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Interlaminar failure behavior of GLARE laminates under short-beam three-point-bending load

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In this paper, interlaminar failure behavior of GLARE-3/2-0.3 laminates under short-beam three-point-bending load were investigated with various span length-to-specimen thickness ratios (L/h). Failure modes and damage characteristics at different loading stages were observed by Scanning Electron Microscopy (SEM) to assess the failure behavior. It was found that failure modes changed accordingly with varying L/h ratios. A valid shear dominant failure mode was obtained at the L/h ratio of 8. Moreover, there were significant differences in failure modes and damage characteristics among three GLARE variants. The results also showed that lay-up configuration of glass/epoxy layer strongly affected load-deflection response, especially the failure load, and corresponding failure mode.

1. Introduction

GLARE is a member of the family of Fiber Metal Laminates (FMLs) consisting of alternating layers of thin aluminum metal sheets and glass/epoxy composites in between [1–4]. GLARE materials are commercialized in six different standard grades. During fabrication of laminates, the glass/epoxy layers are stacked in different fiber orientations between aluminum alloy sheets, resulting in different standard GLARE grades [2]. GLARE laminates have been applied to the aircraft structures, like fuselage and wing leading edges, owing to excellent fatigue, impact and damage tolerance as well as a weight-saving capability [5–8]. As a kind of hybrid laminated composite, GLARE has a complex multi-interface system including the interfaces of metal sheet-matrix, fiber-matrix and fiber-metal sheet, etc. However, these interfaces at different layers of GLARE are sensitive to interfacial debonding by shear load due to bending or torsion [9]. Delamination is one of the most critical failure mechanisms of laminated composites [10]. Further propagations of local debonding result in a failure of the structure during service in aircraft structures [11]. Obviously, characterizing the interlaminar shear failure resistance of GLARE with the reliable method is essential. Practically, a relatively accurate assessment of interlaminar shear failure resistance provides some information of quality control and material screening.

The interlaminar shear failure resistance is referred to as the interlaminar shear strength (ILSS). Many shear tests have been developed for the estimation of the ILSS of composite materials [10,12]. These shear tests methods have also been employed extensively to measure the interlaminar shear strength of FMLs in previous studies. Hinz et al. conducted a double-notch shear test (DNS) to investigate interlaminate shear properties [13]. For the double-notch shear test, however, a compression load is applied on both end of the specimen, and the buckling of specimen is easy to occur during loading process. In addition, the mean of three-point bending was also reported for investigation of ILSS of FMLs [14,15]. The last test method for determining shear strength of FMLs is a short-beam test. Park et al. performed a short-beam test to evaluate the extent of hydrothermal degradations as a function of water absorption and thermal cycles [16] and Botelho et al. also determined the ILSS of FMLs by using the same test [17].

The short-beam shear test is the chief method for determining the interlaminar shear strength of GLARE laminates [11,18,19], since this method is characterized by simplicity and feasibility. At present, the standard short-beam shear test method is the ASTM standard D2344 for high-modulus fiber-reinforced composite materials [20]. The standard method recommends that the span-to-thickness ratio of short-beam specimen be 4 to 5 and the test yield apparent interlaminar shear strength [20]. When adopted for short-beam three-point-bending of GLARE, a relatively small span-to-thickness (L/h) ratio as recommended by ASTM D2344 may

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cause a local buckling due to lower shear strength and possibly local waviness in laminated composite layers. However, experimentally sound failure observation to corroborate the selection of appropriate L/h ratio for GLARE has not been proposed.

In reality, apparent interlaminar shear strength of short-beam shear test depends on span-to-thickness ratios [21]. Testing GLARE with short-beam three-point-bending method is also limited to the selection of the span-to-thickness ratio. It is necessary, therefore, to know the reliable L/h ratio for determining apparent ILSS of GLARE. In the present paper, three GLARE-3/2-0.3 variants were utilized to conduct a detailed study of the influence of the lay-up configuration on the interlaminar shear failure behavior, especially the selection of L/h ratio, under short-beam three-point-bending load. Failure modes for varying span-to-thickness ratios were evaluated to determine the reliable L/h ratio for the short-beam shear test of GLARE. The failure mechanism of different failure modes was also studied.

2. Experimental

2.1. Materials preparation

GLARE laminates used in this experiment are composed of alternating three layers of high strength aluminum alloy sheets (2024-T3, 0.3 mm thickness per sheet) and two S4-glass/epoxy composites (consisting of two unidirectional prepregs with a nominal thickness of 0.125 mm), which can be called GLARE-3/2-0.3 [22] (Fig. 1(a)). Three representative laminates were prepared: GLARE 2A-0/0-0.3, GLARE 3-0/90-0.3 and GLARE 6-±45-0.3. Actually, three different variants possess their own characteristics for aircraft structures. GLARE 2A exhibits good tensile strength in the direction of the fiber/resin layer, which is suited for locations where the load is mainly in the longitudinal direction. GLARE 3 is defined for the most upper part of the fuselage where loading ratio is one, due to the combination of pressure loads and the bending of the fuselage under its own weight [22]. GLARE 6 stacked at +45° and −45° is characterized by good shear and off-axis properties.

All aluminum alloy sheets were treated prior to the autoclave cure, including degreasing with acetone, alkali cleaning-acid cleaning and anodizing in a phosphoric acid electrolyte [23]. Then, the surface was treated with an epoxy based primer in order to prevent further oxidation by air, which could also enhance the durability of the bond between glass/epoxy layers and aluminum alloy sheets. After lay-up process, these stacks were put into a vacuum bag and cured in an autoclave under controlled temperature and pressure conditions, as this fabrication process could minimize the void content [24]. Fig. 1(b) is the hot-pressing curve for curing the laminates.

The specimen size was 20 mm × 10 mm (length × width), where the specimen size depended on our previous work. Five specimens were prepared for each case. Moreover, specimens were machined with a carbide end mill from the finished laminates to obtain a better finished surface, especially not allowing any interfacial debonding through the cross-sections.

2.2. Experiment procedures

According to classical beam theories, the specimen subjected to three-point-bending load undertakes shear force and tension-compression stress within the beam. A shear dominant failure occurs in short-beam test with the lower span-to-thickness ratios. The apparent ILSS of the three-point shear test of GLARE laminates is given by the following equation:

$$\tau = \frac{3F}{4bh} \tag{1}$$

where F is the first peak load in the short-beam three-point-bending test, b and h is the average measured width and thickness of the specimen, respectively.

Fig. 2 depicts a general arrangement of the short-beam three-point-bending test. The specimen is supported by two supports that can be adjusted to different L/h ratios with rounded tips of 2 mm radius, and loaded by a loading nose of radius 3 mm which is located above the specimen at the center of the span. In the experiment, the nose moved with a rate of 1 mm/min. The deflection and load value were obtained by using the recording devices of the testing machine when the preliminary contact force was about 5 N without any deformation of the specimen.

Span-to-thickness ratios (L/h ratios) varying from 5 to 12 were

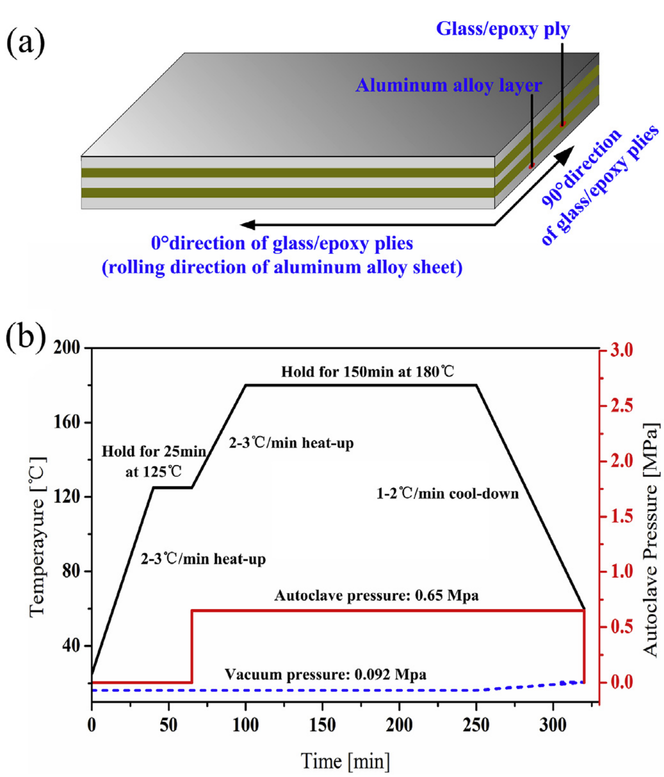

Fig. 1. (a) Schematic view of the construction of GLARE-3/2 laminate, (b) the hot-pressing curve.

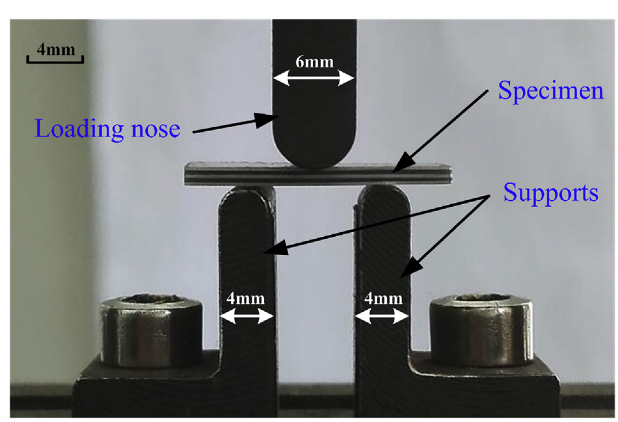

Fig. 2. The apparatus for the short-beam three-point-bending test.