



Interlaminar failure behavior of GLARE laminates under double beam five-point-bending load

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ABSTRACT

GLARE laminates were prepared in this work to characterize their interlaminar shear failure behavior by Double Beam Shear (DBS) method. The effect of span-to-thickness ratio (L/h ratio) and lay-up configuration on the interlaminar failure feature of the laminates was investigated respectively. The results indicated that the failure mode in DBS method was single interlaminar shear delamination due to the existence of pure shear stress points. Furthermore, the apparent interlaminar shear strength (ILSS) values measured by DBS method were higher than those of Short-beam Shear (SBS) method, which were closer to the true value. However, the two methods did not show exclusiveness.

1. Introduction

GLARE, consisting of alternative layers of thin aluminum alloy layers and glass/epoxy composites layers [1], has found its important application in aeronautics industry due to excellent fatigue, impact and damage tolerance. However, debonding and delamination may develop between fiber/epoxy and metal layers in the case of bending load or torsion, representing the typical failure modes of Fiber Metal Laminates (FMLs) [2–5]. Apparently, an appropriate evaluation method for interlaminar shear resistance plays a key role in the quality control of FMLs [6]. Researchers mainly used Short-beam Shear (SBS) method (ASTM-D2344) to measure the interlaminar shear behavior of GLARE laminates [7–9] because a standard test method to estimate the interlaminar shear properties of GLARE has not been established [10–12]. However, the span-to-thickness ratio (L/h ratio) of 4 or 5 is usually chosen according to ASTM-D2344 [13], which is inappropriate for GLARE laminates. The main reason is that the SBS method is only applicable to the high-modulus fiber-reinforced composite materials [14,15]. Thus, we have already investigated the interlaminar failure behavior of GLARE-3/2-0.3 laminates under short-beam three-point-bending load, and found that specimens with L/h ratio of 8 yielded a relatively accurate interlaminar shear strength value [16].

Theoretically speaking, the interlaminar shear strength value of GLARE obtained by SBS method is smaller than true value due to the unavoidable influence of bending stress. Aimed at finding a more

reliable method to evaluate the interlaminar shear resistance of GLARE, the Double Beam Shear (DBS) method could be introduced. G. Zhou et al. from Loughborough University conducted DBS method to characterize the apparent interlaminar shear properties of resin matrix composites [17]. They found that the DBS method guaranteed interlaminar shear failure between two pure shear points by promoting the dominance of interlaminar shear strength (ILSS). Unlike the homogeneous resin matrix composites, GLARE laminates possess multiple interfaces, including the interfaces between aluminum alloy sheet and matrix, fiber and matrix, composite and aluminum alloy sheet [18]. Consequently, the fixture for evaluation of interlaminar shear behavior should be designed and the key parameters (L/h ratio and lay-up configuration) should be considered.

In this paper, failure mode was evaluated to determine the effective interlaminar shear failure for GLARE laminates under double beam five-point-bending load. The influence of the L/h ratio and the lay-up configuration on the interlaminar shear failure behavior and mechanisms under DBS method were investigated. Finally, the respective failure characteristics and apparent interlaminar shear strength of GLARE laminates under DBS and SBS methods were compared.

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Table 1
The fundamental performance of the Aluminum alloy (2024-T3).

Thickness (mm)	Elasticity modulus (GPa)	Coefficient of thermal expansion (°C)	Yield strength (MPa)	Tensile strength (MPa)
0.3	73.1	22.68×10^{-6}	305	455

2. Experimental

2.1. Materials preparation

The Aluminum alloy plates was 0.3 mm thick layers (2024-T3) supported by Southwest Aluminum (Group) Co., Ltd, and the fundamental performance of the Aluminum alloy plates is given in Table 1. Moreover, the surface treatment of the aluminum layers was conducted to achieve a better bonding with the fiber reinforced composites. The phosphoric acid anodizing (H_3PO_4 140 g/L, 25 °C, 10 V, 20 min) was adopted to construct a rough surface. The high strength glass fiber (HS4) was provided by Nanjing Glass Fiber Research Institute and the high temperature epoxy resin (E302-2) was provided by Sichuan Xinwanxing Carbon Fiber Composites Co., Ltd, and the fundamental performance of the S4-glass/epoxy composites is listed in Table 2. Aluminum alloy plates with a thickness of 0.3 mm, S4-glass/epoxy composites consisting of two unidirectional prepregs with a nominal thickness of 0.125 mm were used in constituent materials of alleged GLARE-3/2-0.3 [19]. Four kinds of laminates were prepared as follows: GLARE 2A-0/0-0.3, GLARE 3-0/90-0.3, GLARE 4A-0/90/0-0.3 and GLARE 6- $\pm$ 45-0.3. Specimens with dimensions of 40 mm $\times$ 10 mm were cut from the massive FMLs by using wire electrical discharge machining (WEDM) technique. Additionally, to achieve a better polished surface, all specimens were processed by carbide end milling cutter [20]. Each group contained five qualified specimens without interfacial debonding.

2.2. Experiment procedures

Double Beam Shear method is not the standard method for interlaminar shear test of composite materials, and the corresponding fixture cannot be acquired directly. Therefore, the five-point-bending fixture was designed for DBS method as shown in Fig. 1(a) and the dimensions of the indenter are illustrated in Fig. 1(b). The material chosen for fixture is Cr12MoV, which is widely utilized in the production of standard tools and gauges. Convenient to adjust the indenters and the holders, the rail type is designed for the precise control of L/h ratio.

Fig. 2(a) shows that the double beam five-point-bending test is conducted in a beam specimen of rectangular cross section symmetrically supported by three holders and loaded by two indenters, which the distance (L) between the two holders is equal to the indenter span. The five-point-bending test is named as DBS method since two short beams are formed by three equidistant holders. It also needs to choose the appropriate span-to-thickness ratio, so that the effective interlaminar shear failure occurs when the specimen is subjected to a small bending disturbance [21]. The existence of two pure shear points in the beam specimen can assure pure shear stress under double beam five-point-bending load [22], as indicated in Fig. 2(b). In addition, the loading rate of the experiment is 1 mm/min. According to DBS method theory for homogeneous material [23], the interlaminar shear strength is given by

Table 2
The fundamental performance of the S4-glass/epoxy composites.

Surface Density (g/cm ³)	Resin content (wt%)	Thickness (mm)	Width (mm)
170 $\pm$ 5	30 $\pm$ 2	0.125 $\pm$ 0.05	1000

$$\tau = \frac{33P}{64bt} \quad (1)$$

where P represent the load in response to the occurrence of delamination, b and t denote the average measuring width and thickness of the specimen, respectively.

Indeed, the Eq. (1) is based on the assumption that the interlaminar shear failure occurs at the centreplane when the shear stress reaches the maximum. However, the centreplane for GLARE laminates is the aluminum layer and its shear strength is larger than that between the aluminum sheets and GF/EP layer. We still used the formula applied for homogeneous material due to the following reasons.

Firstly, according to our experimental results below, the debonding is near the centreplane instead of the other interface between aluminum sheets and GF/EP layer. The error is quite limited in this situation. Secondly, the values deflection of ILSS also exists in this kind of material, including fiber composite material, because the bending stress is unavoidable. It is the reason that interlaminar shear strength obtained by these methods is still called the apparent ILSS. Actually, the newly developed DBS method is less affected by bending stress than the traditional SBS method. In this way, the relatively more accurate results could be obtained. Thirdly, the stacking structure of all the GLARE laminates analyzed in this work was 3/2 configuration. There are some additional structures in GLARE, like 4/3, 5/4, etc. We intended to seek a relatively reasonable evaluation methodology that could be widely used in fiber mental laminates. For the sake of the unity of the formula, we referred to the formula for calculating the ILSS of homogeneous material.

3. Failure behavior and mechanisms

3.1. Failure mode and mechanisms

Compared to the multiple failure mode of GLARE laminates in SBS method, it is single expression of interlaminar shear delamination in DBS method. In Fig. 3, the specimens on both sides have no evident shear failure. Near the neutral layer, between the two indenters and intermediate holder, effective interlaminar shear failure at the interface of aluminum alloy and composite layer occurs in four kinds of GLARE. The reason is that the large residual stress caused by the difference in the coefficient of expansion exists in the interface, where is prone to generate failure [24]. However, the existence of pure shear stress points weakens the influence of bending stress on failure behavior, which causes the specimens to fail under the small displacement. Namely, the whole shear failure process is completed near the elastic section, and no large local compression deformation occurs.

As can be seen clearly from the Fig. 4, the typical failure process of GLARE-3/2 under DBS method present two-stage failure, which could be divided into four parts. The first part is an elastic section, and the GLARE specimen shows an elastic deformation at this stage, that is, after unloading the applied load, the sample can be completely recovered without any failure. Before the peak load occurs, the yield of aluminum sheets causes the sample enter the plastic deformation stage. Due to the excellent interfacial bonding of the GLARE laminates, the bonding effect between glass fiber reinforced composite layer and aluminum alloy layer continues to maintain good adhesion, and the specimen does not show any failure. Because of the interfacial debonding, the curve indicates a sharp decline when the applied load reaches the maximum and at this point, the calculated ILSS is the apparent interlaminar shear strength. Subsequently, the applied load increases at a relatively small slope until the end of the debonding failure to further overcome the interfacial cohesion. In the last stage, the laminates were in bending deformed state after the failure subjected to the transverse shear stress completion.

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