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Fatigue crack growth modeling of attachment lugs

Slobodanka Boljanović *, Stevan Maksimović

VTI-Aeronautical Department, Ratka Resanovića 1, 11000 Belgrade, Serbia

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ABSTRACT

In the present paper, computational procedures for the strength analysis of two cracked lug configurations are proposed. The authors consider the lug with single through-the-thickness crack as well as with single quarter-elliptical corner crack. The stress analysis and the fatigue life evaluations are tackled for both configurations. Numerical approaches based on quarter-point (Q-P) singular finite elements are developed for stress intensity factor calculations. Furthermore, the finite element analysis is applied in order to evaluate the polynomial expression for the stress intensity factor calculation of the lug with one through-the-thickness crack. The residual life estimation of cracked lugs is analyzed by employing the crack growth law based on a two-parameter driving force model. Moreover, the crack growth path for the lug with quarter-elliptical crack is simulated. The reliability of the proposed procedures is verified using experimental fatigue crack growth data. Fatigue life calculations and crack path simulations show a very good agreement with experimental observations.

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1. Introduction

Integrity and service operations of engineering structures are often achieved due to the employment of the lug type joints. In aerospace systems the lugs represent an essential type of joint since they connect wings to fuselage, engines to engine pylons, flaps, ailerons and spoilers to wings. During service, the lug type joints are subjected to cyclic loading and all loads are transferred through the pin. At the interface between pin and lug, the combination of high stress concentration and fretting could potentially lead to crack initiation and then crack growth under cyclic loading. To assess the safety level of lugs under service conditions, the bearing capacity and remaining life must be reliably estimated with the implementation of adequate procedures.

In general, the complex process that could lead even to catastrophic failure under cyclic loadings is theoretically investigated by introducing adequate fatigue laws with inclusion of appropriate criteria either for initiation phase or crack growth phase. In order to ensure operational safety of a structure, a significant aspect in engineering practice is the high quality of estimations for the crack growth analysis by applying computational procedures. Within the context of fracture mechanics, different crack growth laws can be employed for the fatigue life evaluations of structural components. As is well-known, thanks to experimental investigations Paris and Erdogan [1] introduced an empirical relationship (based on the stress intensity factor) for the crack growth analysis. Moreover, Liu [2] and later Duggan [3] developed their equations for the fatigue life estimations based on deformations ahead of crack tip. Then, Pook and Frost [4] took in consideration crack tip geometry and suggested their relations for the evaluation of crack growth rate.

Furthermore, Elber [5] has modified the Paris law and proposed crack closure concept. In this concept, the mean stress effects are introduced in order to analyze the crack growth process. Thereafter, Erdogan and Roberts [6], Walker [7] and later Kujawski [8] examined the same effect and introduced the two-parameter driving force models. They found that the crack growth rate can be expressed as a function of the maximum stress intensity factor and the stress intensity factor range. Additionally, Glinka et al. [9] and Wu et al. [10] studied the damage accumulation ahead of the crack for determining their crack growth laws. The crack growth process depends upon the stress intensity factor which governs the stress field at the crack tip. In the literature, researchers employed different methods to obtain approximate solutions of stress intensity factors of various crack configurations [11–21].

For a complex configuration such as the lug type joint, it is important to investigate the phase when failure could occur. In practical experience, the shapes of detected cracks in the lug can be most often approximated either as quarter-elliptical corner crack(s) or through-the-thickness crack(s).

Thus, James and Anderson [22] introduced the stress intensity factor solutions for lugs with through-the-thickness crack(s) based on experimental data. Later, Liu and Kan [23], then Schijve and Hoeymakers [24] suggested empirical relationships for the stress intensity factor calculations based on their experimental investigations. Aberson and Anderson [25] performed finite

* Corresponding author. Tel.: +381 63 805 60 85; fax: +381 11 35 11 282.
E-mail addresses: slobodanka.boljanovic@gmail.com, s.maksimovic@open.telekom.rs (S. Boljanović).

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Nomenclature

a	crack length in depth direction
b	crack length in surface direction
C	fatigue crack growth constant
da/dN	crack growth rate in depth direction
db/dN	crack growth rate in surface direction
D	diameter of the hole of the lug
E	elastic modulus
f_{w1}	finite-width correction factor for one crack emanating from a circular hole
f_1	Bowie correction factor for single crack emanating from a circular hole
g_ϕ	curve fitting angular function
G_1	correction factor for a pin loaded lug with one crack emanating from a hole
N	number of loading cycles up to failure
M_e	boundary correction factor
M_1	front-face correction factor
P	external force
Q	elastic shape factor
R	load/stress ratio
S	external nominal stress
t	thickness of the lug
w	width of the lug
ΔK	stress intensity factor range
ΔP	force range
ΔS	stress range
ϕ	angle location
ν	Poisson's ratio

Subscripts

A	depth position
B	surface position
f	failure
max	maximum value (of a given load)
T	through-the-thickness
0	initial
I	mode of loading

element analyses of through-the-thickness problems employing crack tip singularity elements. Moreover, Impellizeri and Rich [26] proposed the weight function method for analyzing the same configurations.

Meanwhile, Raju and Newman [27] calculated the stress intensity factors for different corner cracked geometries employing the 3-D finite element analysis. Schijve [28] developed a simple interpolation method to compute the stress intensity factors of the corner cracked problems analyzed by Raju and Newman. Atluri and Kathiresan [29] directly computed the stress intensity factors applying hybrid 3-D crack elements. Sih and Li [30] suggested that the strain energy density function, based on the finite element method, can be used for the stress intensity factor evaluations. Heliot et al. [31] obtained the stress intensity factors applying the boundary integral equation method. Shah and Kobayashi [32] studied the same problems employing the alternating method.

The present paper examines the strength of the attachment lugs subjected to cyclic loadings. Two configurations are considered: the lug with one through-the-thickness crack as well as with single quarter-elliptical corner crack. For both configurations the fatigue life is estimated by employing the two-parameter driving force model. The stress analysis is performed by applying analytical and/or numerical approaches. Furthermore, the number of loading cycles up to failure of the lug with single through-the-thickness crack is experimentally investigated. Additionally, the authors evaluate the crack growth path of the lug with single quarter-elliptical corner crack. The validations of the developed procedures/models for crack growth analysis are illustrated by comparison with available experimental data.

2. Stress intensity factor of the attachment lug

The interaction between the pin and lug with the combination of fretting and stress concentration can lead to initiation, then crack growth and finally cause failure. The complex configuration of the lug has to be adequately described by the stress intensity factor for the calculation of the crack growth rate and the critical length of a fatigue crack. The stress intensity factor can be determined by applying analytical and numerical methods. In the present paper, both methods are tackled in order to calculate stress intensity factor of the lug with either a quarter-elliptical corner crack or a through-the-thickness crack.

2.1. The single quarter-elliptical corner crack

In engineering practice, cyclic loadings could often lead to appearance of single quarter-elliptical corner crack at the hole of a pin-loaded lug. To aid structural integrity, the evaluation of stresses in the vicinity of cracks is very important. For the pin-loaded lug with single quarter-elliptical corner crack (Fig. 1), the relationship of the stress intensity factor can be expressed as follows [33]:

$$\Delta K_I = \Delta S\sqrt{\frac{\pi a}{Q}} M_e f_1 G_1 \sqrt{\frac{1}{\cos\left(\frac{\pi D}{2w}\right)}} g_\phi \tag{1}$$

where the elastic shape factor Q can be expressed as the square of the elliptic integral of the second kind:

$$Q = 1 + 1.47\left(\frac{a}{b}\right)^{1.64}, \left(\frac{a}{b} \leqslant 1.0\right). \tag{2}$$

The boundary correction factor M_e is given by:

$$M_e = \left(M_1 + \left(\sqrt{Q\frac{b}{a}} - M_1\right)\left(\frac{a}{t}\right)^p\right) f_{w1}, \tag{3}$$

where the front-face correction M_1 is a function of a/b i.e.:

$$M_1 = 1.2 - 0.1\frac{a}{b}, \quad \left(0.02 \leqslant \frac{a}{b} \leqslant 1.0\right) \tag{4}$$

and

$$p = 2 + 8\left(\frac{a}{b}\right)^2. \tag{5}$$

The influence of the finite width is included by the correction factor f_{w1}:

$$f_{w1} = \sqrt{\frac{1}{\cos\left(\frac{\pi}{2}\frac{D+b}{w-b}\right)}}. \tag{6}$$

The Bowie correction f_1 in the case of a single corner crack [34] can be expressed as follows:

$$f_1 = 0.707 - 0.18\lambda + 6.55\lambda^2 - 10.54\lambda^3 + 6.85\lambda^4 \tag{7}$$

$$\text{where } \lambda = \frac{1}{1 + \frac{2b}{D}\cos(0.85\phi)}. \tag{8}$$

The curve fitting angular function as a correction factor is given by:

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