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Characterizing the off-axis dependence of failure mechanism in notched fiber metal laminates

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ABSTRACT

Fiber metal laminates (FMLs) are usually more complicated in the failure aspect as compared to their constituents, especially when complex load is applied. In this paper, notched FMLs and the constituents, i.e., the aluminum and glass fiber reinforced plastic (GFRP) were subjected to off-axis tensile loading to evaluate the failure mechanism. Initial attention was paid on the off-axis dependence of mechanical responses, especially on its relation to the notch size. As expected, off-axis dependence of notched strength and notch sensitivity were closely related to the notch size, but different for GFRP laminates and FMLs due to their different damage behavior. Finite element model was employed to predict accurately the mechanical responses of FMLs, particularly for elucidating the damage mechanism. Failure of notched FMLs under off-axis loading was a combined transverse fracture and shear-off, while it was shear-dominated in notched GFRP laminates. Transverse fracture in aluminum appeared first, followed by the fiber breakage, which was postponed by the extensive subcritical damage. Thereafter, shear-failure in fiber and aluminum layers were encountered instantaneously at the descending part. Thus, the critical failure of off-axis notched FMLs was still tension-dominated as that in the on-axis case, but aluminum played the critical role.

1. Introduction

Fiber metal laminates (FMLs) are typical for hybrid technology in aeronautics, which consist of thin metal sheets and alternative bonded fiber reinforced plastic. Various FMLs have been explored by combining different kinds of the above two constituents [1–6]. The concept of FML was originally proposed for improving the fatigue resistance of metallic fuselage, based on the bridging effect introduced by fibers [7]. In addition, other outstanding performances have also been recognized, such as high strength and corrosion resistance benefit from composite layers [8], as well as the excellent resistance to impact and moisture that profit by metal sheets [9–11]. These advantages make FMLs more damage tolerant, and among them the glass fiber reinforced aluminum laminate (GLARE) has been successfully applied in the A380 aircraft, which is a major step in the quest for damage tolerance in aeronautics [12].

In view of the damage tolerance design concept, it is particular important to evaluate the ability of a structure to sustain damage during its service life. In addition to the foreign damages, some inevitable design features like rivet holes or even larger windows, doors and inspection holes can also constitute a risk to the structure components, since the presence of these blunt notches usually leads to undesired stress concentration and possibility of premature failure. A few experimental investigations on notched FMLs were carried out in open literatures, which mainly focused on revealing the influences of notch geometry [13,14], specimen width and notch size [15] and fiber-matrix adhesion [16] on notched strength. It has been concluded that the notched strength was more sensitive to the specimen width and notch size than to the notch geometry. A higher notched strength could be achieved by adopting a weak fiber-matrix adhesion, for which the fracture of fibers were postponed. Based on the experimental investigations, a few models were proposed to predict the notched strength of FMLs, such as the average [17] and point stress criteria [15], effective crack growth model (ECGM) [18], and the metal volume fraction approach [19]. Among them, the ECGM has considered the damage, whereas others usually depended on the pre-determined strength, which were more empirical. In addition, finite element analyses (FEA) were also performed on the notched FMLs [20–22], where the thermal residual stress was not considered, but in reality it can has some influences on the prediction accuracy of the notched strength.

Most of previous investigations on notched behavior of FMLs were limited to the axial loading condition, except the investigations by De

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Vries [23], Hagenbeek et al. [24], Bosker [25] and Kawai et al. [26], in which the effect of off-axis angle on notched strength was evaluated. Experimental investigation by De Vries [23] concluded that the notched strength of cross-ply FMLs decreased towards an off-axis angle of 45°. Bosker [25] proposed a model based on the Norris interactive failure criterion and MVF approach, which could well predict the notched strength of FMLs under arbitrary in-plane loading conditions, including the off-axis loading case. In addition to the off-axis dependence of notched strength, the effect of off-axis angle on notch sensitivities of FMLs was investigated by Kawai et al. [26]. Meanwhile, an anisotropic size effect law was derived based on the proposed multi-axial criterion, which could predict the effects of notch size and off-axis angle on notched strength of FMLs with a limited number of parameters. Investigation on off-axis dependence of notched behavior of FMLs will be of great significance, because the structure components in aircrafts may sustain complex loads, including the off-axis case. It should be noted that the state of art prediction methods [24–26] are sufficient in the engineering field, since the stress engineer requires only the methods to predict the notched strength. In consideration of the hybrid nature, the notched strength of FMLs will be dictated by both the metal and fiber layers, and their roles will be changed with the loading condition, which are closely related to their competitive damage evaluation behavior. Thus, in addition to the prediction methods for notched strength in engineering aspect, the failure mechanism and its off-axis dependence should be of the same importance. It is not only for the academic interest, i.e., how different will the hybrid FMLs behave under off-axis loading as compare to the constituents and how can it influence the mechanical responses, but also for the guidance of optimization design of FMLs. In other words, well understating of the off-axis dependence of failure mechanism in notched FMLs will provide information for effectively tailoring them to the requirements in off-axis loading scenarios.

The purpose of the present paper is to investigate the off-axis dependence of failure mechanism in notched FMLs. Tensile tests were conducted on FMLs with different notch sizes and off-axis angles, as well as on the constituents. Initial attention was paid on the different off-axis dependence of their mechanical properties, particularly on their relationships with the notch size. Based on the experimental results, finite element models (FEM) with incorporating the thermal residual stress effect were validated to predict effectively the mechanical responses. Then, with the aids of FEA and optical examinations of the etched specimens, the off-axis dependence of progressive damage process and failure sequence in notched FMLs were characterized to elucidated the detailed failure mechanisms.

2. Experimental procedures

2.1. Materials and specimens

FMLs in present study consist of 2024-T3 aluminum sheets and unidirectional S4C9-glass/SY-24-epoxy prepregs (AVIC Composite Corporation Ltd., China). This glass fiber prepreg has a fiber content of 74.7% by weight (approximately 59.6% by volume), whose properties provided by the supplier are listed in Table 1. In order to improve the bonding performance between aluminum sheets and prepregs, surface treatments on aluminum sheets were conducted by using the phosphoric acid anodizing method. Where four main steps were included: (1) manually degreasing with acetone; (2) alkaline cleaning with a mixture of sodium hydroxide (25–30 g/L) and sodium carbonate (25–30 g/L) solution for 1 min; (3) deoxidizing with nitric acid solution (300–500 g/L) for 5 min; (4) anodizing with phosphoric acid solution (120–140 g/L) under a DC voltage of 10 ± 1 V for 20 min. After drying of the anodized aluminum sheets, a D-12 epoxy primer (AVIC Composite Corporation Ltd., China) was sprayed on them. All FML panels have a symmetric 3/2 configuration, in which three aluminum layers and two GFRP layers were alternately laid up. Each GFRP layer consists two orthogonal plies. Thus, the configuration of FMLs can be given as [Al/0/90/Al/90/0/Al]. For GFRP laminates, the same stacking sequences as GFRP layers in FMLs were used. The stacked laminates were vacuumed in a vacuum bag, and then cured at 120 °C and 0.5 MPa for two hours in autoclave.

Table 1
Mechanical properties of unidirectional GFRP laminate.

Elastic parameters	Longitudinal stiffness E_1 (GPa)	54.6
	Transverse stiffness $E_2 = E_3$ (GPa)	10.5
	Shear stiffness $G_{12} = G_{13}$ (GPa)	5.5
	Shear stiffness G_{23} (GPa)	3.9
	Poisson's ratio ν_{12}	0.33
Strength parameters	Longitudinal tensile strength X_t (MPa)	1850
	Longitudinal compressive strength X_c (MPa)	1037
	Transverse tensile strength Y_t(MPa)	62.2
	Transverse compressive strength Y_c (MPa)	144
	Longitudinal shear strength S^L (MPa)	129
	Transverse shear strength S^T (MPa)	76.1

Specimens with dimensions of 250 mm in length and 25 mm in width were cut from FMLs, GFRP laminates and aluminum sheets using the water jet cutting method. In the present study, four different off-axis angles (0°, 15°, 30°, and 45°) were selected to investigate the off-axis effect, for consideration of the cross-ply configuration adopted in FMLs and GFRP laminates. For each off-axis condition, four different hole diameters were chosen (2.5 mm, 5.0 mm, 7.5 mm and 10.0 mm). It is noted that the larger holes were also machined by the water jet cutting method, and polished further. Whereas the holes with diameter of 2.5 mm were machined with the drill, because the machining accuracy of water jet cutting could not be effectively controlled for this case. Specimen geometry and dimensions are shown in Fig. 1. Gauge length and clamping region were 150 mm and 50 mm, respectively. Thickness of the FML specimen was 1.8 mm, which was calculated based on the thickness of aluminum sheet (0.4 mm) and GFRP prepreg (0.15 mm). The calculated thickness differed slightly from the measured values. Thickness of the GFRP laminate was also 1.8 mm approximately, in which twelve layers were stacked. Specimen coordinate system (x-y) and the principle directions ($1-2$) of the GFPR layers are also shown in Fig. 1.

2.2. Test methods

Quasi-static tensile tests were conducted on a 50 kN screw-driven testing machine INSTRON 5569. All specimen edges were polished before tests for eliminating the unexpected stress concentration. Tensile load along x-direction (Fig. 1) was increased at cross-head displacement control with a rate of 1.0 mm/min and the strain in the same direction was measured with the laser extensometer LE-05.

Post-failure specimens were chemically etched to remove the outer aluminum layers and the damage patterns were examined with Canon 700D camera. In addition, in order to investigate the damage process, specimens were loaded to some percentages (approximately 65%, 75%, 85%, 95% and 98%) of their ultimate strength, and then progressive damage behavior was characterized with employing the OLYMPUS stereo microscope. The adopted etching process was performed in sodium hydroxide solution with a concentration of 120 g/L and a temperature of 70 °C. Specimens after etching were ultrasonically cleaned in water to remove the impurities embedded in GFRP layers.

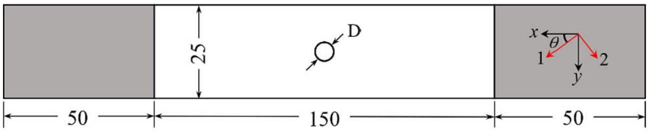

Fig. 1. Geometry and dimensions of specimen (dimensions in mm).

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