}K_{III}^2 \quad (9)$$

where the factors a_{ij} are the functions of the angle υ, and are defined as

$$a_{11} = \frac{1}{16G\pi}\left[(1+\cos\theta)(k-\cos\theta)\right],$$

$$a_{12} = \frac{1}{16G\pi}\sin\theta\left[2\cos\theta-(k-1)\right], \quad (10)$$

$$a_{22} = \frac{1}{16g\pi}\left[(k+1)(1-\cos\theta)+(1+\cos\theta)(3\cos\theta-1)\right]$$

where G is the shear modulus and *k* is a constant depending upon stress state, and is defined as: $k=(3-\nu)/(1+\nu)$ for plane stress. The direction of crack growth is determined by minimizing this equation with respect to the angle theta (υ). In the mathematical form, the strain energy density criterion can be stated as

$$\left[2(1+k)\mu\right]\tan^4\frac{\theta}{2}+\left[2k(1-\mu^2)-2\mu^2+10\right]\tan^3\frac{\theta}{2}- \\ -24\mu\tan^2\frac{\theta}{2}+\left[2k(1-\mu^2)+6\mu^2-14\right]\tan\frac{\theta}{2}+ \\ +2(3-k)\mu=0 \quad (11)$$

$$\left[2(k-1)\mu\right]\sin\theta-8\mu\sin2\theta+\left[(k-1)(1-\mu^2)\right]\cos\theta+ \\ +\left[2(\mu^2-3)\right]\cos2\theta\rangle 0 \quad (12)$$

$$\mu = K_I/K_{II} \quad (13)$$

Once *S* is established, crack initiation will take place in a radial direction υ, from the crack tip, along which the strain energy density is minimum.

A main advantage of this criterion is its ease and simplicity, and its ability to handle various combined loading situations.

MTS criterion

This criterion [14] states that the direction of crack initiation coincides with the direction of the maximum tangential stress (MTS) along a constant radius around the crack tip. It can be stated mathematically as

$$\frac{\partial\sigma_\theta}{\partial\theta}=0,\ \frac{\partial^2\sigma}{\partial\theta^2}\le 0 \quad (14)$$

Using the stress field in the polar co-ordinates and applying the MTS –criterion the following equation is obtained

$$\tan^2\frac{\theta}{2}-\frac{\mu}{2}\tan\frac{\theta}{2}-\frac{1}{2}=0 \quad (15)$$

$$\frac{3}{2}\left[\left(\frac{1}{2}\cos^3\frac{\theta}{2}-\cos\frac{\vartheta}{2}\sin^2\frac{\theta}{2}\right)+ \right. \\ \left. +\frac{1}{\mu}\left(\sin^3\frac{\theta}{2}-\frac{7}{2}\sin\frac{\theta}{2}\cos^3\frac{\theta}{2}\right)\right]\langle 0 \quad (16)$$

where μ is defined in eq. (13). This criterion is the simplest of all but very effective. The MTS criterion has been found to be good for brittle fracture.

The crack growth direction angle in the local coordinate plane perpendicular to the crack front can then be determined for each point along the crack front. In this work, the crack inclination angle is taken into account in the calculations by means of the values of the SIF K_I and K_{II}, because their values are the function of the orientation of the crack plane.

Numerical examples

In order to demonstrate the accuracy and efficiency of the methodology discussed in the preceding sections two crack growth applications are described. The first application describes crack growth in an aircraft wing lug and the second illustrates the use of the finite element methodology to simulate crack trajectory under mixed-mode.

Example 1. Fatigue crack growth in an aircraft wing lug

This example describes the analytical and numerical methods for obtaining the stress intensity factors and for predicting the fatigue crack growth life for cracks at attachment lugs. Straight-shank male lug is considered in the analysis, Fig.2. Three different head heights of lugs are considered in the analysis. The straight attachment lugs are subjected to axial pin loading only. The material properties of lugs are (7075 T7351)[12]: σ_m=432 N/mm^2 ⇔ Ultimate tensile strength, σ_{02}=334 N/mm^2, C_F=3. 10^{-7}, n_F=2.39, K_{IC}=2225 [N/mm$^{3/2}$].

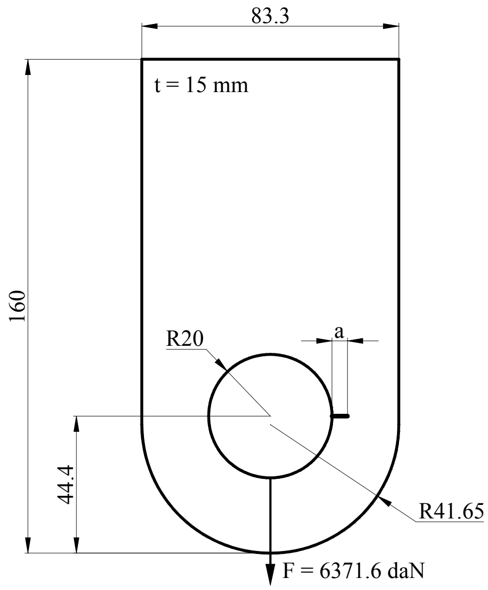

Figure 2.Geometry of cracked lug 2

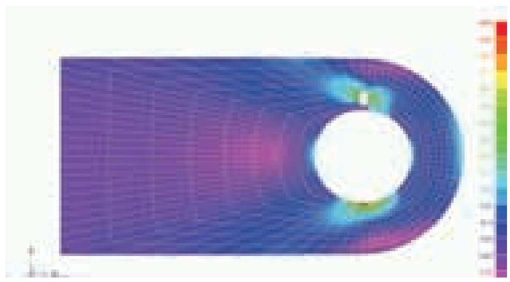

Figure 3. Finite Element Model of a cracked lug with stress distribution

Table 1. Geometric parameters of lugs [12]

Lug No.	Dimensions [mm]				
	2R	W	H	L	t
2	40	83.3	44.4	160	15
6	40	83.3	57.1	160	15
7	40	83.3	33.3	160	15

The stress intensity factors of cracked lugs are calculated under the stress level: $\sigma_g = \sigma_{max}$=98.1 N/mm^2, or the corresponding axial force, $F_{max} = \sigma_g\,(w\text{-}2R)\,t$ = 63716 N. The presented finite element analysis of cracked lug is modeled with special singular quarter-point six-node finite elements around the crack tip, Fig.3. The load of the model, a concentrated force, F_{max}, was applied at the center of the pin and reacted at the other end of the lug. Spring elements were used to connect the pin and the lug at each pairs of nodes having identical nodal coordinates all around the periphery. The area of contact was determined iteratively by assigning a very high stiffness level to spring elements which were in compression and a very low stiffness level (essentially zero) to spring elements which were in tension. The stress intensity factors of lugs, analytic and finite elements, for through-the-thickness cracks are shown in Table 2. Analytic results are obtained using the relations from the previous sections, eq. (1).

Table 2. Comparisons of analytic and FE results for SIF, K_I

Lug No.	a [mm]	$K_{I\,max}^{MKE}$	$K_{I\,max}^{ANAL.}$
2	5.00	68.784	65.621
6	5.33	68.124	70.246
7	4.16	94.72	93.64

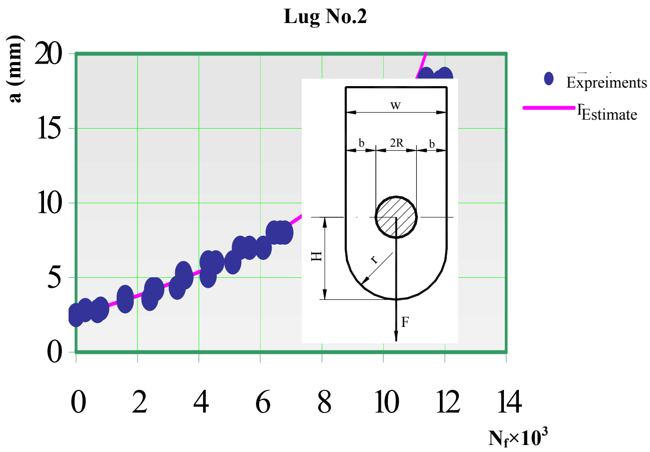

Figure 4. Crack propagation at the lug – Comparisons analytic results with tests (H=44.4 mm); k_t=2.8

Fig.4 shows a comparison between the experimentally determined crack propagation curves and the load cycles calculates to Walker low [3] for several crack lengths. A relatively close agreement between the test and the presented computation results are obtained. The analytic computation methods presented in this work can satisfy requirements for damage tolerance analyses of notched structural components such as lugs-type joints.

Example 2. Crack growth from the riveted holes

In this section, we consider the modeling of crack propagation in a plate with cracks emanating from one hole subjected to a far-field tension, σ, Fig.5. In the initial configuration the left crack has 0.1 in and is oriented at angle υ=33.6^o to the left hole. The change in the crack length for each iteration is taken to be a constant, Δa = 0.1 in, and the cracks grow for eight steps. In this analysis the maximum tangential stress (MTS-criterion) is used to determine the crack trajectory or the angle of crack propagation.

In this work, the crack inclination angle is taken into account in the calculations by means of the values of the SIF K_I and K_{II}, because their values are a function of the orientation of the crack plane. These parameters were calculated numerically with the finite element method.

Fig.7 shows the stress contour and the crack trajectory for the last configuration. In this crack growth analysis quarter-point (Q-P) singular finite elements are used with the MTS-criterion. These results are compared with an extended finite element method (X-FEM) [13], Table 3 and Fig.8.

The extended finite element method allows for the modeling of arbitrary geometric features independently of the finite element mesh. This method allows the modeling of crack growth without remeshing [13, 15].

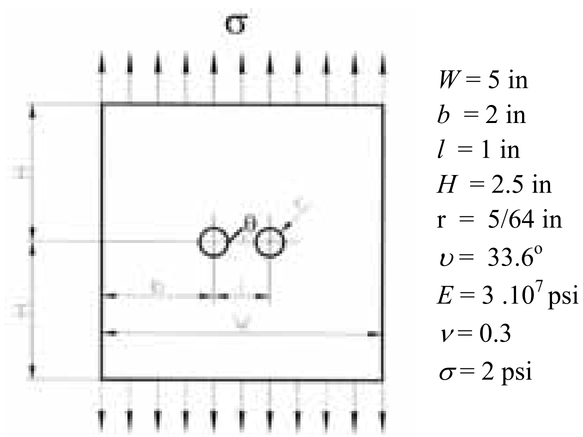

Figure 5. Geometry and load of the riveted crack problem

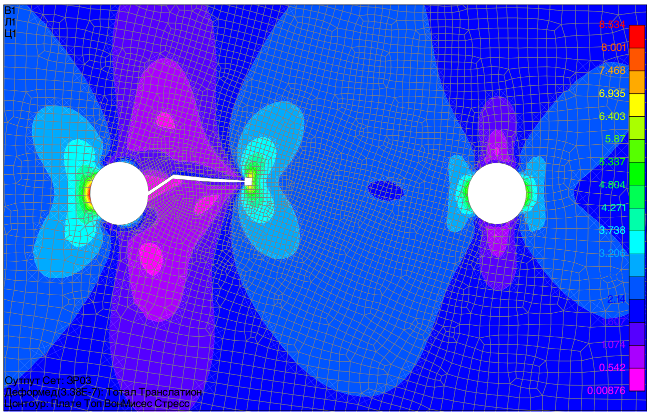

Figure 6. The crack trajectory after the third step

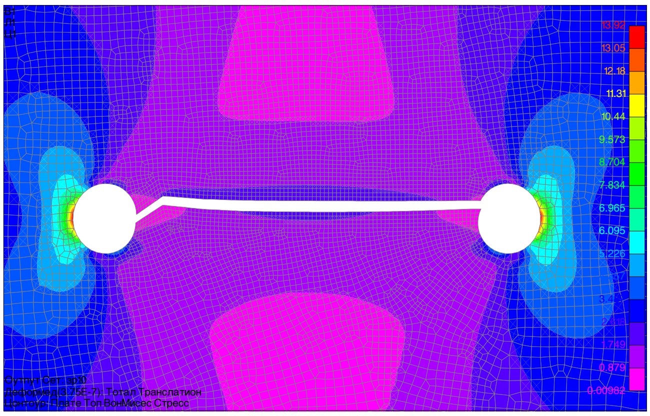

Figure 7. The crack trajectory using the Q-P elements and the MTS-criterion

Table 3: Position of the left crack tip during crack growth

X-FEM [13]		Presented Q-P singular FE solutions	
X_c [in]	Y_c [in]	X_c [in]	Y_c [in]
2.144	2.544	2.144	2.544
2.260	2.538	2.2436	2.535
2.376	2.531	2.3435	2.531
2.493	2.531	2.4435	2.5299
2.610	2.534	2.5435	2.5294
2.727	2.533	2.6435	2.5294
2.840	2.530	2.7435	2.5303
2.92	2.51	2.8436	2.5321

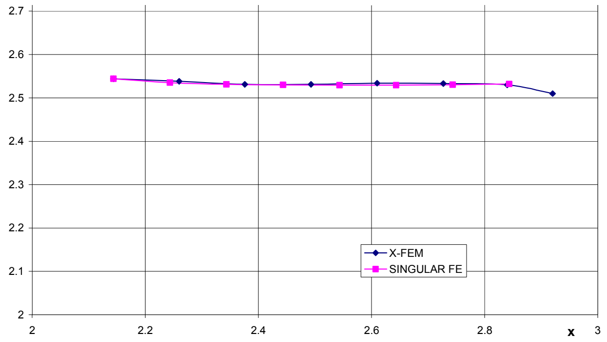

Figure 8. Comparison of the crack trajectory using the present QP singular FE with X-FEM

In this example the MTS criterion is used. The predicted crack trajectories using the Q-P singular finite elements and the X-FEM method are nearly identical. These computation results for the crack growth trajectory under mixed modes are compared with experiments. Good agreements are obtained.

Conclusions

Attention in this work is focused on the crack growth analyses of damaged structural components under fracture mechanics for mode I and the mixed modes. The finite element method is a robust and efficient technology that can be used to investigate the impact crack on the performance of notched structural components.

The aim of this work is to investigate the strength behavior of the notched structural elements such as the cracked lugs. In the fatigue crack growth and the fracture analysis of lugs, an accurate calculation of SIFs is essential. An analytic expression for the stress intensity factor of the cracked lug is derived using the correction function. The contact finite element analysis for the true distribution of the pin contact pressure is used for the determination of stress concentration factors that is used in the correction function. Good agreement between the derived analytic SIFs of the cracked lug with finite elements is obtained.

Two applications were discussed in this work to demonstrate the effectiveness of finite element based computer codes in evaluating the impact of fatigue crack growth on structural components. The applications described a fatigue crack growths analysis of lugs with complex geometry and loading. In this paper the predicted crack trajectory using quarter-point singular finite elements together with the MTS criteria were nearly identical to the trajectories predicted with X-FEM. The computation results of damaged lug type structural components are compared with the experiments. Good correlations between the computation and the experiments are obtained as well.

References

[1] MIL-A-83444, Airplane Damage Tolerance Requirements.

[2] MAKSIMOVIĆ,K.: *Strength analysis of structural components with respect to damage tolerance damages under dynamic loads*, Master Thesis, 2003.

[3] WALKER,K.: *The effect of stress ratio during crack propagation and fatigue for 2024T3 Aluminum,* ASTM STP 462, Effects of environment and complex loading history on fatigue life, 1970.

[4] BARSOUM,R.S.: *Triangular quarter-point elements as elastic and perfectly plastic crack tip element*s, Int. J. Numer. Meth. Engng., 1977, 11, pp.85-98.

[5] SIH,G.C.: *Mechanics of fracture initiation and propagation*, Kluwer, The Netherland, 1991.

[6] SIH,G.C.: *Strain-energy-density factor applied to mixed mode crack problems*, Engineering Fracture Mechanics, 1974, 5, pp.365-377.

[7] GDOUTOS,E.E.: *Fracture Mechanics Criteria and applications*, Kluwer, The Netherland, 1990.

[8] JEONG,D.Z.: *Mixed mode fatigue crack growth in test coupons made from 2024-T3 aluminum*, Theoretical and Appl. Frac. Mech., 2004, 42, pp.35-42.

[9] MAKSIMOVIĆ,S.: *Fatigue Life Analysis of Aircraft Structural Components*, Scientific Technical Review, 2005, Vol.LV, No.1, pp.15-22.

[10] MAKSIMOVIĆ,K., NIKOLIĆ-STANOJEVIĆ,V., MAKSIMOVIĆ,S.: *Efficient Computation Method in Fatigue Life Estimation of Damaged Structural Components*, FACTA UNIVERSITATIS Niš, Series Mechanics, Automatic control and Robotics 2004, Vol.4, No.16.

[11] MAKSIMOVIĆ,K.: *Estimation of residual strength for aircraft structural elements,* J. Technical Diagnostics, 2002, No.3.

[12] GEIER,W.: *Strength behavior of fatigue cracked lugs*, Royal Aircraft Establishment, LT 20057, 1980.

[13] JOVIČIĆ,G.: *An extended Finite Element Method for fracture mechanics and fatigue analysis*, Ph D thesis, University of Kragujevac, 2005.

[14] ERDOGEN,F., SIGH,G.C.: *On the crack extension in plates under plane loading and transverse shear*, J. Basic Engng. 1963, 85, pp.519-27.

[15] JOVIČIĆ,G., ŽIVKOVIĆ,M., MAKSIMOVIĆ,K., ĐORĐEVIĆ,N.: *The crack growth analysis on the real structure using the X-FEM and EFG methods*, Scientific Technical Review, 2008, Vol.LVIII, No.2, pp.21-26.

Received: 08.03.2009.

Analiza širenja zamorne prskotine strukturalnih elemenata sa inicijalnim oštećenjem pri modu-I i mešovitim modovima

Rad se bavi uspostavljanjem metoda za procenu veka strukturalnih elemenata sa inicijalnim oštećenjem pri modu-I i mešovitim modovima mehanike loma (I i II).

U radu se razmatraju proračunske metode i procedure za analize širenja prskotine i procenu preostalog veka za prskotine koje su locirane na mestima koncentracije napona. Za analize preostalog veka potrebni su faktori intenziteta napona (FIN) u analitičkoj formi. Za određivanje FIN koriste za probleme proračunske procene preostalog veka koriste se najčešće analitičke i metod konačnih elemenata. U radu su korišćene analitičke/numeričke metode i procedure za određivanje FIN I u obliku kakav je neophodan za procene preostalog veka strukturalnih elemenata sa inicijalnim prskotinama. Da bi smo dobili FIN u analitičkom obliku za strukturalne elemente sa inicijalnim prskotinama korišćeni su specijalni singularni konačni elementi. Kriterijumi na bazi gustine energije deformacije kao i MTS (maksimalni normalni napon u tangentnom pravcu) kriterijumi su korišćeni za određivanje trajektorije širenja prskotine ili inicijalnog ugla širenja prskotine u tankozidnim strukturama sa prskotinama lociranim na mestima koncentracije napona. Rezultati proračuna su poređeni sa eksperimentima.

Ključne reči: **mehanika loma, širenje prskotine, zamorni vek, konačni elementi, mešoviti modovi, trajektorija širenja prskotine.**

Анализ расширения усталостной трещины структурных элементов с начальным повреждением в I – моде и в смешанных модах

Вывод: В настоящей работе рассматриваются методы для оценки ресурса структурных элементов с начальным повреждением в И-моде и в смешанных модах механики излома (I и II).

В работе ещё рассматриваются расчётные методы и процедуры для анализа расширения трещины и оценки остаточного ресурса для трещин обнаруженых на местах концентрации напряжений. Для анализа остаточного ресурса нужны факторы интенсивности напряжений (ФИН) в аналитической форме. Для определения ФИН для проблем расчётной оценки остаточного ресурса чаще всего используются аналитические методы и метод конечных элементов. В настоящей работе использованы аналитические/цифровые методы и процедуры для определения ФИН И в форме необходимой для оценок остаточного ресурса структурных элементов с начальными повреждениями. Чтобы получить ФИН в аналитической форме для структурных элементов с начальными повреждениями использованы специальные сингулярные конечные элементы. Критерии на основе плотности энергии деформации, а в том числе и МТС-критерии (максимальное нормальное напряжение в тангенциальном направлении) использованы для определения траектории расширения трещины или начального угла расширения трещины в тонкостенных структурах с трещинами обнаружеными на местах концентрации напряжений. Результаты расчёта сравниваны с экспериментами.

Ключевые слова: механика излома, расширение трещины, срок усталости, конечные элементы, смешанные методы, траектория расширения трещины.

Analyse de la croissance de la fissure des éléments structuraux au endommagement initial sous le mode I et les modes mixtes

Ce papier traite l'élaboration de la méthode pour l'évaluation de la durée de vie des éléments structuraux aux endommagements initiaux sous le mode I et les modes mixtes de la mécanique de fracture (I et II). On a considéré les méthodes numériques et les procédés pour analyser la croissance de la fissure et l'estimation de la vie résiduelle des fissures situées aux points de la concentration de tension. Pour faire cette analyse les facteurs de l'intensité de tension (FIT) sont nécessaires en forme analytique. Pour déterminer FIT on utilise le plus souvent la méthode analytique ainsi que la méthode des éléments finis. Dans ce travail on a employé les méthodes analytiques, numériques et les procédés pour la détermination de FIT-I en forme nécessaire pour l'évaluation de la vie résiduelle des éléments structuraux ayant les fissures initiales. Pour obtenir FIT en forme analytique pour les éléments structuraux aux fissures initiales on a utilisé les éléments finis singuliers. Les critères à la base de la densité d'énergie de déformation ainsi que MTS (tension maximale normale dans le sens tangentiel) ont été employés afin de déterminer la trajectoire de la fissure ou bien l'angle initiale de la croissance de la fissure chez les structures aux parois minces avec les fissures situées aux points de la concentration de tension. Les résultats de la computation ont été comparés avec les résultats expérimentaux.

Mots clés: **mécanique de fracture, croissance de la fissure, durée de fatigue, éléments finis, modes mixtes, trajectoire de croissance de la fissure.**