Study on damage tolerance properties of fiber metal laminates

Yu E Ma[1,*] **Zhongchun Xia**[1] **Shuang Yun**[1] **XiaoFeng Xiong**[2] **QingMao Zhang**[2]

[1] BOX 118, School of Aeronautics, Northwestern Polytechnical University, 710072, P.R. China,

[2] AVIC ChengDu Aircraft Design & Research Institute, ChengDu, P.R. China, 610041

* Corresponding author: ma.yu.e@nwpu.edu.cn

Abstract Fatigue crack growth rates in different notched fiber metal laminates under constant amplitude fatigue loading were studied experimentally and numerically. An modified numerically approach was used for predicting the crack growth rate with delamination growth, where the effective stress intensity factor in the metal layer is modulated by a bridging stress intensity factor. Then, fatigue lives of different notched fiber metal laminates were calculated. Good agreement was achieved between the predictions and experimental results.

Keywords Fiber metal laminates, crack growth , delamination growth, bridge stress, fatigue lives

1.Introduction

In modern aircraft fuselage design, advanced composite materials are increasingly utilized. A special family of such materials are the hybrid composites, also known as fiber metal laminates (FMLs), consisting of alternating layers of Al alloy and glass fiber reinforced epoxy. This material provides improved fatigue characteristics, considerable fire resistance and provides improved damage behaviour[1].

This paper deals with a numerical approach of this material, focusing on the fatigue crack growth rates in different notched FMLs. The numerical approach developed by Alderliesten[2] for predicting the fatigue crack propagation of FMLs is modified, and good agreement is achieved between the predictions and experimental results.

2.Experiments

The FMLs studied in this paper were consists of three layers of Al alloy 2024-T3 with the thickness of 0.254mm per layer and two layers of [0/90/0] glass/epoxy prepreg with the thickness of 0.15 mm per glass fiber layer. The dimensions of the specimens are 700 mm in length (L) and 140 mm in width (W). FMLs specimens were designed with 3 different notch sizes($2a_s$): 5mm, 10mm and 20mm. Constant amplitude fatigue testing was conducted using an MTS testing machine, as is shown in Fig 1. Fatigue tests were performed according to ASTM E 468-2004 at room temperature with a frequency of 10 Hz and a stress ratio of R = 0.1. The maximum applied stress was 160 MPa. Crack lengths and the cycles correspondingly were recorded. Crack growth rates were plotted in Fig 2.

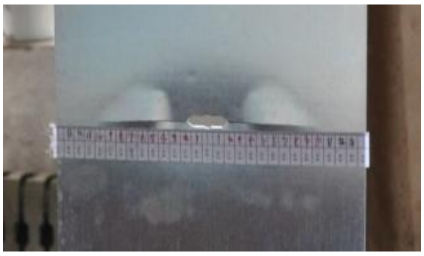

Fig 1 Delamination shape in FML during testing

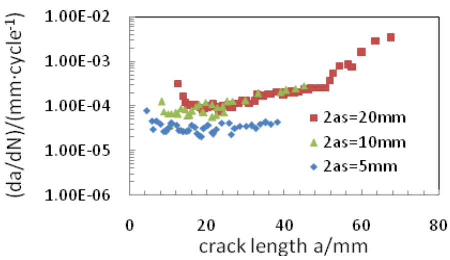

Fig 2 Crack growth rates

3.Model development

In this study, some details of the numerical approach developed by Alderliesten[2] were modified so that the predictions will have a better agreement with the experimental results. The numerical approach is based on a crack opening displacement relationship, as shown in Fig 3.

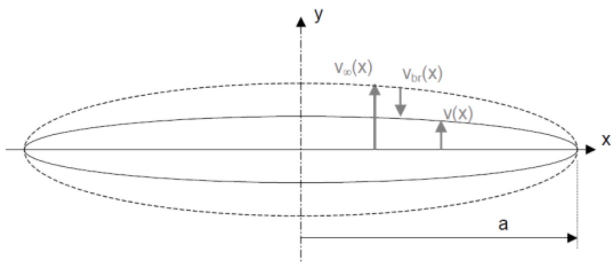

Fig 3 Definition of the crack opening displacement

$$v_\infty(x) - v_{br}(x) = \delta_f(x) + \delta_{pp}(x) \tag{1}$$

where $v_\infty(x)$ and $v_{br}(x)$ denote the crack opening displacement due to the remote applied stress and bridging stress in Al layer, respectively. $\delta_f(x)$ and $\delta_{pp}(x)$ are the deformation in the glass/epoxy prepreg and adhesive layers, respectively. The crack opening displacement away from the notch caused by the remote stress can be expressed as below

$$v_\infty(x) = 2\frac{S_{al}}{E_{al}}\sqrt{a^2 - x^2} \tag{2}$$

where E_{al} and S_{al} are the elastic modulus and the remote stress of the Al layer, respectively. The crack opening displacement $v_{br}(x)$ caused by bridging stress in Al layer can be calculated

$$v_{br}(x) = \int_0^a v(x, x_p) dx_p \tag{3}$$

The crack opening displacement $v(x, x_p)$ caused by point load is expressed as equation (4) and (5).

If $|x| < x_p$

$$v(x,x_p) = \frac{4S_{br,al}dx_p}{\pi E_{al}}\left(\tanh^{-1}\sqrt{\frac{a^2 - x_p^2}{a^2 - x^2 + b^2(x)}} + \frac{\frac{1}{2}(1+\upsilon)b^2(x)}{x_p^2 - x^2 + b^2(x)}\sqrt{\frac{a^2 - x_p^2}{a^2 - x^2 + b^2(x)}} \right) \tag{4}$$

and if $|x| > x_p$

$$v(x,x_p) = \frac{4S_{br,al}dx_p}{\pi E_{al}}\left(\tanh^{-1}\sqrt{\frac{a^2 - x^2}{a^2 - x_p^2 + b^2(x)}} + \frac{\frac{1}{2}(1+\upsilon)b^2(x)}{x_p^2 - x^2 + b^2(x)}\sqrt{\frac{a^2 - x^2}{a^2 - x_p^2 + b^2(x)}} \right) \tag{5}$$

where υ is Poisson ratio of the Al layer. $b(x)$ is the delamination shape function. $S_{br,al}$ is the bridging stress in Al layer.

The deformation caused by the elastic fiber extension is expressed as (6)

$$\delta_f(x) = \frac{S_f + S_{br,f}(x)}{E_f} b(x) \tag{6}$$

where E_f is the elastic modulus of glass/epoxy prepreg, and $S_{br,f}$ is the bridging stress in glass/epoxy prepreg. S_f is the stress in glass/epoxy prepreg at the notched zone. The bridging stress in Al layer and glass/epoxy prepreg has a relationship given as(7)

$$\frac{S_{br,al}}{S_{br,f}} = \frac{n_{f1}t_{f1} + n_{f2}t_{f2}}{n_{al}t_{al}} \tag{7}$$

For the numerical solution, the crack geometry is divided into N elements with equal width $w = \frac{a - a_s}{N}$.

The stress intensity factor as a result of the far field stress present in the Al layers follows from the linear elastic theory for monolithic metals

$$K_{farfield} = S_{al}\sqrt{\pi a} \tag{8}$$

Since the bridging stress in Al layer for a given delamination shape is calculated, the stress intensity factor caused by the bridging stress is expressed as followed

$$K_{bridging} = 2\sum_{i=1}^{N} \frac{S_{br,al}(x_i)w}{\sqrt{\pi a}} \frac{a}{\sqrt{a^2 - x_i^2 + b^2(x_i)}} \left(1 + \frac{1}{2}(1+\upsilon)\frac{b^2(x_i)}{a^2 - x_i^2 + b^2(x_i)}\right) \tag{9}$$

The bridging stress in Al layer impedes the crack growth, so the stress intensity factor at the crack tip is expressed as(10)

$$K_{tip} = K_{farfield} - K_{bridging} \tag{10}$$

In order to calculate the crack growth rate with Paris equation, an effective stress intensity factor range must be determined. Take the effect of stress ratio and the geometry into consideration, the effective stress intensity factor is expressed as(11)

$$\Delta K_{eff} = \left(1 - R^{1.35}\right)K_{tip}\sqrt{\sec\left(\frac{a\pi}{W}\right)} \tag{11}$$

where W is the width of the specimen.
Now, the crack growth rate can be obtained as (12)

$$\frac{da}{dN} = C_{cg}\Delta K_{eff}^{n} \tag{12}$$

4.Results and conclusions

All the equations above are solved by MATLAB. Triangle is chosen as the delamination shape, that is $b(x) = b(a_s)\times\left(1 - \frac{x - a_s}{a - a_s}\right)$. $b(a_s)$ is a ratio of maximum delamination length to crack length, which is based on experimental observations. $b(a_s)$ for the FMLs with notch length of 20mm is 0.35 . $b(a_s)$ for the FMLs with notch length of 10mm is 0.35. $b(a_s)$ for the FMLs with notch length of 5mm is 0.175. Bridging stresses distributions in the FMLs with 3 differernt notch sizes along the crack length was plotted in Fig 4 when crack lengths comes to 65mm.The comparisons between experimental and predicted crack growth rates are plotted in Fig 5, Fig 6, Fig 7 when notch length is 20mm,10mm,5mm ,respectively.
The fatigue lives of FMLs can be obtained by the equation (13)

$$N = \int_0^a \frac{1}{C_{cg}\Delta K_{eff}^{n}}da \tag{13}$$

Using above equations, the fatigue lives for the notched fiber metal laminates can be calculated, as is plotted in Table 1.

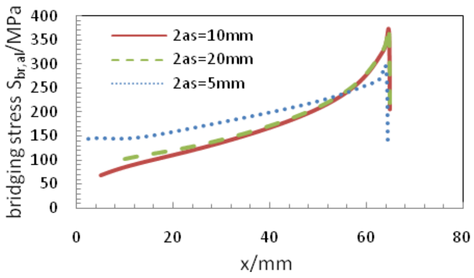

Fig 4 Bridging stresses distributions in t

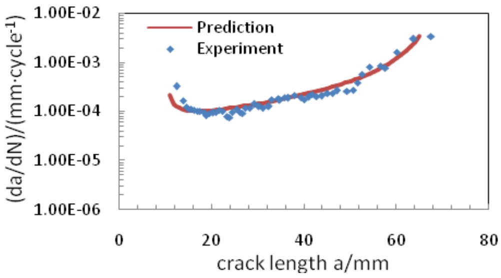

Fig 5 Comparison for as is 20mm

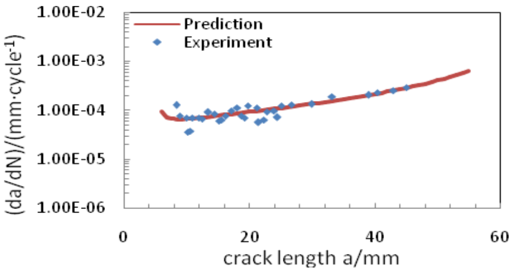

Fig 6 Comparison for as is 10 mm

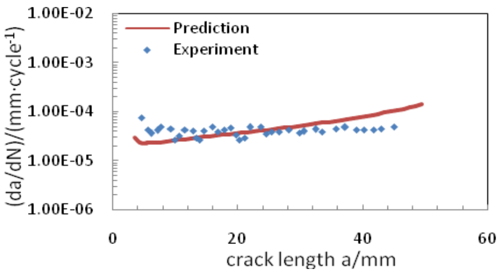

Fig 7 Comparison for as is 5mm

Table 1 The comparisons between experimental and predicted fatigue lives of FMLs

$2a_s$ (mm)	Experiments（N）	Predictions（N）	Errors（%）
5	1024000	1067019	4.2
10	355600	363672	2.3
20	296000	277720	6.2

Actually, the accuracy of this numerical approach depends on the delamination shape and the ratio . The delamination shape can be ellipse, parabola, triangle and cosine. Through the calculation, triangle seems to be the best delamination shape, cosine to be the second, parabola and triangle don'tfit well with the experimental results. The predictions are also sensitive to the radio .But a range of the radio can be determined by experimental observations so that the errors can be controlled.

This paper proposes a modified numerical approach for predicting the fatigue crack growth rates in different notched FMLs. By using MATLAB, the fatigue crack growth rates and the fatigue lives of different notched FMLs are calculated, and good agreement is achieved between the predictions and experimental results.

References

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