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EFFICIENT COMPUTATION METHOD IN FATIGUE LIFE ESTIMATION OF DAMAGED STRUCTURAL COMPONENTS

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Abstract. *This paper focuses on developing efficient computation method in fatigue life estimations of damaged structural components. The aim of this paper is to examine the strength behavior of an important constructional element, the lug, when fatigue cracked, and to propose a stress intensity solution considering various lug geometries. The structural fatigue failure of a common connecting joint used to attach aircraft wing-fuselage components was investigated too. In the fatigue crack growth and fracture analysis of lugs, accurate calculation of the stress intensity factor (K) is essential. To obtain efficient algorithm in crack growth analysis here is derived analytic model for the stress intensity of damaged lug. For this purpose numerical modeling was used to determine stress intensity factor (K) solution for an aluminum lug with a through-the-thickness crack. A contact stress analysis was used to analyze the load transfer between the pin and lug. Fracture mechanics approaches are used to estimate the propagation life. It contains the developed analytical methodologies for determining the stress intensity factors for single through the thickness cracks in the aircraft attachment lugs, and for predicting the growth behavior of these cracks. Computational investigation of the lug not only enables the stress intensity to be determined, but also shows the interrelationship between the essential lug parameters, the crack propagation behavior and the stress distribution in a non-cracked lug. Finally, it is possible to evaluate a stress intensity solution for cracked lugs in the form of a semi-empirical approach, which takes into account the essential lug parameters.*

Key words: *damage tolerance analysis, fracture mechanics, crack growth, damaged lugs, analytic methods.*

1. INTRODUCTION

During the past decade, the influence of fracture mechanics on the design, manufacture, and maintenance of aircraft has steadily increased. However, some cracks still cannot be detected during routine maintenance inspection. Under service loading, such cracks will grow and fracture can occur if the crack length reaches a critical dimension

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before it can be detected and the part repaired or replaced. To assure aircraft safety, it is necessary to develop damage tolerance design requirements[1,2], which include the prediction of fatigue crack growth life and residual strength of the structure by assuming that small initial flaws exist at critical locations of new structure due to various material and manufacturing and process operations. For the application of damage tolerance concepts, it is necessary to make a reliable estimate of the number of load cycles required to propagate the crack from the minimum detectable size to the critical size. Inspection intervals have to be based on this estimate, or fatigue crack propagation to critical size should take so much time that it covers the whole service life. The accurate prediction of fatigue crack growth in an essential element in the structural integrity strategy for aircraft structures is important. The development of linear elastic fracture mechanics (LEFM) techniques has enabled predictions to be performed for various cracking scenarios in numerous locations throughout the structure under a variety of possible loading conditions. Since the plastic zone during fatigue crack growth is generally small, the crack growth analysis can be based on stress intensity factors, even in the case of high toughness materials. It is apparent that application of the elastic parameter K to fracture problems is justified if yield zone accompanying the crack tip is small compared to crack length. If the size of the plastic zone around the crack tip is very much smaller than all other significant dimensions of the structure and the defect, the value of parameter K is not significantly changed. When the plastic zone becomes large, as in relatively ductile material, the value of parameter K becomes questionable. Several plastic zone models have been proposed to predict the non-linear characteristics at crack tips. The most commonly used plastic zone model is the theoretical circular zone proposed by Irwin which is used to form an effective half crack length equal to the original half crack length plus the radius of the plastic zone size. The effective crack length is assumed to produce the same elastic stress field as that of the original crack with the plastic zone. It is well known that fatigue predictions, in general, have a low accuracy. However, it should be pointed out that a ±10% error in K_I can result in a very substantial error in crack growth life in aluminum aircraft structures. Therefore, finite element methods were used in this investigation to obtain an accurate solution by tacking into account actual boundaries of the configuration.

Fracture mechanics approaches are used to estimate the propagation life. Fracture mechanics approaches require that an initial crack size be known or assumed. For components with imperfections or defects an initial crack size may be known. Once the damage tolerance design requirements for aircraft attachment lugs are established, the analytical methods necessary to satisfy the crack growth and residual strength requirements are needed. In particular, stress intensity factors for cracks in attachment lugs are needed. Such stress intensity factors will depend upon the complexities of structural configurations, crack geometry, applied loads, and the fit between the pin and the lug.

2. Damage tolerance analysis

Damage tolerance evaluations have become a requirement for both passenger [1] and military [2] aircraft. Damage tolerance involves designing under the assumption that flaws exist in the structure. The initial design then focuses on making the structure sufficient tolerant to the flaws such that the structural integrity is not lost. The objective of the damage tolerance analysis is to predict crack growth and airframe residual strength given initial damage on Principal Structural Element (PSE) or Critical Structural Element (CSE). Durability and damage tolerance are the basic characteristics which a modern aircraft must possess and must demonstrate it possesses. The damage tolerance is required by the regulation so that flight safety is guaranteed. Lewicki et al.'s [3,4] work on determining the effect of gear rim thickness on crack trajectories is a good example of how damage tolerance can be applied to gears. Knowing how the gear's geometry affects the failure mode allows a designer to select geometry such that, if a crack were to develop, the failure mode would be benign. Information on the growth of cracks in engineering structures and the residual strength of cracked structures is necessary for prediction of service lives of structures subjected to fatigue loading and for the establishment of safe intervals. The crack propagation rate and fracture are controlled by the stress intensity at the crack tip. A fail-safe, or damage tolerant, design can be achieved by making use of an effective barrier to retard fast propagation of a crack under normal operating conditions (stress levels); reinforcements also increase the residual strength of the cracked structure. These barriers or reinforcements redistribute the stress field in the vicinity of the crack tip; in other words, they provide a region of low stress intensity in the path of the advancing crack front. Research efforts are required to develop analysis methods for designing fail-safe structures having various structural geometries under various loading conditions. The stress intensity factors are the key parameters to estimate the characteristic of the crack. In the developing of fracture mechanics, it has been assumed that the residual strength for a structural component is controled by, K, stress intensity factor (SIF) at the crack tip. According to this assumption, the structural element will fail when K reaches some critical value K_c. The aim of this work is to investigate the strength behaviour of an important aircraft structural element, the lug, when fatigue cracked and to consider a stress intensity solution considering the various lug geometries. The well known references does not at present include a stress intensity solution for different lug geometries, assuming a unilateral crack with straight crack front.

3. THE FINITE ELEMENT METHOD IN FRACTURE MECHANICS

The finite element method (FEM) is one of the most popular numerical methods for constructing approximate solutions of differential equations. While the FEM is well developed and robust, it is not particularly well suited to model evolving discontinuities. The construction of a discontinuous space with finite elements necessitates alignment of the element topology with the geometry of discontinuity. Over the course of the past several years, much attention has been focused on developing new approximations which do not require a mesh for their construction. These so-called 'meshfree' or 'meshless' methods construct approximations from a set of nodal data and are associated weight functions with compact support on the domain.

Meshless methods have been applied to problems in applied mechanics for which the use of a traditional finite element mesh present significant difficulties. However, meshless methods require considerably greater computational resources than FEM. An alternative to meshless methods concerns the development of finite elements which are capable of representing inter-element discontinuities. These elements are then used locally about the crack geometry to represent the arbitrary discontinuity. Many of the advantages of these methods can be realized in the partition of unity framework, where local enrichment functions are incorporated into the approximation in a straightforward fashion [5]. The essential feature is the multiplication of the enrichment functions by nodal shape functions. The enrichment is able to take on a local form by only enriching those nodes whose support intersects a region of interest. Belitschko and Black [6] adopted the partition of unity concept to model crack growth, by locally enriching a finite element approximation with the exact near tip crack fields. A key feature of these methods was the incorporation of discontinuous enrichment functions, and the use of mapping procedure to model arbitrary discontinuities. The incorporation of the near-tip fields also provided for accurate stress intensity factor calculations on relatively coarse meshes. In these problems an enrichment strategy must be used to model arbitrary discontinuities in the framework of two-dimensional linear elasticity.

In contrast to the classical approach of modeling cracks with finite elements, with discontinuous enrichment the crack geometry is represented independently of the mesh. The near-tip enrichment is also incorporated into approximation to provide for accurate calculation of stress intensity factors.

The enriched approximation for displacement field *u(x)* takes the form:

$$u^h(x) = \sum_{i \in I} u_i \Phi_i(x) + \sum_{j \in J} b_j \Phi_j(x) H(x) + \sum_{k \in K} \Phi_k \left(\sum_{l=K}^{4} C_k^l F_l(x) \right) \quad (3.1\ )$$

in which: Φ_i are the nodal shape functions, I is the set of all n nodes in the mesh, J is the set of node associated with the crack interior, and K is the set associated with crack tip. The enrichment function $H(x)$ is discontinuous across Γ_d . In the above, u_i and b_j are vectors of nodal degrees of freedom. The near tip functions $F_l(x)$ are derived from the exact asymptotic displacements near a crack tip in a two-dimensional body subjected to general mixed mode loading. In the previous context of linear elasticity, a method has been discussed which incorporates local discontinuous functions into standard finite element approximations. An important feature of the previous method concerns the direct enhancement of the approximating space with discontinuous enrichment functions. This FE formulation allows for the modeling of discontinuities whose geometries are independent of the finite element mesh. With discontinuous enrichment the crack geometry is described independently of the mesh, and so there is no need to remesh the domain at each stage of crack advance. This FE method is especially efficient in describing structure crack trajectory predictions. Erdogen and Sih have postulated that crack extension starts at the crack tip and grows in direction of the greatest tangential stress. Under general mixed mode loading, the tangential stress near a crack tip,$\sigma_{\theta\theta}$, is given by

$$\sigma_{\theta\theta} = \frac{1}{\sqrt{2\pi r}} \left(K_I \cos^3 \frac{\theta}{2} - 3K_{II} \sin \frac{\theta}{2} \cos^2 \frac{\theta}{2} \right) \quad (3.2)$$

where r and θ are polar coordinates with the origin at the crack tip. The direction of the greatest tangential stress is determined by taking the derivative of eq. (3.2) with respect to θ, setting expression to equal zero, and solving for θ. Performing the math, this predicted crack propagation angle, θ_m, is given by

$$\theta_m = 2arctg\frac{1}{4}\left(\frac{K_I}{K_{II}} \pm \sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8}\right) \qquad (3.3)$$

From eq. (3.3), the predicted crack propagation angle is a function of the ratio of K_I and K_{II}. In these problems an enrichment strategy must be used to model arbitrary discontinuities in the framework of two-dimensional linear elasticity. Of critical importance in computational fracture mechanics is the determination of the parameters which characterize the stress and displacement fields in the vicinity of a crack tip. If the stress intensity factor exceeds the critical value of the material K_c, crack growth and ultimately structural failure are possible. The development of finite element approximations with local enrichment improves the accuracy of the standard formulation, without the additional computational cost associated with meshless approximations.

Determination SIF by degenerated six-node triangular finite element

To determine stress intensity factors of lufs here the collapsed 6-noded singular finite element used. Once a finite element solution has been obtained, the values of the stress intensity factor can be extracted from it. Three approaches to the calculation of stress intensity factor can be used; the direct method, the indirect method and the J-integral method. In this paper the indirect method has been selected. In this method the values of stress intensity factor are calculated using the nodal displacements in the element around the crack tip [7].

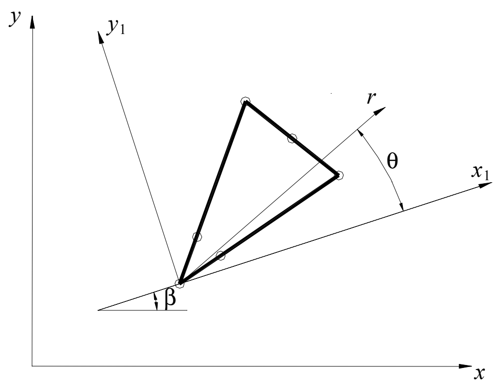

Fig. 3.1. Degenerated six-node triangular elements around crack tip

For the case of a crack oriented along $x_1 = x$, the displacements on the crack surface are found by substituting $\beta = 0^0$, $\theta = \pm\pi$ in equation (3.3.1), i.e.:

$$u = \pm\frac{K_{II}\cdot(k+1)}{2\cdot G\cdot\sqrt{2\cdot\pi}}\cdot\sqrt{r} + 0(r)$$

and (3.4)

$$v = \pm\frac{K_I\cdot(k+1)}{2\cdot G\cdot\sqrt{2\cdot\pi}}\cdot\sqrt{r} + 0(r)$$

The same displacements can be expressed in terms of the nodal displacements at A, B i C, Fig. 3.2.

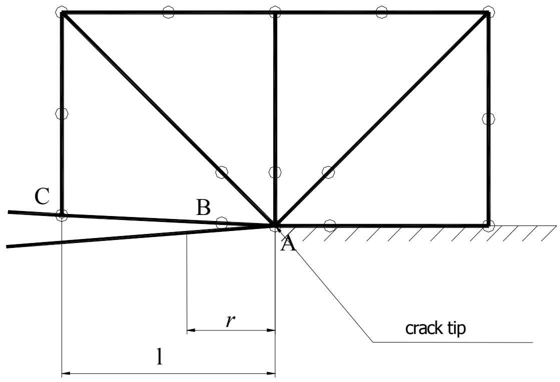

Fig. 3.2. Element nodes along crack surface

$$u(r) = u_A + (-3 \cdot u_A + 4 \cdot u_B - u_C) \cdot \sqrt{\frac{r}{l}} + (2 \cdot u_A - 4 \cdot u_B + 2 \cdot u_C) \cdot \frac{r}{l}$$
$$v(r) = v_A + (-3 \cdot v_A + 4 \cdot v_B - v_C) \cdot \sqrt{\frac{r}{l}} + (2 \cdot v_A - 4 \cdot v_B + 2 \cdot v_C) \cdot \frac{r}{l} \tag{3.5}$$

When r becomes small, the stress intensity factors can be obtained by comparing the $\sqrt{r}$ terms in equation (3.5), thus:

$$K_I = \frac{2 \cdot \sqrt{2 \cdot \pi} \cdot G \cdot (4 \cdot v_B - v_C - 3 \cdot v_A)}{(k+1) \cdot \sqrt{l}}$$

and (3.6)

$$K_{II} = \frac{2 \cdot \sqrt{2 \cdot \pi} \cdot G \cdot (4 \cdot u_B - u_C - 3 \cdot u_A)}{(k+1) \cdot \sqrt{l}}$$

Numerical tests are shown that this triangular six-node crack finite element is very accurate. In practical finite element modeling these finite element can form "super element", Fig. 3.2.

4. PREDICTION CRACK GROWTH ANALYSIS METHODS

Methods to predict fatigue crack growth under variable amplitude loading have developed that attempt to account for load interaction effects. In general, they are based upon linear elastic fracture mechanics concepts. These methods can be modified to include crack-type plasticity models. These assume that load interaction effects (crack growth retardation) occur due to the large plastic zone developed during the overload. Crack-tip plasticity models are based on the assumption that crack growth rates under variable amplitude loading can be related to the interaction of the crack-tip plastic zones.

To account for such spectrum load-interactive effects, several crack-growth retardation models have been proposed. The well-known models of this type were developed by Wheeler and Willenborg. The Wheeler model predicts that retardation in the crack growth rate following an overload may be predicted by modifying the constant amplitude growth rate. The effects remain active as long as the crack-tip plastic zones developed on the following cycles remain within the plastic zone of the overload.

For tension-tension cyclic loading (R>0) cases, the Walker equation[8] can be used

$$\frac{da}{dN} = C[(1-R)^{m-1}\,\Delta K_{ef}]^{n}\,;\ R \geq R^{+}_{cut} \tag{4.1}$$

where R^{+}_{cut} is the cutoff value of the positive stress ratios, N is the number of applied fatigue cycles, a is the crack length, R is the stress ratio, ΔK_{ef} is the efective stress intensity factor range, and C, m, n – are empirically derived constants. To determine the ΔK_{ef}, in this paper Vroman`s model is adapted[9]:

$$\Delta K_{ef} = \frac{4}{3}\left[K_{\max} - \frac{3}{4}(K_{\min}) + \frac{1}{3}K_{\max,ol}\sqrt{\frac{a_{ol}+r_{yol}-a_i}{r_{yol}}}\right] \tag{4.2}$$

where: K_{max} and K_{min} are the maximum and minimum values of the stress intensity factors corresponding to the maximum and minimum stress of the applied load cycle; a_{ol} and $K_{max,ol}$ are the crack size and the stress intensity factor value corresponding to the previously applied tensile overload. Value r_{yol} is the radius of the plastic zone produced by the tensile overload. It is determined from

$$r_y = \frac{1}{2\pi}\left[\frac{K_{\max}}{\sigma_y}\right]^2 \tag{4.3}$$

These terms are defined graphically in Fig. 4.1. This model predicts that retardation decreases proportionally to the penetration of the crack into the overload zone with maximum retardation occuring immediately after the overload.

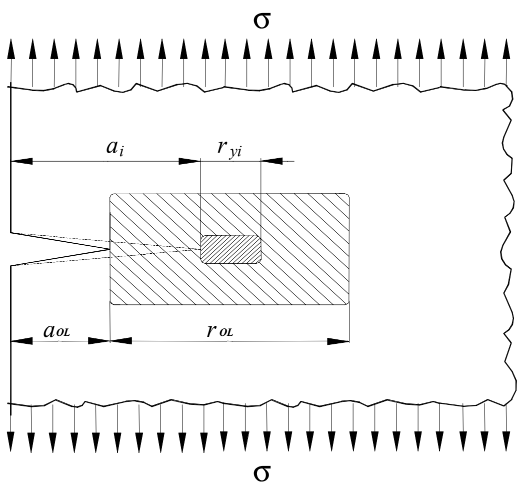

Fig. 3.3. Plastic zone size around crack tip

This model can be used to predict the fatigue crack growth under spectrum loading without the assstance of empirical factors or data.

The effective stress intensity factor range ΔK_{ef} in Vroman model (4.2) can be reformulated as:

$$\Delta K_{ef} = (K_{\max} - K_{\min}) - \frac{1}{3}\left[\sqrt{\frac{a_{ol} + r_{yol} - a_i}{r_{yol}}} - K_{\max}\right] \tag{4.4}$$

It can be seen from eq. 4.4 that the numerical value of ΔK_{ef} is always less than $\Delta K = K_{max} - K_{min}$, when the overload is existing, hence, the corresponding value of the fatigue crack growth rate is smaller than its constant amplitude counterprint, resulting in crack growth retardation.

5. THE ANALYTIC FORMULATION OF THE LUG SIF

Lugs are essential components of an aircraft for which proof of damage tolerance has to be undertaken. Since the references does not contain the stress intensity solution for lugs which are required for proof of damage tolerance, the problem posed in the following investigation are: selection of a suitable method of determining othe SIF, determination of SIF as a function of crack length for various form of lug and setting up a complete formula for calculation of the SIF for lug, allowing essential parameters

The stress intensity factors are the key parameters to estimate the characteristic of the crack. Based on the stress intensity factors, fatigue crack growth and structural life predictions have been investigated. The lug dimensions are defined in Fig. 5.1.

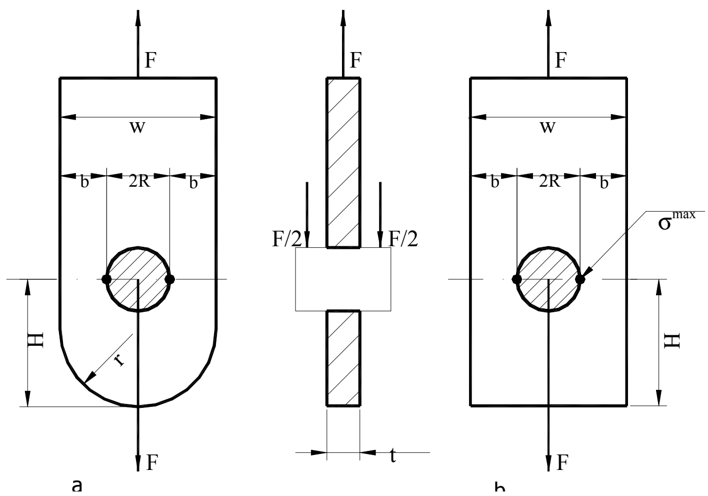

Fig. 5.1. Geometry and loading of lugs

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

$$K = Y_{SUM}\,\sigma\sqrt{\pi a} \tag{5.1}$$

where: Y – correction function, a – the crack length. This function is essential in determining of the the stress intensity factor. The correction function is defined using experimental and numerical investigations. This function can be defined in the next form [10,11]:

$$Y_{SUM} = \frac{1.12 \cdot k_t \cdot A}{A + \frac{a}{b}} \cdot k \cdot Q \tag{5.2}$$

$$k = e^{r\sqrt{a/b}} \tag{5.3}$$

$$b = \frac{w - 2 \cdot R}{2} \tag{5.4}$$

$$r = -3.22 + 10.39 \cdot \left[\frac{2 \cdot R}{w}\right] - 7.67 \cdot \left[\frac{2 \cdot R}{w}\right]^2 \tag{5.5}$$

$$Q = \frac{U \cdot \frac{a}{b} + 10^{-3}}{\frac{a}{b} + 10^{-3}} \tag{5.6}$$

$$U = 0.72 + 0.52 \cdot \left[\frac{2 \cdot R}{H}\right] - 0.23 \cdot \left[\frac{2 \cdot R}{H}\right]^2 \tag{5.7}$$

$$A = 0.026 \cdot e^{1.895 \cdot \left(1 + \frac{a}{b}\right)} \tag{5.8}$$

The stress concentration factor k_t is very important in calculation of correction function. In this investigation analytic polynomial expressions[11] are used for k_t.

6. Numerical Examples

In aircraft structures, lug-type joints are frequently used to connect major structural components or in linkage structure. Attachment lugs are some of the most fracture critical components in aircraft structure, and the consequences of a structural lug failure can be very severe. Therefore, it is necessary to develop damage tolerance design requirements, similar to MIL-A-834444, for attachment lugs to ensure the safety aircraft. Once the damage tolerance design requirements for aircraft attachment lugs are established, the analytical methods necessary to satisfy the crack growth and residual strength requirements are needed. In particular, stress intensity factors for cracks in attachment lugs are needed. To illustrate computation procedure in fatigue life estimations here the lugs structural components are considered.

6.1. The Analytic Comparisons with Test results

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. 5.1a. Three different head heights of lug are considered in the analysis. The straight attachment lugs are subjected to axial pin loading only.

Material properties of lugs are (7075 T7351)[10]: σ_m=432 N/mm^2 $\Leftrightarrow$ Ultimate tensile strength, σ_{02} = 334 N/mm^2, C_F = 3. 10^{-7}, n_F = 2.39, K_{IC} = 2225 [N/mm$^{3/2}$].

Table 6.1.1. Geometric parameters of lugs [10]

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 Stres Intensity Factor Calculations: The stress intensity factors of cracked lugs are calculated under stress level: σ_g = σ_{max}= 98.1 N/mm^2, or corresponding axial force, $F_{max} = \sigma_g\,(w - 2R)\,t$ = 63716 N. In present finite element analysis of cracked lug is modeled with special singular six-node finite elements around crack tip. The loaded model by a concentrated force, F_{max}, was applied at the center of the pin and reacted at the other and of the lug. Spring elements were used to connect the pin and 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 to spring elements which were in compression and very low stiffness (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 6.1.2. The analytic results are obtained using relations from previous section 5.

Table 6.1.2. Comparisons analytic and FE results for SIF, KI

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

A good agreement between finite element and analytic results is obtained. It is very important because we can use analytic derived analytic expresions in crack growth analyses. Figures 6.1.1 and 6.1.2 show finite element models of cracked lug tipe structure with single crack. For through-the-thickness cracks, the 2-D cracked finite element method properly models the crack tip stress singularity and the distribution of pin bearing pressure.

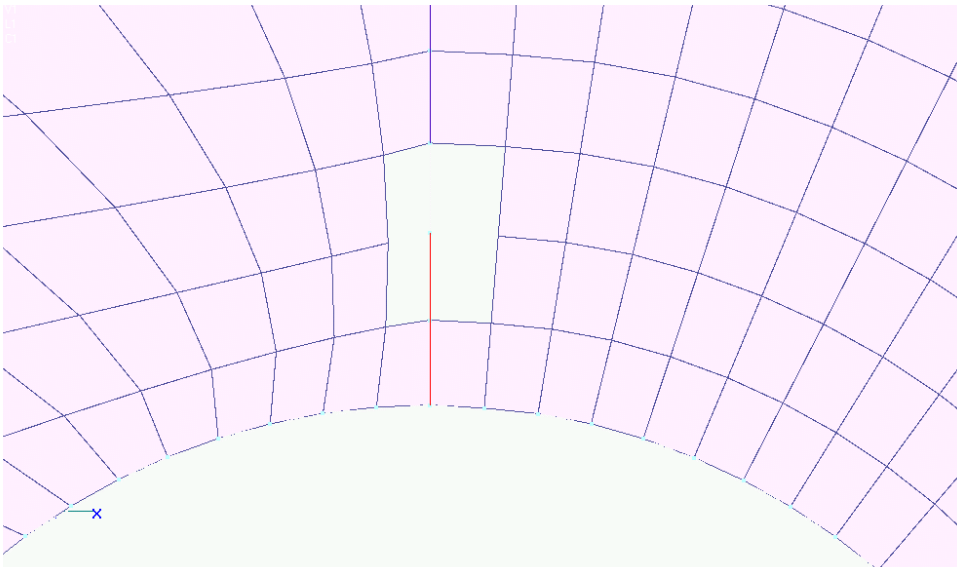

Fig. 6.1.1 Detail of FE Model with "super element" around crack for lug No. 2

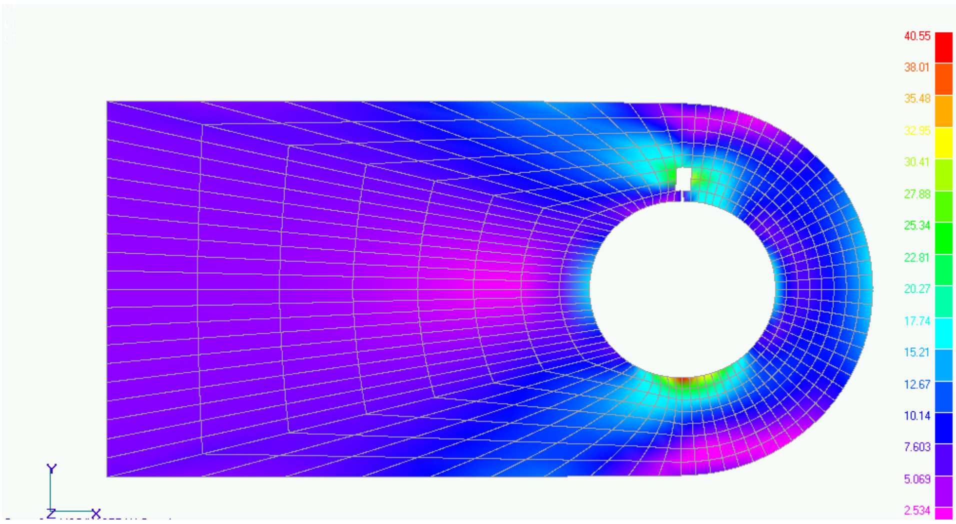

Fig. 6.1.2. Finite Element Model of cracked lug No. 2 with stress distribution

Crack Propagation Analysis: In this investigation crack propagation analysis was performed. Lug No. 2, defined in Table 6.1.1, with initial crack $a = 2.5$ mm was analyzed. Figure 6.1.3 shows a comparison between the experimentally determined crack propagation curves and the load cycles calculates to Elber low for several crack lengths. A relatively close agreement between test and calculations is obtained. The test carried out with $R = 0.1$

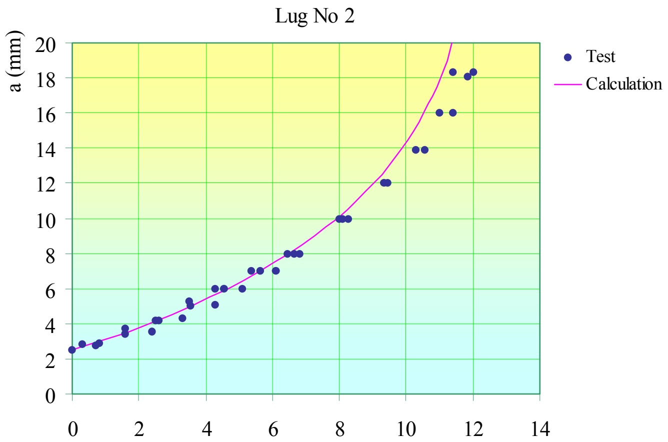

Fig. 6.1.3. Crack propagation at lug No. 2-Comparisons analytic results with tests (H = 44.4 mm); k_t = 2.8

6.2. The effect of head height of lug on stress intensity factor

In practical design of cracked structural components such as lugs it is important to know effects of its geometric parameters on fracture mechanics parameters. In this analysis stress intensity factor is considered. In Figure 6.2.1 relations between stress intensity factor, K_{max}, and head height H of lug is shown. The lug geometrical characteristics given in Fig. 6.1.1 are given in this analysis.

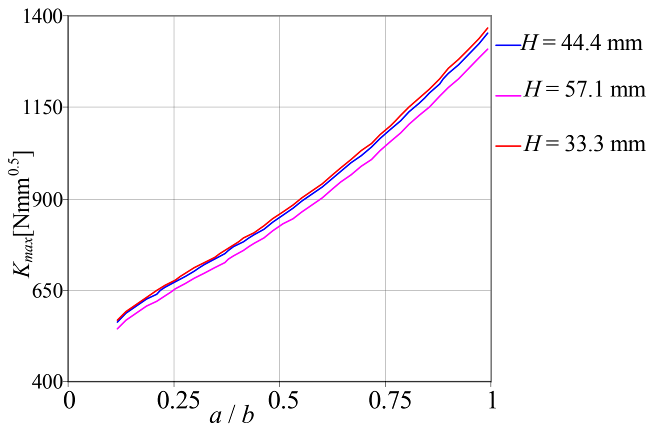

Fig. 6.2.1. Effect of head height on SIF H and crack length, a, Lug No: 7 (H = 33.3), 2(H = 44.4), 6(H = 57.1)

From Fig. 6.2.1 can be seen that SIF increases when crack increases. The effect of head height H on SIF is evident but not is so large. In a similar manner the effects of another geometric lug parameters on SIF can be investigated.

7. CONCLUSIONS

This work presents the analytic methods and procedures for obtaining the stress intensity factors and predicting the fatigue crack growth life for cracks at attachment lugs. The analytic and finite element methods are used to obtain stress intensity factors for damaged lugs. A good agreement between analytic and FE results are obtained. The crack propagation calculations on lugs with through-the-thickness crack were performed. For through-the-thickness cracks, the 2-D cracked finite elements are found to be reliable and versatile. A relatively close agreement between test and calculation can be used. In crack propagation calculations of damaged lugs analytic expressions for stress intensity factors are used. The analytic computation methods presented in this work can satisfy requirements for damage tolerance analyses of structural components such as lugs-type joints.

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EFIKASAN METOD PROCENE VEKA STRUKTURALNIH ELEMENATA SA INICIJALNIM OŠTEĆENJIMA

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Ovaj rad se bavi istraživanjem efikasne metode procene veka srukturalnih elemenata sa inicijalnim oštećenjima. Suština ovog rada je analiza čvrstoće važnog elementa konstrukcije, uške, kada se pojavi prskotina usled zamora, i predlaganje rešenja za intezitet napona uzimajući u obzir različitu geometriju uške. Takođe, se vršilo istraživanje struktura preloma usled zamora kod uški, koje spajaju krilo aviona sa trupom aviona. Precizni proračun faktora inteziteta napona (K) je veoma važan kod analize porasta prskotine i analize loma. Za dobijanje efikasnog algoritma pri analizi porasta prskotine, izveden je analitički model za intezitet napona oštećene uške. U ovu svrhu korišćeno je numeričko modeliranje za određivanje faktora inteziteta napona (K) kod uške izrađene od aluminijuma koja ima prskotinu u poprečnom preseku. Analiza kontaktnih napona se koristila da bi se analiziralo prenošenje optetrećenja između osovinice i uške. Za procenu radnog veka korišćena je mehanika loma. Ona sadrži razvijene analitičke metode za određivanje faktora inteziteta napona za jednu prskotinu kod uške i predviđanje porasta ovih prskotina. Numeričkom analizom uške ne samo da se omogućuje određivanje inteziteta napona, već pokazuje međusobnu zavisnost između važnih parametara uške, proces širenja prskotine i prenošenje napona na deo oko prskotine. Na kraju, postoji mogućnost da se izračuna intezitet napona uški sa prskotinom u obliku polu-empirijskog pristupa, koji uzima u obzir važne parametre uške.

Ključne reči: *Analiza tolerancije oštećenja, mehanika loma, porast prskotine, oštećene uške, analitičke metode.*