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FATIGUE STRENGTH SIMULATION OF AIRCRAFT LUG

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Abstract: A computational models for the strength estimation of cracked aircraft lug are formulated. The crack growth propagation is investigated through the stress analysis and fatigue life calculation. The stress field around the crack tip and the stress intensity factor are evaluated by applying analytical approach. The fatigue life up to failure is simulated by employing two different crack growth laws.The estimations are compared with avaiable experimental data, and good correlation between different results are obtained.

Keywords: fatigue, crack growth, aircraft lug, strength evaluation

INTRODUCTION

The damage tolerance design of aerospace structures can be achieved if bearing loads are transferred through the lug-type joint. Such connection between the pin and lug represents potential zone where high stress concentration, fretting, corrosion and material defects could cause the crack growth and even sudden failure. To ensure operational safety of a structure under cyclic loading, it is essentially important to develop the reliable computational models.

Within the context of fracture mechanics, the complex propagation process has to be considered through adequate crack growth laws. Paris and Erdogan [1] found that the crack extension under cyclic loading can be described by crack growth rate as a function of the stress intensity factor. Elber [2] introduced crack closure concept and took into account the effective stress intensity factor instead of the stress intensity factor. Further, Erdogan and Roberts [3] proposed the maximum stress intensity factor and the stress intensity factor range for the crack growth analysis. Walker [4] and later, Huang and Moan [5] recognized that the stress ratio together with the stress intensity factor range can be used to describe the crack propagation.

From the engineering point of view, the complex stress field of pin-loaded lug configuration has to be considered through the stress intensity factor by applying different methods. Schijve and Hoemakers [6] proposed an empirical solutions for the stress intensity factor. Impellizeri and Rich [7] suggested to employ the weight function for analyzing through-the-thickness lug problems. Hsu [8] studied the same configurations by applying singular finite element method. Pian et al [9] suggested that the crack growth of through-the-thickness crack initiated in the lug can be investigated by using the hybrid finite element method.

In the present paper, the computational procedure for the fatigue life analysis of the pin-loaded lug with through-the-thickness crack emanating from a hole is developed. In the crack growth estimation, the stress analysis and the residual strength evaluation are considered. For the stress analysis analytical approach is employed. The predictive capability of proposed models is discussed through the adequate comparisons between crack growth evaluations and experimental data.

CRACK GROWTH SIMULATION UNDER CYCLIC LOADING

During exploitation of structural components, cyclic loadings with different levels cannot be avoided. Complex fatigue process can often lead to unexpected failures of components. From the engineering point of view, the main issue is the evaluation of the reliable computational models while including the adequate loading parameters. The crack propagation of structural components can be investigated through the crack growth rate calculation and the fatigue life estimation.

The strength assessment of components can be realized through the adequate crack growth laws.

The present authors theoretically investigated the propagation process of the lug with through-the-thickness crack(s) by employing two different relationships for crack growth rates, the first one proposed by Huang and Moan [5] i.e.

$$\frac{da}{dN} = C\left(M\Delta K_I\right)^m \tag{1}$$

where $M = (1-R)^{-\beta}$ for $0 \le R < 0.5$

and then, the following relationship introduced by Erdogan and Roberts [3]:

$$\frac{da}{dN} = C K_{I\max}^2 \Delta K_I, \tag{2}$$

where $K_{I\max}$ and ΔK_I are the maximum stress intensity factor and stress intensity factor range, respectively, R denotes stress ratio and C, m and βr represent constants experimentally obtained.

In the fatigue fracture analysis, the relationships for crack growth rates enable that the number of loading cycles up to failure can be computed. After integration Eqs.(1) and (2) the expressions for final number of loading cycles up to failure can be written as follows:

$$N = \int_{a_0}^{a_f} \frac{da}{C\left((1-R)^{-\beta}\Delta K_I\right)^m}, \tag{3}$$

$$N = \int_{a_0}^{a_f} \frac{da}{C K_{I\max}^2 \Delta K_I}. \tag{4}$$

where a_0 and a_f denote initial and final crack length, respectively.

The number of loading cycles up to failure is here estimated for adequate crack increments by applying two different crack growth laws where service cyclic loading conditions are taken into account through either stress ratio R or the maximum stress intensity factor $K_{I\max}$, respectively. Since the relationships for stress intensity factor are complex, relevant numerical methods related to the integration of complex functions are employed in developed computational model.

STRESS INTENSITY FACTOR EVALUATION

Under cyclic loading the service life of engineering structures often can be reduced by cracks initiated in the zones of stress concentration or manufacturing defects. In order to ensure the safety design and exploitation, the crack propagation process has to be investigated through the stress intensity factor calculation. Such fracture parameter includes external loading, geometry and material of the structural component, and for the lug with through-the-thickness crack(s) emanating from a hole (Figure1) it can be expressed as follows [10, 11]:

$$\Delta K = \Delta S\sqrt{\pi a}\, f_{wn} f_n \sqrt{\frac{1}{\cos\left(\frac{\pi D}{2w}\right)}}\, G_n \tag{5}$$

where ΔS is the stress range, a presents the crack length, D denotes diameter of the hole of the lug and w is width of the lug.

The Bowie correction can be expressed by f_n (n = 1 for single crack and n = 2 for two-symmetric cracks)on the following way [12]:

$$f_n = \begin{cases} 0.707 - 0.18\lambda + 6.55\lambda^2 - 10.54\lambda^3 + 6.85\lambda^4; & n=1 \\ 1.0 - 0.15\lambda + 3.46\lambda^2 - 4.47\lambda^3 + 3.52\lambda^4 & ; n=2 \end{cases} \tag{6}$$

where

$$\lambda = \frac{1}{1 + \frac{2a}{D}} \tag{7}$$

The pin-loaded effect is included through the correction factor G_n given by:

$$G_n = \begin{cases} \frac{1}{2} + \frac{w}{\pi(D+a)}\sqrt{\frac{D}{D+2a}}\ ; & n=1 \\ \frac{1}{2} + \frac{w}{\pi(D+2a)} & ; n=2 \end{cases} \tag{8}$$

The finite-width correction factor f_{wn} can be calculated by employing the following relationship:

$$f_{wn} = \sqrt{\frac{1}{\cos\left(\frac{\pi}{2}\frac{D+na}{w-2b+na}\right)}} \tag{9}$$

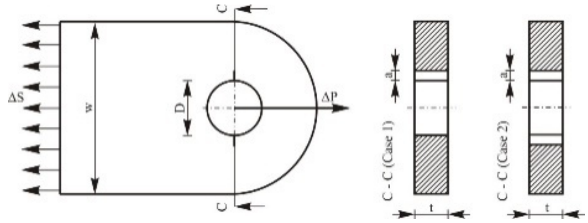


Figure 1. Geometry of the lug with through-the-thickness crack.

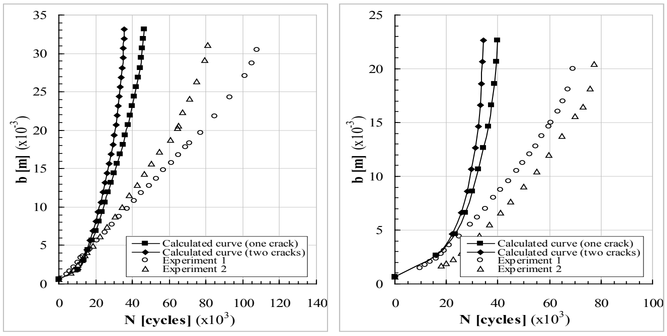
NUMERICAL RESULTS

The efficiency of the proposed mathematical models for residual strength analysis of the lug with through-the-thickness crack(s) is considered through a few numerical examples. In such examples, the fatigue life up to failure is estimated by employing two different crack laws.

Example 1. The strength estimation of the lug with through-the-thickness crack(s)

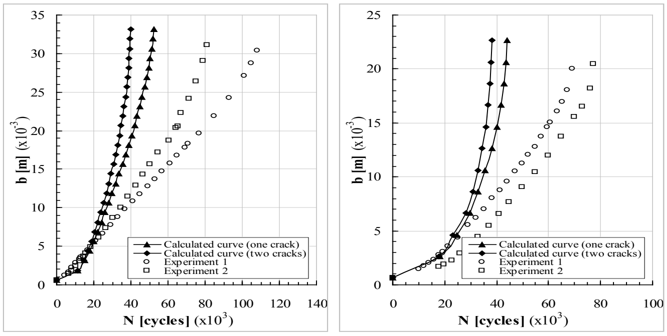
The first example examines the residual life simulation of the lug with one crack and two-symmetric cracks emanating from a hole (Figure1). Geometry sizes of the lug, made of 7075 T6, are as follows: a_0=0.635 mm, t=12.7 mm D=38.1 mm [13]. The fatigue evaluations are performed for two different width of lug w (114.3 mm, 85.72 mm). The strength of considered lug configurations is investigated under axial cyclic loading with constant amplitude (a far field maximum gross stress S_{max}=41.38MPa, R=0.5), and the following material parameters are assumed: $C_B=2.55*10^{-10}$, $m_B=3.06$ [14].

According to the mentioned geometries, material and loading parameters, the strength of lug is evaluated through the stress intensity factor calculation by applying appropriate relationships (Eqs (5)-(9)) for either single crack or two-symmetric cracks.



(a) (b)

Figure 2. Crack length versus number of loading cycles (by using Eqs.(3) and (5)-(9)).



(a) (b)

Figure 3. Crack length versus number of loading cycles (by using Eqs.(4) and (5)-(9)).

Experiment for the lug with one crack from Ref.[13]:

(a) w = 114.3 mm, 1- ABPLC84, 2-ABPLC91;
(b) w = 85.72 mm, 1 – ABPLC47, 2 – ABPLC94.

Since two different crack growth laws are considered, the residual life up to failure is computed using either Eq.(3) or Eq. (4) together with Eqs.(5)-(9). Obtained results for the number of loading cycles versus crack length by employing Huang and Moan, and Broek's crack growth laws are presented in Figure2 and Figure3, respectively.

At the same Figures, all computed results for fatigue life up to failure are compared with experimental data. The comparison between different results shows a good agreement. Additionally from Figure2 and Figure3 it can be also deducted that the crack growth law expressed by Eq.(3) is slightly conservative than that one presented by Eq.(4) when compared to experimental results.

Example 2. The residual life calculation of the lug under spectrum loading

This section considers the evaluation of the number of loading blocks up to failure. The considered lugs with either single crack or two-symmetric cracks (Figure1) have the following geometry parameters: $a_0=1.25$ mm, w=80 mm, D=35 mm, t=10 mm. External spectrum loading (Figure4) is axial with three different stress levels. The values of loading levels are shown in Table1. The considered plate is made of the same material as in the previous one.

Table 1. Maximum gross stress and appropriate number of loading cycles for considered load spectra.

Load level	I	II	III	IV	V	VI
Smax [MPa]	28.75	47.50	75.00	55.00	43.75	22.50
ni [cycles]	100	70	10	50	30	200

The strength of lug with through-the-thickness crack(s) under spectrum loading includes the stress intensity factor calculation and the crack growth rate simulation. Since the propagation process is investigated through two different crack growth laws, the number of loading blocks up to failure is estimated either by applying Eq. (3) or Eq. (4) together with Eqs (5)-(9). For both lug configurations, the computed number of loading blocks against the crack length is shown in Figure5a and Figure5b by using as a crack growth law, Eq. (3) or Eq. (4), respectively.

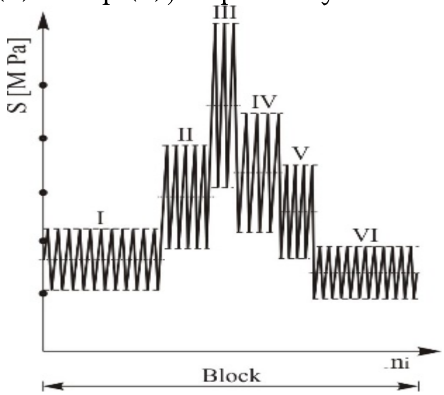
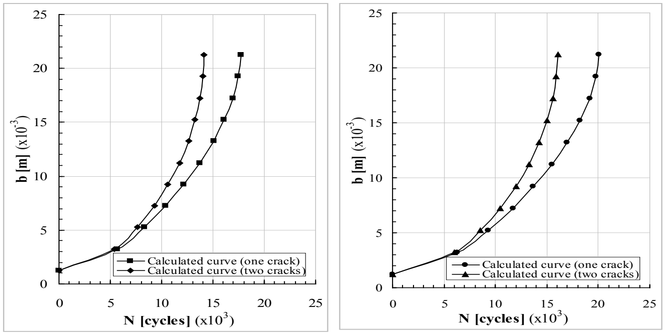


Figure 4. Load Spectra.



(a) (b)

Figure 5. Crack length versus number of loading blocks.

The comparison presented in Figure5 implies that developed computational model based on the crack growth law expressed by Eq.(1) gives slightly lower number of loading blocks up to failure than the one where Eq.(2) is employed.

CONCLUSION

The residual strength under cyclic loading of the lug with through-the-thickness crack is theoretically simulated. The crack propagation process is investigated through two different crack growth laws, and the stress intensity factor is calculated by employing analytical approach. The proposed models are verified by comparison with fatigue crack growth data. The implementation of Huang and Moan crack growth law gives slightly conservative fatigue evaluations than the one proposed by Erdogan and Roberts. Good agreement between computed results and experimental data shows that mathematical models are applicable in engineering practice for the reliable strength estimation of the lug with through-the-thickness cracks.

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