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Blunt notch strength of hybrid boron/glass/aluminum fiber metal laminates

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ABSTRACT

The notch strength of high modulus hybrid fiber/metal laminates (FMLs) was investigated. The composite layers used in this material, which contain both boron fibers and S2-glass fibers, were adhesively bonded to 2024-T3 aluminum sheets and consolidated using an autoclave process. The results of tensile tests clearly showed that high modulus FMLs with a good ductility can be achieved by mingling of boron and glass fibers. The effects of notch sizes and constituents on the failure behavior were determined. The experiments showed that the notched hybrid FMLs exhibited excellent strength retaining characteristics even with the presence of large notches. Microscopy, X-ray radiography and chemical removal technique were used to examine the fracture characteristics of hybrid FMLs. A finite element analysis (FEA) model was established to analyze the notch behavior of hybrid FMLs. Experimental results of the blunt-notch strength are in good agreement with the stresses calculated by computational modeling of hybrid FMLs.

1. Introduction

Fiber metal laminates (FML) are hybrid composites consisting of alternating thin layers of metal sheets adhesively bonded to fiber-reinforced epoxy prepreg. Glass fiber reinforced aluminum (GLARE) is one such material. It contains aluminum alloy and glass fibers and has been evaluated for many potential applications in aircraft structures [1]. Because GLARE embodies the advantages of both the metal and fiber components of the composite, it not only improve ultimate strength, fatigue properties and corrosion resistance when compared to monolithic aluminum alloys but also enhance the bearing strength, impact resistance and ductility when compared to conventional fiber-based composite laminates [2–5]. GLARE has been integrated into primary aircraft structure as the upper fuselage skin for the Airbus A380, where weight reduction and improved damage tolerance are crucial.

One of the more serious shortcomings of current-generation GLARE laminate is its low Young's modulus. As a result of the low tensile modulus of S2 glass fiber (86.9 GPa) used in GLARE, the resulting modulus of the fiber prepreg layer (containing 60% volume fraction of glass fibers) is only about 55 GPa. This is even lower than the Young's modulus of the aluminum alloy (72 GPa). Consequently, the Young's modulus of GLARE is inevitably lower than that of monolithic aluminum. A low Young's modulus may seriously affect the candidacy of GLARE laminates in aircraft structures, especially where the stiffness is a dominant design requirement.

Premature crack initiation is another critical shortcoming of GLARE. In previous research [6–8], GLARE has shown good fatigue resistance and a low crack propagation rate during fatigue tests due to the bridging effect. However, during the initial stage of cyclic loading, the significant load carried by the aluminum layer will be higher than the load carried by S2 glass/epoxy prepreg. The presence of high stress in the aluminum layer causes a short fatigue crack initiation life of GLARE [6]. In order to reduce the stress level in the aluminum layer and to retard the fatigue crack initiation of GLARE, it is necessary to increase the modulus of the composite layer [9,10].

2. Hybrid boron/glass/aluminum fiber metal laminates

Recently, a new generation hybrid fiber metal laminate with enhanced stiffness and improved crack initiation properties is developed as a solution to the aforementioned shortcomings of GLARE. These hybrid FMLs consist of aluminum layers and hybrid fiber prepregs that contain a mixture of glass and boron fibers. Boron fibers were used as a constituent of hybrid prepreg because of their high Young's modulus (400 GPa) in comparison with S2-glass fibers (86.9 GPa). The mechanical properties of boron fiber and glass fiber are listed in Table 1. Due to the high modulus of boron fibers, the overall modulus of hybrid FMLs can be improved and is higher than the conventional GLARE. In addition, the hybrid prepreg with a high Young's modulus with an improved load carrying ability incur the low stress level in aluminum layers. Thus, the

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Nomenclature

C_{11}	compressive failure stress along fiber direction (MPa)
C_{22}	compressive failure stress transverse to fiber direction (MPa)
C'	degraded stiffness matrix
D	diameter of circular notch on the sample (mm)
d_f	damage variable of fiber damage
d_m	damage variable of matrix damage
d_s	damage variable of shear damage
E	elastic modulus (GPa)
E_1	elastic modulus along *x* direction (GPa)
E_2	elastic modulus along *y* direction (GPa)
G	shear modulus (GPa)
S_{12}	axial failure shear stress (MPa)
S_{23}	transverse failure shear stress (MPa)
T_{11}	tensile failure stress along fiber direction (MPa)
T_{22}	tensile failure stress transverse to fiber direction (MPa)
t	thickness (mm)
W	width of sample (mm)

Greek letters

$\varepsilon_{failure}$	strain to failure
δ	current equivalent displacement in finite element analysis
δ_i	equivalent displacement at failure initiation in finite element analysis
δ_f	equivalent displacement when the materials completely degrades in finite element analysis
σ_0	ultimate strength of unnotched sample (MPa)
σ_{ij}	stress state in finite element analysis (MPa) (i, j = 1–3)
σ_n	ultimate strength of notched sample (MPa)
σ_{max}	ultimate strength (MPa)
$\sigma_{y,0.2\%}$	yielding stress (MPa)
ν_{12},ν_{21}	Poisson ratio

use of boron fibers not only increases the modulus of FMLs but also postpones the crack initiation and hinders the crack propagation during fatigue testing [9,10]. Moreover, due to the relatively large diameter and high modulus, boron fibers have outstanding compression properties [11] which enables this new designed hybrid FMLs to be used in the compression-dominant structure.

Some of the tensile properties and fatigue behaviors of hybrid FMLs are reported in previous work [9,10]. However, there is still a need to understand other important properties, such as the residual strength of a notched sample, compression strength, impact behavior and bearing strength. Since notches such as windows, doors, and rivet holes are necessary in an aircraft fuselage structure, the residual strength of a notched material is an important design parameter in engineering applications [1,4,5]. Several researches had been done on the notch behavior of various FMLs [12–14]. In this paper, we investigate the blunt-notch properties of notched hybrid FMLs and use finite element analysis to validate the experimental results.

Table 1
Mechanical properties of boron fiber and S2-glass fiber [20,21].

	Boron fiber	S2-glass fiber
Tensile strength	464 ksi (3200 MPa)	625 ksi (4300 MPa)
Tensile modulus	58 msi (400 GPa)	12.6 msi (86.9 GPa)
Diameter	~100 μm	~10 μm
Density	2.6 g/cm^3	2.49 g/cm^3
Strain to failure	0.8–0.9%	5%

3. Experimental details

Two different types of hybrid FMLs were fabricated for this research. Metal layers used in both hybrid FMLs were Aluminum 2024-T3 alloy sheets. The composite layers in type I hybrid FMLs were one layer of 0° boron fiber/epoxy prepreg sandwiched between two layers of 0° S2-glass fiber/epoxy prepregs. The layup sequence of type I hybrid FMLs was [Al/0,S2/0,B/0,S2/Al]. On the other hand, the composite layers in type II hybrid FMLs were three layers of unidirectional commingled hybrid fiber prepregs which contained 100 boron fibers per inch on a glass fiber prepreg of 60% fiber volume fraction. The stacking layup of type II hybrid FML was [Al/0,B-S2/0,B-S2/0,B-S2/Al].

The S2 glass fibers and boron fibers used in hybrid prepreg tapes were approximately 10 μm and 100 μm, respectively. The epoxy used in this hybrid prepreg is Cytec CYCOM 381 epoxy resin. The boron fibers were inserted into glass fiber prepreg to a density of 100 fibers per inch, using a proprietary process. The fabrication process of hybrid prepreg tapes were carried out by Specialty Materials, Inc. The hybrid prepreg tapes were then placed in between aluminum sheets and cured in autoclave. The schematic figures of stacking sequence of type I and type II hybrid FMLs are shown in Fig. 1(a) and (b), respectively. Table 2 shows the mechanical properties of the constituents of hybrid FMLs used in this study.

The nominal thickness of an aluminum layer and a single layer of fiber prepreg is 0.4 mm and 0.13 mm, respectively. Both type I and type II hybrid FMLs were consolidated using an autoclave curing process. Images of the cross-section views of both hybrid FMLs are shown in Fig. 2(a) and (b). Fig. 2(c) shows that boron fiber was well commingled with S2-glass fibers. The volume fraction of boron fibers of various types of FMLs after curing process can be determined by cross-section view shown in Fig. 2. The boron fibers volume fraction in cured type I and type II hybrid prepregs are about 6% and 18%, respectively.

All the specimens were cut from 305 mm × 305 mm hybrid FML panels. The unnotched samples used for tensile tests were 152 mm in length and 25 mm in width. To determine the effect of boron fibers on the stress–strain curve of tensile tests, two GLARE 2-2/1 samples, five type I hybrid FMLs samples, and five type II hybrid FMLs samples were prepared and tested. The GLARE 2-2/1 samples contain two layers of 0.4 mm aluminum alloy and three layers of 0.13 mm unidirectional S2-glass fiber/epoxy prepregs. Foil resistance strain gauges with a length of 6.35 mm (0.25 in.) was attached at middle of the unnotched sample to measure the strain response during tests. Then, the stress–strain curve of GLARE 2 sample was used as the baseline to which hybrid FMLs would be compared.

The notched samples used in this research were 152 mm in length, and 38 mm in width. The open-hole notches were prepared through the center of the specimen using carbide-tipped drill bits. In this research, the blunt notch tests were repeated multiple times on type I and type II FMLs with various notch diameters equals to 1/8, 1/4 and 1/2 in. Sixteen blunt notch tests were performed in total and average ultimate stresses are listed in Table 3.

In order to avoid the residual stress and delamination around notch, a starter hole with smaller diameter was first machined and then carefully enlarged to the required size. Foil resistance strain gauges with a length of 6.5 mm (0.25 in.) were attached alongside the notches. The aluminum alloy tabs were attached on both ends of all the specimens by aluminum putty adhesive. The geometries of samples are shown in Fig. 3.

Static tensile tests were performed using a 22kips servo-hydraulic Instron test frame with a cross-head speed of 0.05 in./min. All the specimens were loaded along the longitudinal direction.