Crack Growth Analysis In Aircrft Wing Lug Section And Fatigue Life Estimation

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Abstract

A computational model for estimating the residual fatigue life of attachment lugs is proposed. In strength analysis, the lug with single quarter-elliptical corner crack as well as with single through the thickness crack is examined. Stress intensity factor, as an important parameter for fatigue life estimation, is determined by applying analytical and numerical methods. The model is verified using experimental fatigue crack growth data. Predictions of fatigue crack propagation behaviours are in a good agreement with analytical observations.

Keywords— Notched Structural Components, Analytic SIF of lugs, Finite elements, Crack growth.

1. Introduction

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. The lug type joint consists of two or three parts connected with only one fastener. In the lug type joint, the combination of high concentration and fretting could potentially lead to appearance of the crack initiation, and then crack growth under cyclic loading. Fatigue, as a complex process, could be so dangerous and even to cause failure of lug, i.e. components that are connected by lug type joint. Due to previous reasons it is very important to assess, analyse and/or predict the crack initiation and crack growth behaviour of lugs.

In general, when analysing crack growth phase, the most often it is possible to identify corner cracks, as well as through-the-thickness crack in the lugs. From the engineering point of view corner crack are usually approximated by quarter-elliptical crack. For reliable prediction of crack growth rates and fracture strengths of attachment lugs accurate stress analysis is needed.

These tools include Computer Aided Design (CAD), Finite Element Modelling (FEM) and Ansys (Structural Analysis). Computer 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. The aim of this work is to investigate the strength behaviour of an important aircraft notched structural elements such as cracked lugs and riveted skin.

2. Probabilistic effects in crack growth

Bent looks at how to include random effects in a risk analysis of fatigue failure. A study by Yang looks at crack propagation in fastener holes of aircraft structures and in a centre cracked panel with both subjected to random spectrum loading. Yang models the crack propagation rate as a lognormal process using: In general, to accurately assess fatigue growth of quarter-elliptical corner crack in the lug it is necessary to analyse fatigue growth behaviour at the point of maximum crack depth and at the point of surface crack interaction with the surface. Due to previous reason, the crack propagation process can be described by two coupled equations for crack growth rate as follows:

$$\frac{da}{dN}=C_A K^2_{\mathrm{Imax}A}\Delta K_{IA}$$

$$\frac{db}{dN}=C_B K^2_{\mathrm{Imax}B}\Delta K_{IB}$$

Where CA and CB are material constants experimentally obtained, ΔKA, ΔKB, Kmax$_A$, Kmax$_B$ are the ranges and maximum values of stress intensity factor at the depth A and surface B points, respectively. Final number of loading cycles for the lug with corner crack can be estimated for both directions if expressions for crack growth rate are integrated for depth direction:

$$N=\int_{a_0}^{a_f}\frac{da}{C_A K^2_{\mathrm{Imax}A}\Delta K_{IA}}$$

and for surface direction:

$$N=\int_{b_0}^{b_f}\frac{db}{C_B K^2_{\mathrm{Imax}B}\Delta K_{IB}}$$

Since relationships for stress intensity factors are complex functions, numerical simulations have to be performed to compute fatigue life of attachment lugs up to failure for both directions

3. Micro mechanism of fatigue crack growth analysis

The ability to be able to predict fatigue crack growth (whether deterministically or probabilistically) is hampered by a lack of understanding in how fatigue

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cracks grow. Although there exist hundreds of thousands of reports or articles on fatigue crack growth, much of this literature aims to document what happens and not why it happens. An understanding of why things happen is important because it sets the limits of applicability of various data sets, or at least includes variables that may need to be considered in the analysis. It also provides the starting point for a mechanistically based model. So we shall start with a brief summary of crack growth in aluminium alloys.

4. Stress intensity factor

In general geometry of notched structural components and loading 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 linear fracture mechanics analysis of the pin-lug assembly. Analytic results are obtained using relations derived in this paper. Good agreement between finite element and analytic results is obtained. It is very important because we can to use analytic derived expressions in crack growth analyses. Lugs are essential components of an aircraft for which proof of damage tolerance has to be undertaken. Since the literature 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 of the 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 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.

The stress analysis can be considered by applying analytical and numerical approaches. The present authors tackled both approaches for stress intensity factor evaluation of the attachment lugs. As the pin-loaded lug with single quarter-elliptical corner crack [Fig.1] is investigated.

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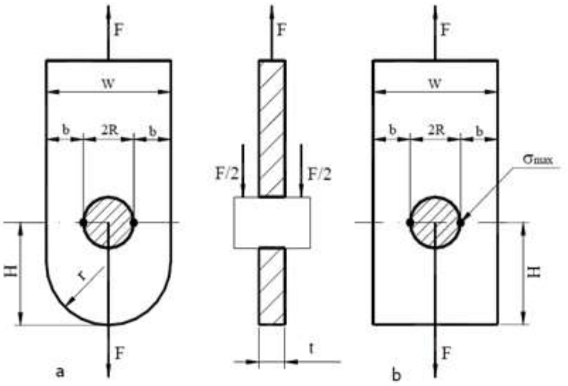

FIGURE 1: Geometry and loading of lugs

In addition to the pin-loaded lug with the quarter-elliptical corner crack, the present authors tackle the lug with single through-the-thickness crack (Fig.1). Due to previous reason, the expression for the stress intensity factor in the case of lug with single quarter-elliptical corner crack is reduced.

Furthermore, a numerical approach is employed for the stress analysis by applying the finite element method. In the package ANSYS, quarter-point (Q-P) singular finite elements are used to simulate the through-the-thickness crack growth in attachment lugs

5. Numerical result

To illustrate computation model for crack growth analysis of attachment lugs with one quarter-elliptical corner crack emanating from the hole or through-the-thickness crack, a few numerical examples are presented in this Section. These examples examine stress analysis as well as fatigue life estimation. In order to verify the validation of presented model for crack growth simulation obtained results are compared with experimental data.

6. Stress analysis of an attachment lug

In this example, stress intensity factor calculation of the lug with single through-the-thickness crack was carried out. The lug made of 7075 T7351 Aluminium Alloy was subjected by cyclic loading with constant amplitude (a maximum force Pmax= 63716 N and stress ratio R = 0.1). Geometry characteristics of the lug with single through-the-thickness crack are: w = 83.3 mm, D = 40 mm, t = 15 mm, b0 = 5.33 mm (the lug No.6). Material characteristics are as follows: σu= 432 MPa, $\sigma 0.2$= 334 MPa.

In addition to analytical approach for stress intensity factor evaluation, numerical approach based on finite element method is introduced in this paper. The lug with single through-the-thickness crack is tackled as contact problem. For this purpose singular six-node finite elements [15] are used. Actually, step-by-step, for each increment of crack length different meshes are modelled by using super-elements around crack tip.

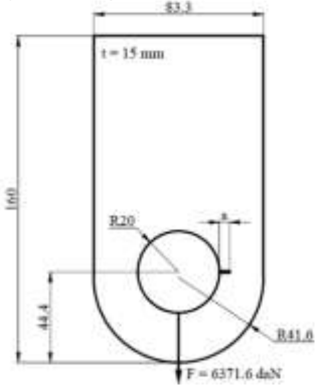

FIGURE 6: Geometry of cracked lug

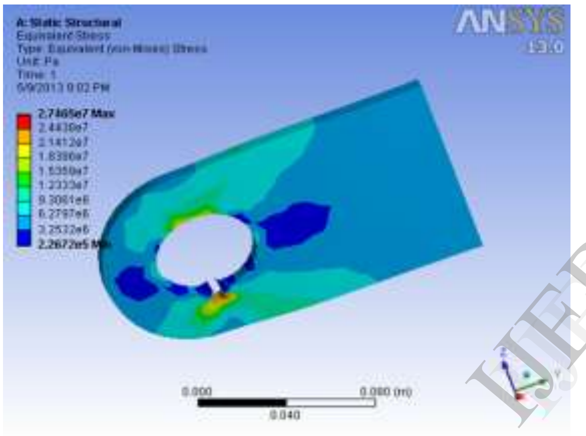

FIGURE 6.1. Finite Element Model of cracked lug with stress distribution

The step-by-step procedure is repeated until the computed crack growth is very close to the final failure of the attachment lug. A representation of the finite

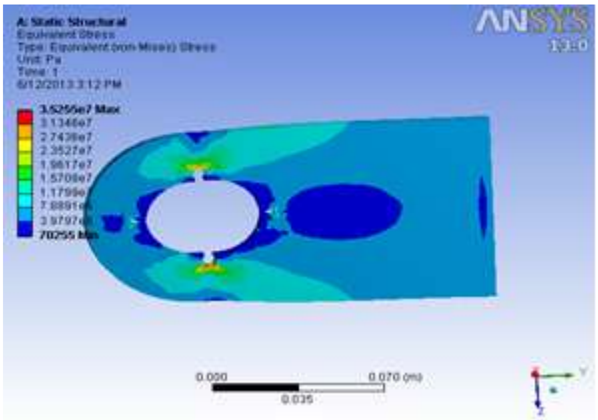

FIGURE 6.2. Finite Element Model of multi cracked lug with stress distribution

Element analysis for the lug with single through-the-ic thickness crack (b = 5.33 mm) is presented in Fig.2 and Fig.3. Moreover, for the same geometry of lug the stress intensity factor is calculated by applying analytical approach Differences between analytical and numerical (FEM) approaches are presented in

Table 1.Lug multi crack compression

Lug multi crack	Stress (pa)	Stain	Total deformation (pa)
Lug 1st crack	2.7465e7 max 9.0428e5 min	0.00038683 max 1.2736e-6 min	1.8272e-5 max 0 min
Lug 2nd crack	2.7801e7 max 1.1833e5 min	0.00039156 max 1.6666e-6 min	1.9883e-5 max 0 min
Lug 3rd crack	3.4725e7 max 75368 min	0.00048908 max 1.0615e-6 min	2.1318e-5 max 0 min
Lug 4th crack	3.5255e7 max 70255 min	0.00049655 max 9.8951e-7 min	2.1897e-5 max 0 min

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Table 6. 1.lug multi crack compression.

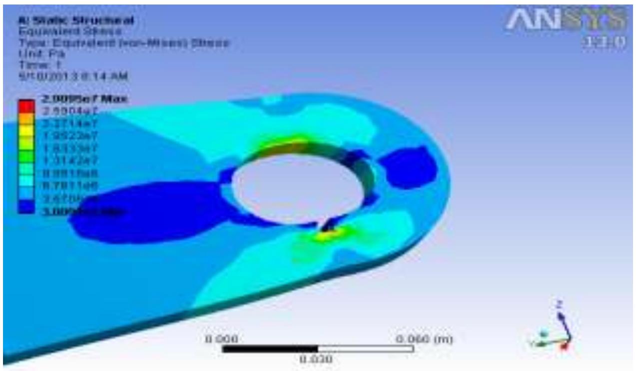

FIGURE 6.3. Finite Element Model of transvers cracked lug with stress distribution

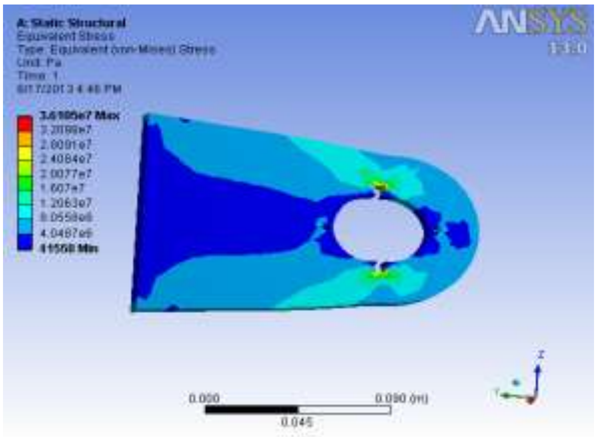

FIGURE 6.4 Finite Element Model of transvers multi cracked lug with stress distribution

Table 6.2 Transvers Lug multi crack compression

Lug multi crack	Stress (pa)	Stain	Total deformation (pa)
Lug 1st crack	2.909e7 max 3.8005e5 min	0.00040979max 5.3528-6 min	1.6606e-5 max 0 min
Lug 2nd crack	2.965e7 max 42428 min	0.0004176max 5.9757e-7 min	1.7329e-5 max 0 min
Lug 3rd crack	3.0478e7 max 81413 min	0.00042927 max 1.1467e-6 min	1.90246e-5 max 0 min
Lug 4th crack	3.6105e7 ma 41558 min	0.00050853 max 5.8532e-7 min	1.9481e-5 max 0 min

Table 6.2. lug multi crack compression.

7. STRESSES-LIFE CURVES, S-N

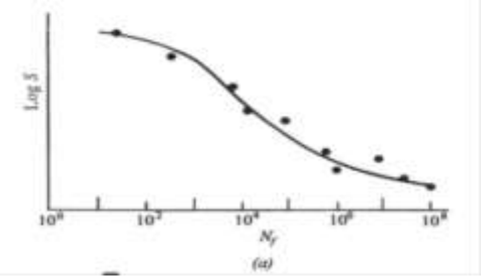

Fig 6. S-N curve in aluminium alloy.

S-N Curves obtained under torsion or bending load-control test conditions often do not have data at the shorter fatigue lives (say 103or 104cycles and less) due to significant plastic deformation.

Torsion and bending stress equations $\tau = Tr/J$ and σ=MY/I can only be used for nominal elastic behaviour.

The number of cycles to form this small crack in smooth un notched or notched fatigue specimens and components can range from a few precent to almost the entire life, as illustrated schematically. The fatigue limit has historically been a prime consideration for long-life fatigue design.

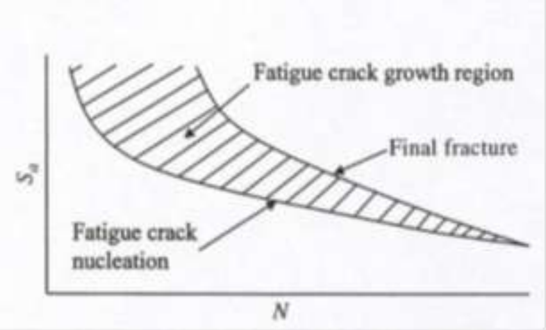

Fig 6.1 S-N curve in Fatigue crack growth

Rotating Bending Fatigue Limits or Fatigue Strengths Based on 108Cycles for Aluminium Alloys.

Cast wrought

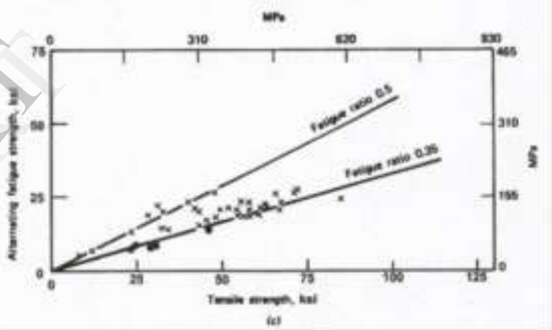

Fig 6.2 Rotating fatigue strength in aluminium alloy.

There is a tendency to generalize that Sf increases linearly with Su. These figures show this is incorrect and data bands tend to bend over at the higher ultimate strengths.

7.1. Constant Amplitude Loading

These load histories are typical of those found in real-life engineering situations. Fatigue from variable amplitude loading involving histories such as these is discussed. Constant amplitude loading is introduced in this paper.

To obtain material fatigue behaviour/properties for use in fatigue design, Some real-life load histories can occasionally be modelled as essentially constant amplitude.

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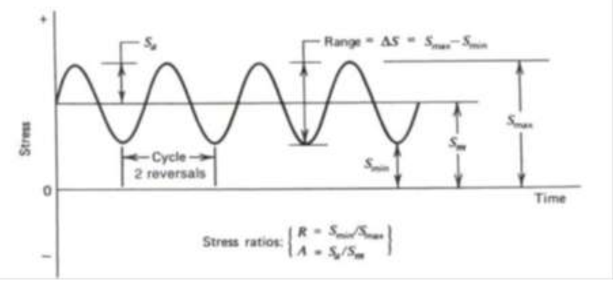

Fig 7.1. Constant amplitude load in aluminium alloy.

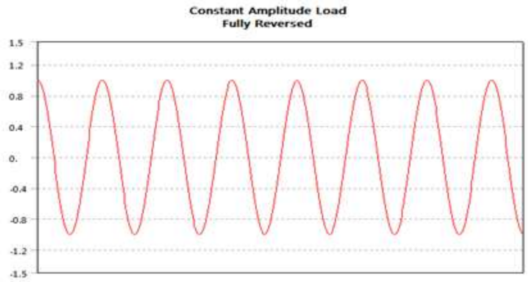

Fig 7.2. Constant amplitude load in fully reversed in aluminium alloy.

$$S_a = \frac{\Delta S}{2} = \frac{S_{max} - S_{min}}{2}$$

$$S_m = \frac{S_{max} + S_{min}}{2} \qquad R = \frac{S_{min}}{S_{max}}$$

$$S_{max} = S_m + S_a \qquad A = \frac{S_a}{S_m}$$

$$S_{min} = S_m - S_a$$

R=-1 and R=0

Stresses can be replaced with load, moment, torque strain, deflection, or stress intensity factors. Fatigue loading calculation.

Diameter of Pin (mm)	Area (mm^2)	Shear Strength (Ʈ) P/2A (kg/mm^2)	Ʈ<0.7UTS
12.7	126.61265	161	F
15.24	182.322	112	F
17.78	248.161	81.9	F
20.32	324.129	62.7	F
22.86	410.225	49.6	T
25.4	506.451	40.1	T

Table 7.1, Design of Lug Pin Diameter calculation

From the above tabular column the iterated value is given for various diameters for the pin, the pins is safe at a diameter of 22.86 mm, but let us take the approximate value 25.4 mm. The outer diameter of the lug component must be 2 times the diameter of the pin assumed by us, and the strut must be 4 times the diameter of the inner pin. The value that we used for brace strut is only 38.1 mm diameter. So the component is not sufficient to withstand.

Thickness (mm)	Constraint Force (kg)	Displacement (mm) $*10^{-1}$	Stress tensor (kg/mm^2) $*10^2$
25.4	$3.1*10^3$	2.96	1.22
27.94	$3.1*10^3$	2.69	1.11
30.48	$3.1*10^3$	2.47	1.02
33.02	$3.1*10^3$	2.28	0.941
35.56	$3.1*10^3$	2.11	0.8741

Table 7.2 Results of Non-Tapered Lug with varying thickness

And so thus the length around the pin is determined by the diameter of the pin, that is the twice of the diameter of the pin value is taken as its length. The width is also judged as four times the diameter of the pin.

For the initial value of the width of the pin is analysed but during the analysis the component failed at the edges due to more tensile stress so thus for preventing this failure the width is increased by 0.5 times the diameter at the edges of both the sides and also making the corners a little tapper rather than having a sharp corner.

Diameter (mm)	**Constraint Force (kg)**	**Displacement (mm) $*10^{-1}$**	**Stress tensor (kg/mm^2) $*10^2$**
2.54	$2.55*10^3$	2.12	0.71

Table 7.3 Result of Tapered lug with varying thickness

And also for a little value of the diameter of the pin the strut is not capable increasing its load for having it to be a solid structure so to eradicate these defect the strut is made as a hollow material having the same area and property to be safe.

8. Conclusions

This journal work presents a computational model for the crack growth analysis of the attachment lug with single quarter-elliptical crack as well as with single through-the-thickness crack. The proposed model examines the stress analysis, the fatigue life estimation and the crack path simulation. In the stress analysis, both analytical approaches are employed to determine the stress intensity factor. In the finite element analyses are conducted using the packages ANSYS and quarter-point (Q-P) finite elements are employed to simulate the stress field around the crack tip.

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