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Some Aspects of the Damage Tolerance Analysis of the LASTA Training Aircraft Structures

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This work focuses on developing an efficient computation method for a strength analysis of aircraft structural components with respect to fatigue and fracture mechanics. Special attention is paid to developing an efficient computation method for the crack growth analysis of damaged structural components. For that purpose, we will define computation procedures for total fatigue life estimation of constructions under cyclic loads of constant amplitude and load spectrum. A general approach to this investigation is based on the application of Strain Energy Density (SED) in residual life estimation of structural elements with initial cracks. To define analytic expressions of the stress intensity factors necessary in the crack growth analysis, singular finite elements are used here. The verification of the proposed computation procedures for fatigue life estimation will be supported with corresponding experimental tests for the determination of low-cyclic fatigue properties of materials and corresponding parameters of fracture mechanics including fatigue tests of representative aircraft structural components.

Key words: **aircraft, training aircraft, aircraft structure, fracture mechanics, material fatigue, fatigue strength, finite element method, life estimation.**

Introduction

GLTHOUGH anomalies in the growth of short cracks have been noted for several years, attempts to model such behavior have only been made recently. Many failures of structural components occur due to cracks initiating from the local stress concentrations. Attachment lugs are commonly used for aircraft structural applications as a connection between components of the structure. In a lug-type joint, the lug is connected to a fork by a single bolt or a pin. Generally, the structures which have the difficulty in applying the fail-safe design need the damage tolerance design. Methods for design against fatigue failure are under constant improvement. In order to optimize constructions, the designer is often forced to use the material properties as efficiently as possible. One way to improve the fatigue life predictions may be to use the relations between the crack growth rate and the stress intensity factor range. To determine the residual life of damaged structural components, two crack growth methods are used here: (1) conventional Forman`s crack growth method and (2) crack growth model based on the strain energy density method. The latter uses the low cycle fatigue properties in the crack growth model [1,2]. Vital structural joints of a structure are designed in accordance with the damage tolerance methodology. Some effects of the types of damaged structural components, such as a lug type structure, on the residual life estimation of the LASTA training aircraft are considered here, Figures 1 and 2.

Figure 2. LASTA Training Aircraft

The Lasta training aircraft is designed in accordance with the damage tolerance approach and experimentally verified with respect to the strength of structures at a laboratory of the Military Technical Institute.

Residual Fatigue Life Models

The conventional Forman`s crack growth model is defined in the form [3]

$$\frac{da}{dN} = \frac{C(\Delta K)^n}{(1-R)K_C - \Delta K} \tag{1}$$

where K_C is the fracture toughness and C and n are

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experimentally derived material parameters. The strain energy density method can be written as 1, [2]

$$\frac{da}{dN} = \frac{(1-n')\psi}{4\,E\,I_{n'}\,\sigma'_f\,\varepsilon'_f}\left(\Delta K_I - \Delta K_{th0}\left(\frac{1-R}{1+R}\right)^{1/2}\right)^2 \qquad (2)$$

where: σ'_f is the cyclic yield strength and ε'_f - the fatigue ductility coefficient, ΔK_I is the range of the stress intensity factor, ψ - a constant depending on the strain hardening exponent n', $I_{n'}$ - the non-dimensional parameter depending on n'. ΔK_{th} is the range of the threshold stress intensity factor and is a function of the stress ratio i.e.

$$\Delta K_{th} = \Delta K_{th_0}\,(1-R)^{\gamma}\,, \qquad (3)$$

ΔK_{th_0} is the range of the threshold stress intensity factor for the stress ratio $R=0$ and γ is a coefficient (usually $\gamma = 0.71$.

Numerical validation

To validate the computation residual fatigue life estimation procedure, some cracked structural components of a light training aircraft, Fig.2, are considered here. This investigation is focused on the cracked wing skin and an attachment lug structural components.

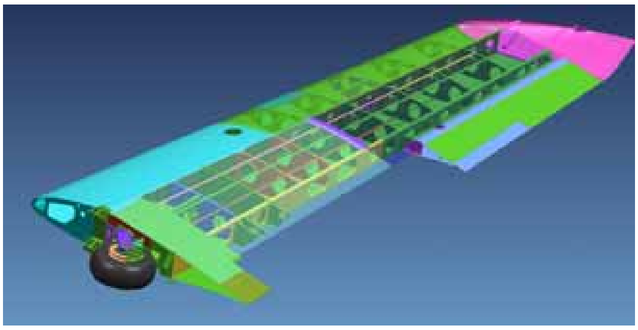
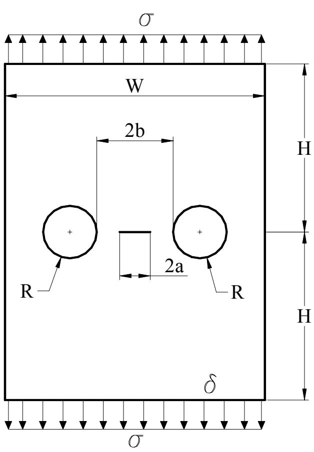


Figure 2. Wing Structure of the Light Training Aircraft

Residual Life Estimation of the Cracked Wing Skin

The investigation considered the residual fatigue life of a skin containing a crack of the length of 2a symmetrically placed between two circular holes of the radius R and subjected, remotely from the crack, to a uniform uniaxial tensile stress S in the direction perpendicular to the crack, Fig.3.



R=2 mm
b=6 mm
W=26 mm
H=26 mm
δ=1 mm
Material properties:
(duraluminum)
$E=$ 7.1 10^4 MPa
S_y= 334 MПa
σ'_f = 613 MPa
ε'_f = 0.35
n' = 0.121
k' = 710 MPa
K_{IC}=120 MPa m$^{1/2}$
I'_n = 3.067
ψ= 0.95152
ΔK_{th_0} = 8 MPa m$^{1/2}$

Figure 3. Geometric Properties of the Skin with a Crack between two Circular Holes

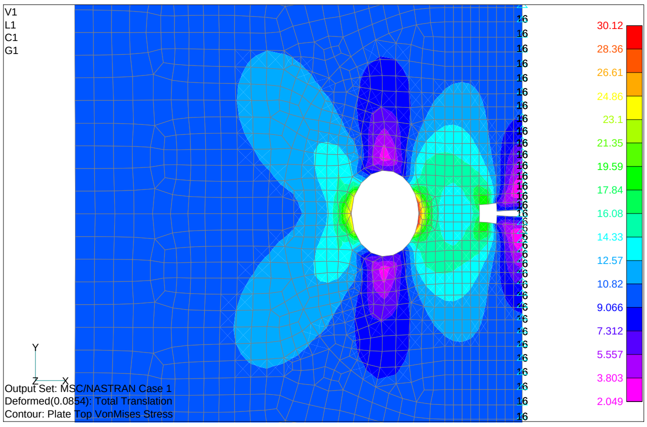


Figure 4. Finite Element Model of the Plate with a Crack Between two Circular Holes

To develop analytic expressions for stress intensity factors (SIFs), using finite elements, it is necessary to determine SIFs for various crack lengths. Fig.4 shows an FE model for the initial crack length of a_0 =2 mm. Table 1 gives the values of the SIFs determined by the FEM for various values of crack lengths.

Table 1. Comparison of SIFs by the FEM with Analytic Solutions

a (mm)	2	2.5	3	3.5	4
K_I (daN/mm^2)	26.077	29.426	32.289	36.225	40.196
a/b	0.333	0.417	0.500	0.583	0.667
$K_0 = \sigma\sqrt{\pi a}$	25.060	28.018	30.692	33.151	35.440
$Y=K_I/K_0$ (FEM)	1.041	1.047	1.059	1.090	1.134
$Y=K_I/K_0$ (ANAL)	1.09	1.1	1.12	1.145	1.19
Difference between Analytic and FEM (%)	4.5	4.8	5.5	4.8	4.7

The graphical comparisons of the corrective functions determined by the analytic formulae and the FEM are given in Fig.5.

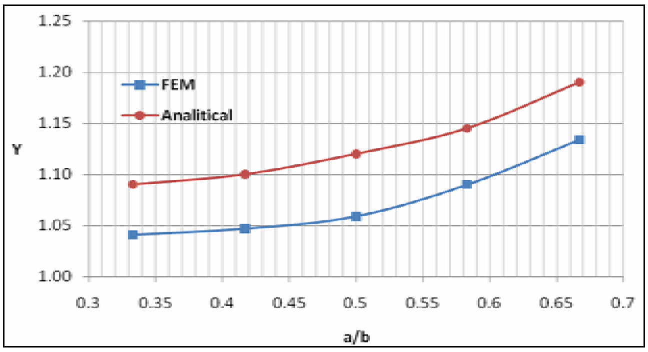


Figure 5. Comparisons of the Corrective Functions Determined by the FEM and the Analytic formulae

Using expressions for the stress intensity factors obtained by finite elements, Table 1 and the relation for the crack growth based on Strain Energy Density (2.2), the relation a-N is defined, Fig.5.

It means that the relationт a-N, Fig.6, or the residual life estimation of a skin/plate with a crack between two circular holes for cyclic loads S_{max}=55.16 MPa (R=0) is determined by SED and the analytic expressions of the stress intensity factors defined by the FEM. The presented computation procedure, which combines the finite element method to establish analytic expressions for SIFs and SED in which cyclic material properties are used, represents a general approach to the residual life estimation of aircraft structural components.

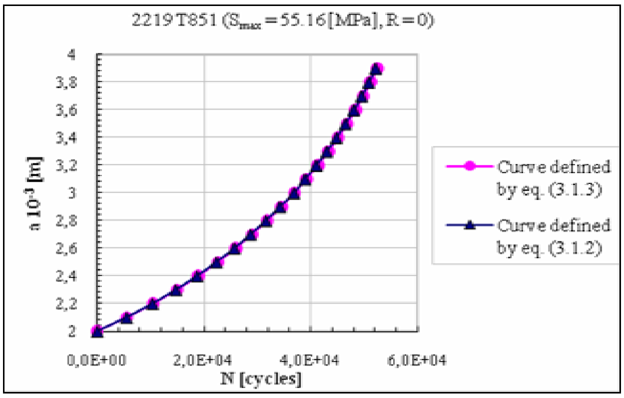


Figure 6. Crack Growth Analysis of the Plate with a Crack Between two Circular Holes using SED and derived analytic expressions for the SIFs using singular finite elements

Residual Life Estimation of Cracked lugs

Two types of initial damage of lugs are considered: (1) lug with the initial crack through the thickness and (2) lug with the initial semi-elliptic surface crack.

Lug with the crack through the thickness

Cracked aircraft attachment lugs are considered here, Fig.7. Once a finite element solution has been obtained, Fig.8, the values of the stress intensity factor can be extracted from it. To determine the Stress Intensity Factors of the cracked aircraft attachment lugs, the method based on extrapolation of displacements around the crack tip is used.

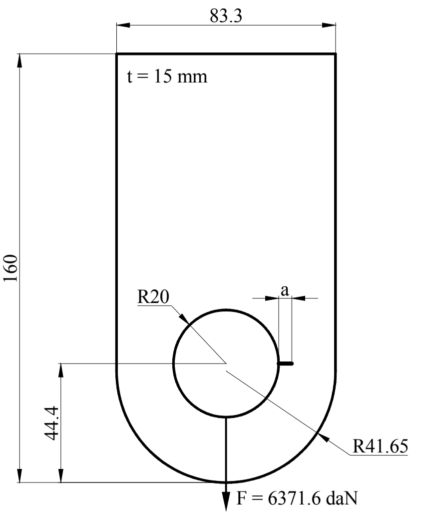


Figure 7. Geometry of cracked lug 2

The subject of this analysis are cracked aircraft lugs under cyclic load of constant amplitude and load spectra. For that purpose, the conventional Forman crack growth model and the crack growth model based on the strain energy density method are used. The material of lugs is Aluminum alloy 7075 T7351 with the following material properties: σ_m=432 N/mm^2 ⇔ tensile strength of material, σ_{02}=334 N/mm^2, K_{IC}=2225 [N/mm$^{3/2}$], dynamic material properties (Forman`s constants): C=3* 10^{-7}, n=2.39, cyclic material properties: σ'_f=613 MPa, ε'_f=0.35, n'=0.121.

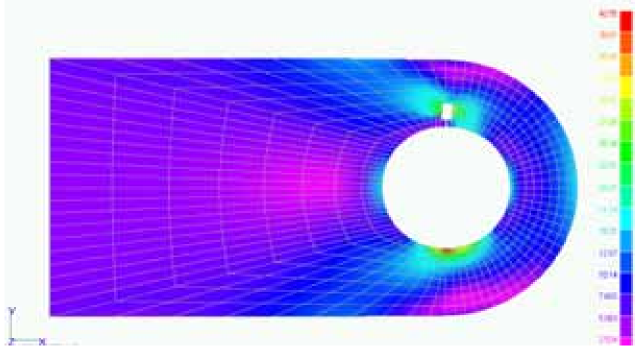


Figure 8. Finite Element Model of the cracked lug with stress distribution

The stress intensity factors (SIFs) of the cracked lugs are determined for the nominal stress levels: $\sigma_g = \sigma_{\max} = 98.1$ N/mm^2 and $\sigma_{\min}$=9.81 N/mm^2. These stresses are determined in the net cross-section of the lug. The corresponding forces on the lugs are defined as F_{max}= σ_g (w-2R) t = 63716 N and F_{min}= 6371.16 N. For the stress analysis, the contact pin/lug finite element model is used. For the cracked lug Fig.7, with the initial crack a_0, the SIF is determined using finite elements, Fig.8. For cracked lug No.2, Fig.7, with the crack through the thickness, the crack growth behavior under two-level load spectra is considered. The first level of load spectra is defined as: σ_{max}=142.8 N/mm^2, σ_{min}=14.28 N/mm^2 for the first 1000 cycles. The second level of load spectra is defined as: σ_{max}=38.1 N/mm^2 and σ_{min}=14.28 N/mm^2. The crack growth numerical simulation of the cracked lug was carried out using the SED method and the conventional Forman`s method, Fig.8.

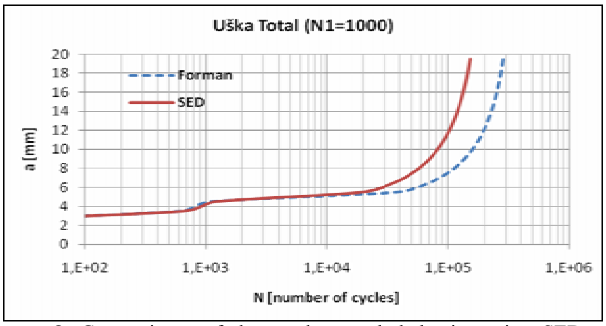


Figure 8. Comparisons of the crack growth behavior using SED and Forman`s methods

Fig.8 shows the results of the crack growth behaviour for the cracked lug using two methods: (1) conventional Forman`s method[2] and (2) strain energy density method[3-7] (SED).

Lug with the initial semi-elliptic surface crack

The crack growth behaviour of the lug with the initial semi-elliptic crack is considered here, as shown in Fig.9.

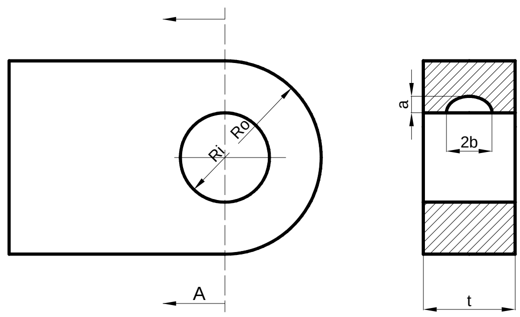


Figure 9. Geometry of lug 2 with the semi-elliptic surface crack

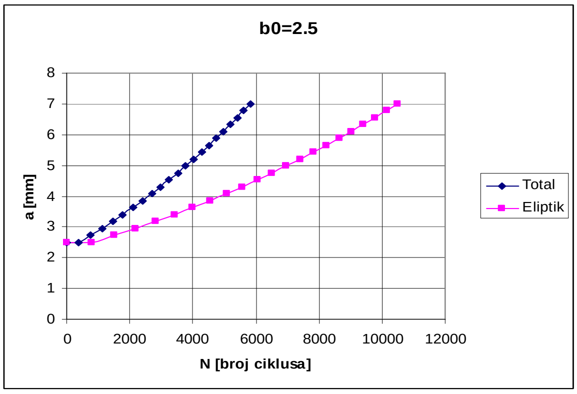


Figure 10. Effect of the type of the surface crack on residual life

The comparisons of the crack growth behaviour of the lugs with two types of damage are shown in Fig.10. From Fig.10, the effect of the type of the initial damage of cracked lugs on the residual life is evident.

Conclusions

This investigation is focused on developing efficient and reliable computation methods for residual fatigue life estimation of damaged structural components. Special attention has been paid to the determination of fracture mechanics parameters of structural components such as stress intensity factors of aircraft structural components. Predictions and experimental investigations for fatigue life estimation of an attachment lug under load spectrum were performed. This investigation leads to the following conclusions: a model for the fatigue crack growth incorporating the low cycle fatigue properties of the material is included; the effects of the shape of damage on the cracked lugs on the residual life are evident; and the comparisons of the predicted crack growth rate using the strain energy density method with the experimental data and the conventional Forman`s model points out to the fact that this model could be effectively used for residual life estimations.

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Neki aspekti primene metode dopustivih oštećenja pri projektovanju školskog aviona ’’LASTA’’

Pažnja u radu je usmerena na razvoj efikasnih proračunskih metoda za analizu čvrstoće elemenata structure aviona sa aspekta zamora i mehaniku loma. Za tu svrhu će biti definisane proračunske procedure za procenu preostalog veka elemenata konstrukcija pod dejstvom cikličnih opterećenja konstantne amplitude i spektra. Opšti pristup ovog istraživanja je zasnovan na primeni gustine energije deformacije (GED) za procenu preostalog veka elemenata konstrukcija sa pretpostavljenim inicijalnim prskotinama. Za definisanje analitičkih izraza za faktore intenziteta napona kakvi su neophodni u proračunskim analizama širenja prskotine u radu su korišćeni singularni konačni elementi. Verifikacija predloženih proračunskih procedura za procene zamornog veka će biti podržana sa odgovarajućim eksperimentima za određivanje zamornih malociklusnih karakteristika materijala i odgovarajućih parametara mehaniku loma uključivši i testove na zamor reprezentativnih elemenata konstrukcije aviona.

Ključne reči: **avion, školski avion, struktura letelice, mehanika loma, zamor materijala, čvrstoća na zamor, metoda konačnih elemenata, procena veka trajanja.**

Некоторые аспекты применения метода допустимых повреждений при проектировании учебно-тренировочных самолётов ’’Ласточка ’’

Внимание в данной работе сосредоточено на развитии эффективных аналитических методов для анализа прочности элементов конструкции самолёта с точки зрения усталости и механики разрушения. Для этой цели будут определены методики расчёта для оценки остаточного ресурса элементов конструкций под действием циклических нагрузок постоянной амплитуды и спектра. Общий подход данного исследования основан на использовании плотности энергии штамма (ВГО) для оценки остаточного срока службы элементов конструкции с предполагаемой начальной трещиной. Для определения аналитических выражений для коэффициентов интенсивности напряжений, которые могут потребоваться при разработке расчётного анализа роста трещин, в исследовании были использованы особые сингулярные конечные элементы. Проверка предлагаемых расчётных процедур для оценки жизненного цикла на усталость будет поддерживаться соответствующими экспериментамы для определения усталости малоцикловых характеристик материала и соответствующих параметров, связанных в том числе с механикой разрушения и испытаниями на усталость важных элементов структуры самолета.

Ключевые слова: **Самолёт, учебно-тренировочный самолёт, структура самолёта, механика разрушения, усталость материала, сопротивление усталости, анализ методом конечных элементов, оценка жизненного цикла.**

Quelques aspects de l’application de la méthode des endommagements tolérés lors de la conception de l’avion école ’’LASTA ’’

Le développement des méthodes efficaces de computation pour l’analyse de la rigidité des éléments chez la structure d’avion sous l’aspect de la fatigue et de la mécanique de fracture font l’objet principal de ce travail. Dans ce but on va définir les procédures de computation pour l’estimation de la durée de vie des éléments de la construction exposés aux effets des charges cycliques de l’amplitude constante et du spectre. L’approche générale de cette recherche est basée sur l’emploi de la densité de l’énergie de déformation pour l’estimation de la durée de vie des éléments de construction avec les fractures initiales. Afin de définir les expressions analytiques pour les facteurs d’intensité de tension qui sont nécessaires dans les analyses de computation sur la propagation de la fracture on a utilisé les éléments finis singuliers. La vérification des procédures proposées de computation pour l’estimation de la durée de fatigue sera supportée par les tests appropriés à la détermination des caractéristiques des matériaux de faible cycle de fatigue et de paramètres correspondants de la mécanique de fracture y compris les tests à la fatigue des éléments représentatifs de la construction d’avion.

Mots clés: **avion, avion école, structure d’aéronef, mécanique de fracture, fatigue de matériel, résistance à la fatigue, méthode des éléments finis, estimation de la durée de vie.**