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Damage Tolerance and Durability of fiber metal laminates for Aircraft Structures
--Multi-site Fatigue Damage

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Abstract

The damage tolerance and durability of hybrid S2-glass reinforced aluminum laminates (GLARE) with multi-site damage were investigated experimentally and analytically. The constant-amplitude fatigue tests were conducted on the GLARE3-3/2 specimens containing multiple open holes or multiple surface slits. The crack growth from multiple damage sites and their interaction were characterized. It was found that the presence of multiple open holes would accelerate through-thickness crack growth rates in the metal layers as two propagating cracks approach each other. Also, the laminates containing multiple surface slits are more damage tolerant than those with multiple open holes. An analytical model was also established for predicting crack growth rates and the predicted results are validated by experiment.

Key words: multiple-site fatigue damage, crack growth, fiber metal laminates
1. Introduction

Fiber metal laminates (FMLs) are a family of hybrid metal and composite materials for light-weight aircraft structural applications. These hybrid FMLs take advantages of metal and fiber-reinforced composites, providing superior mechanical properties to the conventional lamina consisting only of fiber-reinforced lamina or monolithic aluminum alloys. An example of FMLs is S2-glass fiber reinforced aluminum laminate (Trade name GLARE) [1]. Current applications of FMLs include fuselages, leading edges, etc. in the Airbus A380, where weight reduction and improved damage tolerance ability are critical [2-3].

The multiple-site fatigue damage in metallic airframe has received considerable attention since Aloha airline accident in 1988 [4]. Many research works had been conducted to address the multiple-site damage (MSD) problems in metallic aircraft structures to avoid the catastrophic failure in flight [5-7]. However, the crack propagation and fracture characteristics of FMLs are essentially very different from those of metallic alloys. When a FML was subjected to fatigue loading, cracks initiated and propagated in the metal layer along with the progression of delamination in the interface between the metal and fiber prepreg. As a crack propagated, the crack growth in the metal layer was impeded by the fiber bridging mechanism and resulted in a far lower crack growth rate compared to monolithic aluminum alloy. Figure 1 shows the
bridging stress acting on the delamination boundary for a specimen subjected to applied load with the existence of secondary bending moment. Since the fatigue behavior of FMLs with the presence of multiple-site damage has not been well-documented yet, a better understanding of the multiple-site fatigue damage behavior, such as crack growth, cracks link-up, delamination link-up, etc. is necessary for ensuring structural integrity. The purpose of this investigation aimed to study the crack growth behavior in specimens containing multiple circular holes or surface slits.

2. Experimental procedure:

2.1 Materials

The GLARE laminates used in this study are GLARE3-3/2 laminates. GLARE3-3/2 consists of three layers of 2024-T3 aluminum alloy and two layers of 0°/90° S2-glass/epoxy prepreg. The materials properties of GLARE laminates were listed in Table 1.

The specimen has dimensions of 300 mm in length and 75 mm in width. Two types of multi-site damage were introduced: through-thickness open hole and surface slits. The spacing in between two neighboring open holes/slits is 30 mm and the distance in between the top (T) and bottom (B) rows of circular holes/surface slits is 100 mm. In figure 2(a), for through-thickness specimens, two rows of open holes were
carefully prepared with radii of 2.5 mm (length of 4 mm) and the starter notch is 1 mm in length. In figure 2(b), for partial-thickness specimens, two rows of surface slits were carefully prepared with length of 4 mm. The width of slit is 1 mm.

2.2 Experimental procedures

The constant amplitude fatigue testing was conducted using a servo-hydraulic testing machine, INSTRON-8350. The fatigue test was done according to the ASTM D3479 [8]. All constant amplitude fatigue testing was conducted in tension-tension loading at a frequency of 10 Hz and a stress ratio of $R = 0.05$. Testing was conducted in a sinusoidal cyclic waveform under load control. The maximum applied stress levels were 120 MPa and 100 MPa, respectively. The crack lengths as a function of fatigue cycles for GLARE3-3/2 specimens were recorded through continuous monitoring during fatigue testing. After fatigue test, the chemical-mechanical removal method was used to detect the delamination in the interface of metal/prepreg in GLARE laminates. To investigate the fatigue cracking in the inner aluminum layers of GLARE3-3/2, the surface aluminum sheets were etched away by chemical solutions and the composites layers were removed mechanically.

3. Experimental Observation of crack propagation and delamination growth

A. Through-thickness notches
For the case of specimens containing multiple through-thickness open holes, the cracks initiated at the edge of the start notch and propagated perpendicular to the applied loading direction as shown in figure 3. However, these cracks did not initiate from each open hole simultaneously. As the propagating cracks approached each other, they bypassed each other instead of having a direct crack link-up as shown in figure 3, leading to a formation of an eye-shaped region. After the removal of surface metal layers, it was also observed that the crack length in inner metal layer is almost identical to that in the outer metal layer. Meanwhile, the delamination zones in the fiber/adhesive layer appeared to avoid link-up with each other as shown in figure 4.

Since the cracks from each through-thickness open hole did not initiate at the same time, all cracks were divided into two categories: leading cracks (lead-crack) and non-leading (non-lead) cracks as shown in figure 5. Leading cracks are defined to be those that initiated and propagated to become the first direct or indirect crack link-up. The rest of cracks are defined to be non-leading cracks. For comparing the difference of crack growth rates, the averaged lead-crack and averaged non-lead crack growth rates were calculated. The averaged total crack growth rate which is defined as the average of lead and non-lead crack was also calculated for comparison. In the cases of multiple-open-hole crack growth, the crack growth rates as a function of crack length are plotted in figures 6 and 7 for the applied stresses of 120 and 100 MPa,
respectively. The results revealed that crack growth rate is higher during early stage of fatigue loading due to insufficient fiber bridging to reduce the effective stress intensity factor at the crack tip. The presence of multiple-site fatigue cracks would accelerate the crack growth rates. Therefore, as two propagating cracks approached each other, the crack growth rates increased gradually due to the effect of crack interactions. Ultimately, the cracks growth rates reached the peak values when cracks linked up near the eye-shaped region.

B. Surface slits

For the case of specimens containing multiple surface slits, the cracks also initiated at the edge of surface slits and then propagated perpendicular to the applied loading direction as shown in figure 8. However, as the propagating cracks approached each other, they have a direct crack link-up, leading to a formation of a straight line. In other words, the mode I fracture behavior dominated the surface crack growth. This observation is different from the crack propagation behavior in specimens with through-thickness open holes, in which the direction of crack path did not remain the same as crack fronts approached each other. The corresponding delamination profile is shown in figure 9.

In the case of multiple-surface-slit crack growth, the crack growth rates as a function of crack length are shown in figures 10 and 11. As compared to crack growth
of GLARE laminates with open holes, crack growth rate is obviously slower due to stronger fiber bridging effect and higher residual strength, though the secondary bending moment would affect stress level in laminates. Hence, these surface-cracked specimens are more damage tolerant than the through-thickness GLARE specimens.

4. Prediction of fatigue crack growth with multi-site damage

An analytical methodology was established for predicting the crack growth behavior as shown in figure 12.

(a) Crack growth

The empirical Paris-Walker’s equation for monolithic aluminum alloy is used to predict the crack growth rate \((mm/cycle)\) for the constituent metal layer. That is,

\[
\frac{da}{dN} = C_g \left[ (1 - R_c)^{m-1} \Delta K_{eff} \right]^{n_g}
\]

where the empirical crack growth coefficients are \(C_g = 1.27 \times 10^{-11}\), \(n_g = 2.94\) [9], and \(m = 0.63\) [10]. \(\Delta K_{eff}\) is the effective stress intensity factor range actually experienced by the aluminum layer of GLARE at crack tip with the unit of \(MPa\sqrt{mm}\). 

\(R_c\) is the effective stress ratio considering the influence of the residual stress.

\[
R_c = \frac{\sigma_{Al,\text{min}} - \sigma_{Al,\text{op}}}{\sigma_{Al,\text{max}} - \sigma_{Al,\text{op}}}
\]

where \(\sigma_{Al,\text{max}}\) and \(\sigma_{Al,\text{min}}\) are the maximum and the minimum stress in the aluminum layer, respectively. \(\sigma_{Al,\text{op}}\) denotes the crack opening stress in the aluminum layer of GLARE laminates [11]. The stress ratio used to obtaining the crack opening stress is
the actual stress ratio in metal layer of fiber metal laminates.

The effective stress intensity factor for surface crack growth in GLARE laminates is defined as

\[ \Delta K_{\text{eff}} = (K_{I,\text{Al}} - K_{II,\text{br}}) \] (3),

where \( K_{I,\text{Al}} \) is the mode I stress intensity factor in aluminum layer, \( K_{II,\text{br}} \) is the mode II bridging stress intensity factor in a laminate. The derivation of each item in equation 3 is addressed in the following subsequence.

(b) Secondary bending effect

It is known due to the unsymmetrical configuration, such as surface crack growth, there is a secondary bending effect [1]. The secondary bending moment will cause the neutral axis to shift. The displacement of neutral line needs to be put into consideration for stress levels in laminates. Using beam theory, the curvature of neutral line in laminates is governed by [12]

\[ \frac{d^2 w_i}{dx_i^2} - \left( \frac{P}{EI} \right) w_i = 0, \quad i = 1, 2. \] (4)

\[ , \text{where } P \text{ is the applied force in unit of Newton and } w \text{ is the displacement in unit of mm}, \]
\[ E \text{ is the stiffness and } I \text{ is the moment inertia in a laminate}. \]

The general displacement or neutral line curvature is expressed as

\[ w_i = \sinh(\delta_i x_i) + \cosh(\delta_i x_i), \] (5)

\[ , \text{and } \delta_i = \left( \frac{P}{EI} \right)^{1/2}. \] (6)
Therefore, the actual stress level in each layer of FMLs is a superposition of secondary bending stress, and the stresses induced by applied load and curing stress.

(c) Stress intensity factor in metal layer

The applied stress intensity factor in metal layer is expressed as [13],

\[ K_{I,Al} = \sigma_{Al} \sqrt{\pi a F(a,s)} \]  

(7)

where \( \sigma_{Al} \) is the stress level in aluminum layer of GLARE laminates, \( a \) is the total crack length, and \( F(a,s) \) is a geometrical correction term in the spacing \( s \) of two slits (see figure 2). Taking into account the effect of bending effect and applied stress in the metal layer, superposition is used to calculate the actual stress level in metal layer.

(d) Bridging stress

As crack opens in metal layers caused by applied load, the crack opening is restrained by bridging stress acting on the delamination boundary as shown in figure 1. The presence of fiber bridging mechanism in fiber metal laminates would restrain the crack opening in metal layers [1]. Conventionally, the bridging stress is solved indirectly through the crack opening displacement relation [14] through work of Guo and Wu. That is,

\[ u_{w}(x) - u_{br}(x) = \delta_f(x) + \delta_{pp}(x) + \delta_{Al}(x) \]  

(8)

where \( u_{w}(x) \) is the crack opening caused by the applied load and \( u_{br}(x) \) is the crack opening caused by the bridging stress, \( \delta_f(x) \) is the fiber elongation and \( \delta_{pp}(x) \) is the
prepreg deformation. The deformation in metal layer $\delta_{Al}(x)$ is small and therefore it is neglected.

In surface crack growth, the crack opening profile is affected by both the applied load and the secondary bending effect with bridging stresses acting on the delamination boundary to restrain the crack opening. With the absence of applied load, the crack opening relation in analogy to equation (8) is assumed to be expressed as

$$u_b^b(x) - u_{br}^b(x) = \delta_f^b(x) + \delta_{pp}^b(x) + \delta_{Al}^b(x)$$

(9)

where $u_b^b(x)$ is the crack opening caused by the secondary bending and $u_{br}^b(x)$ is the crack opening caused by the bridging stress from secondary bending, $\delta_f^b(x)$ is the fiber elongation from secondary bending and $\delta_{pp}^b(x)$ is the prepreg deformation from secondary bending. The deformation in metal layer $\delta_{Al}^b(x)$ from secondary bending is very small and therefore it is ignored.

Typically, the fiber bridging stress $\sigma_{br}$ is derived in the form of [14]

$$\sigma_{br} = H_j^{-1}Q$$

(10)

where $H = u_{\infty}^t(x) - \delta_{pp}^f(x) - \frac{\sigma_f}{E_f} b(x)$,

$$Q_j = \sum \frac{u_{br}(x_j, x_j) \Delta x_j}{\sigma_{br}(x_j)} - \frac{b(x_j)}{E_f} \delta(i, j).$$

$\delta(i, j) = $ Kronecor factor.

In this paper, constant bridging stress is used, though it depends on delamination
profiles and other factors [14]. The shape functions for through-thickness and surface crack growth can be observed in figures 4 and 9, respectively. It should be noted that in calculating the bridging stress for surface cracks, only layers involved in delamination zone are used. The bridging traction is acting on the surface of metal layer to impede the crack growth, and the bridging stress in Al layer $\sigma_{br,Al}$ is obtained using the relationship of force balance in the FMLs. The bridging stress in the metal layers of a laminate is expressed as [16]

\[
\sigma_{br,Al} = \sigma_{br} \left[ n_{0,f} t_{0,f} + n_{90,f} t_{90,f} \right] / \left( n_{Al} t_{Al} \right) \tag{13}
\]

, where $n$ is the number of layer, $t$ is the thickness of layer, and subscripts $f, Al$ denote fiber (0 or 90 orientation) and aluminum layer.

(e) Bridging stress intensity factor

The corresponding bridging stress intensity factor for a certain point load $(p_j)$ on delamination boundary $(x_j, y_j)$ is expressed as [13,16] (see figure 1)

\[
K_{br,j} = p_j \sqrt{\frac{2}{\pi a}} C_{corr} = \sigma_{br,Al,j} dx \sqrt{\frac{2}{\pi a}} C_{corr}
\]

, and $C_{corr} = \left[ \frac{a}{\sqrt{a^2 - x_j^2 + y_j^2}} \left( 1 + \frac{1}{2} (1 + \nu) \frac{y_j^2}{a^2 - x_j^2 + y_j^2} \right) \right]$ \tag{14}

where $\nu$ is the Poisson's ratio of aluminum sheet, $C_{corr}$ is a correction term for point loads acting on delamination contour.

The superposition principle is used in defining the bridging stress intensity factor
that allows superimposing each individual stress intensity factor caused by a point load.

For center crack symmetrical integration, the overall bridging stress intensity factor is expressed as,

\[ K_{II,br} = 2 \int_0^a K_{br,j} dx_j \]  

(15)

(f) Delamination growth

For GLARE laminates, the delamination growth (mm/cycle) can be expressed as a function of strain energy release rate [17-18]. It yields

\[ \frac{db}{dN} = C_b (\Delta g)^{n_b} = C_b (\sqrt{g_{\text{max}}} - \sqrt{g_{\text{min}}})^{n_b} \]  

(16)

The corresponding empirical coefficients \( C_b \) and \( n_b \) are 0.05 and 7.5, respectively.

The strain energy release rate is attributed to the dominant mode II strain energy release rate. The configuration of GLARE specimen with surface crack can be modeled to be the scenario of only middle layer cracked. Thus, the mode II strain energy release rate is expressed as

\[ g_{II} = \frac{\sigma_{fml}^2}{2n_iE_{AI}} \left[ \gamma^2(n_{AI} - 1) - \lambda^2 n_{AI} t_{AI} + \frac{E_{f,0}}{E_{AI}} n_{f,0} t_{f,0} (\gamma^2 - \lambda^2) + \frac{E_{f,90}}{E_{AI}} n_{f,90} t_{f,90} (\gamma^2 - \lambda^2) \right] \]  

(17)

,where \( n_i \) is the number of interfaces, and is equal to 2 for surface crack growth in this study.

\[ \gamma = \frac{t_{fml}}{(n_i-1)t_{AI} + \frac{E_{f,0}}{E_{AI}} n_{f,0} t_{f,0} + \frac{E_{f,90}}{E_{AI}} n_{f,90} t_{f,90}} \]  

(18)
\[ \lambda = \frac{t_{\text{fail}}}{n_{\text{Al}}t_{\text{Al}} + \frac{E_{f,0}}{E_{Al}} n_{f,0}t_{f,0} + \frac{E_{f,90}}{E_{Al}} n_{f,90}t_{f,90}} \]  

(19)

It should be noted that the secondary bending is not considered in equations above for delamination growth.

The predicted crack growth rates for the averaged lead cracks and non-lead cracks under different applied stress levels are plotted in figures 13 and 14 for specimens containing multiple through-thickness open holes. Since the averaged crack growth rates are similar between lead and non-lead cracks, only averaged lead cracks growth rate is compared to the prediction. The predicted crack growth rates for specimens containing multiple surface slits are plotted in figures 15 and 16. The predicted results under different maximum applied stress are in good agreement with the experimental results for the through-thickness specimens, though deviation exists in the predictions of surface-cracked specimens. The discrepancy might be from the secondary bending effect that would influence the stress states and the strain energy release rates in GLARE laminates with surface-cracked metal layer.

5. Conclusion

The fatigue crack growth behavior of GLARE3-3/2 laminates with multi-site damage has been investigated. In FMLs with multiple-site damage, the combination
of fiber bridging, load transferring, the toughness of the Al sheet, and secondary bending effect control the fatigue crack growth rate. The conclusions are

(1) In specimen with multiple through-thickness open holes, when fatigue cracks emanated from the open holes and propagated, the crack growth rate was faster with the presence of MSD cracks as compared to the case without the interaction of MSD cracks. Also, the propagating cracks tend to bypass each other and form an eye-shaped region before link-up.

(2) In specimens with multiple surface cracks, crack propagated and linked up directly instead of bypassing each other. The crack growth rate is slower than that in through-thickness specimens.

(3) The proposed methodology can be used to predict crack growth rates in fiber metal laminates with the presence of multi-site damage.

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References:


Table 1. Materials properties of Glare laminates

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<td>$E_y$ (GPa)</td>
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<td>$\sigma_{yy}$ (MPa)</td>
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<tr>
<td>$t$ (mm)</td>
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Figure 1. Bridging stress in FMLs and crack opening and closing profiles due to applied load and secondary bending moment.
Figure 2. Configuration of GLARE3-3/2 fatigue specimens (a) through thickness (b) part-through thickness.
Figure 3. MSD fatigue cracks propagation in through-thickness GLARE3-3/2 specimens at different sites. (A close look of crack bypass is shown on the left.)

Figure 4. MSD fatigue delamination pattern in the fiber/adhesive layer at different cracks for through-thickness GLARE3-3/2 laminates.
Figure 5. Comparison of crack propagation in through-thickness GLARE3-3/2 specimens. Top: Leading cracks with link-up. Bottom: Non-leading cracks
Figure 6. Average crack growth rate as a function of crack length for through-thickness GLARE3-3/2 laminates at the applied stress level of 120 MPa.

Figure 7. Average crack growth rate as a function of crack length for through-thickness GLARE3-3/2 laminates at the applied stress level of 100 MPa.
Figure 8. Crack propagation in surface-cracked GLARE3-3/2 specimens. Top:
Non-leading cracks. Bottom: Leading cracks and link-up (marked with an arrow)

Figure 9. Delamination growth in surface-cracked GLARE3-3/2 specimens. Top:
Non-leading surface delamination. Bottom: Leading surface delamination and link-up
Figure 10. MSD crack growth rate as a function of crack length at applied stress of 120 MPa for surface-cracked GLARE specimen.

Figure 11. MSD crack growth rate as a function of crack length at applied stress of 100 MPa for surface-cracked GLARE specimen.
Figure 12. A flow chart of crack growth prediction model.
Figure 13. Comparison of predicted averaged leading crack growth rates and experimental results as a function of crack length at applied stress of 120 MPa with applied stress ratio of 0.05 for through-thickness GLARE3-3/2.

Figure 14. Comparison of predicted averaged leading crack growth rates and experimental results as a function of crack length at applied stress of 100 MPa with applied stress ratio of 0.05 for through-thickness GLARE3-3/2.
Figure 15. Comparison of predicted averaged leading crack growth rates and experimental results as a function of crack length at applied stress of 120 MPa with applied stress ratio of 0.05 for GLARE3-3/2.

Figure 16. Comparison of predicted averaged leading crack growth rates and experimental results as a function of crack length at applied stress of 100 MPa with applied stress ratio of 0.05 for GLARE3-3/2.