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A comparative study of the pin-bearing responses of two glass-based fibre metal laminates

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ABSTRACT

The pin-bearing behaviour of two commercially available glass-based fibre metal laminates (FMLs), GLARE® 2 and GLARE® 3, is presented. Results shown include bearing stress, strain, stiffness and strength, surface strains in the vicinity of the hole, and damage progression using microscopy. The initial stiffness, the bearing strain at which non-linearity first occurs and the initial rate of stiffness loss were similar for both materials, indicating that the initial bearing behaviour of these FMLs is dominated by the metal layers. Microscopy results provided experimental evidence that delamination first occurs in FMLs as a result of interlaminar normal stresses from pin loading and not because of buckling of the metal layers. Final failure for both materials involved complete separation of layers caused by out of plane deformation. The ultimate bearing stress and strain were significantly higher for GLARE® 2 than for GLARE® 3, which the micrographs indicate is due to the higher bending stiffness of the reinforcing layers in GLARE® 2, which delays out of plane deformation during the final failure sequence. Measurements of surface strains showed similar initial behaviour for both materials, in agreement with the analysis of the bearing stress–strain curves, and provided additional insight into the final failure sequence of the two materials.

1. Introduction

Fibre metal laminates (FMLs) are a family of advanced aerospace materials that consist of alternating layers of metal and fibre-reinforced plastic. FMLs originated at Fokker/TU Delft in the Netherlands in the 1970s and since then have undergone extensive development [1–4]. Early FMLs, known as ARALL, were based on Aramid fibres while more recent versions, known as GLARE®, utilise high strength S2-glass fibres. The works of Vlot et al. [1] and Gunnink et al. [2] provide comprehensive reviews of the development of these materials.

FMLs boast a large number of favourable characteristics, such as excellent fatigue performance, high residual and blunt notch strengths and low density [1]. In addition, their burn-through resistance is superior to that of aluminium alloys [3] and they have good corrosion resistance (since corrosion stops at the prepreg layers [5]). The tensile strength of GLARE® increases with increasing strain rate [6], and it has performed well under high-velocity impacts such as those due to bird strikes on aircraft [7,8]. Another beneficial feature of FMLs is that the number and orientation of the prepreg layers can be varied to best suit different applications and a number of variants are commercially available. Such characteristics make these materials attractive for structural applications, particularly in the aerospace industry. For example, GLARE® has found extensive application on the Airbus A380, with approximately 380 m^2 of the material used in the upper fuselage skin [9].

The focus of this paper is on the in-service behaviour of FMLs, specifically in jointed configurations. Such an investigation is warranted since bolted and riveted joints represent potential weak points in a structure, and their efficient design is therefore critical to the load-carrying capability and weight of the structure.

Previous work by Wu and Slagter [10] on the bearing strength of jointed FMLs showed that lateral constraint (in the form of washers and bolt torquing) could increase bearing strength by more than 20%, since it restrains delamination growth. The pin-bearing strength of a FML, which involves no lateral support, was investigated by Van Rooijen [11], who argued this case is important for design purposes since it is impossible to obtain full lateral restraint with all in-service joints. Slagter [12] discusses the mechanisms behind pin-bearing failure of FMLs. The author postulates that an area of delamination forms in the laminate and when this reaches a critical size, the aluminium layers buckle and cause joint failure. It is assumed that the initial formation of delamination is due to normal interlaminar stresses at the hole edge induced by the pin loading and occurs prior to any buckling. The author references a three-dimensional numerical analysis of Marshall et al. [13] as evidence for this theory since the results show the motion of the pin causes tensile interlaminar normal stresses at the hole edge. He also presents some experimental evidence in the form of a FML sample that was tested to a point just before failure. The outer aluminium layer was etched away, revealing an area of delamination

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in the prepreg layer. Caprino et al. [14] also provided some experimental evidence by presenting an optical micrograph showing extensive delamination between the glass and metal layers of a fully failed pin-loaded FML. Krimbalis et al. [15] showed analytically that the stress needed to buckle the glass prepreg layers in GLARE® is small compared to that of the aluminium and concluded that the contribution of the glass layers to the overall bearing strength of the laminate is negligible.

The damage mechanisms occurring in joints involving conventional composites can be significantly influenced by a change in layup. Similar differences may occur for FMLs and an understanding of this effect is therefore needed for design considerations. Hence, this paper examines the effect of layup on the bearing behaviour of jointed FMLs. Two commercially available variants are considered, one having a cross ply (0/90) layup of the prepreg layers and the other having unidirectional (0/0) glass fibre layers. Results presented include bearing stress, strain, stiffness and strength, surface strains in the vicinity of the hole and damage progression using microscopy. The results from the present work are currently being used by the authors in the development of a damage model for FML joints.

2. Experimental methods

The specimen geometry and loading are shown in Fig. 1a, while a schematic of the experimental set-up is shown in Fig. 1b. The pin-bearing test set-up, as used here, is generally considered to represent a worst case scenario for in-service conditions since out of plane deformation is unconstrained leading to lower joint strengths. A 6 mm neat-fit hardened steel pin was inserted into the hole and then loaded under displacement control via a specially designed testing frame. The deflection of the pin was measured using two Epsilon displacement gauges, the results from which were averaged to determine the pin displacement. The measured displacements were relayed to a Measurements Group System 6000 data acquisition module and recorded.

The two laminates chosen for the present study were GLARE® 3 3/2 0.4L and GLARE® 2 3/2 0.4L. Both materials consisted of three layers of 0.4 mm thick 2024 aluminium alloy and four layers of 0.125 mm thick glass fibre-reinforced prepreg (S2-glass fibres and FM 94 resin). The layups of the two material systems were [AL/0/90/AL/90/0/AL] for GLARE® 3 and [AL/0/0/AL/0/0/AL] for GLARE® 2 (where AL represents an aluminium layer and 0 and 90 refer to the orientation of the prepreg layers, with respect to the loading direction). As can be seen the two material systems differed only in that GLARE® 3 has a crossply (0/90) configuration while GLARE® 2 contains unidirectional (0/0) glass fibre layers. The total thickness measured for both laminates was approximately 1.8 mm.

Bearing failure was the only failure mode considered. This failure mode is defined as local crushing of the material adjacent to the hole and normally occurs when the width to hole diameter ratio (w/d) and the edge-distance to hole diameter ratio (e/d) are large. Based on previous work on composites [16] and FMLs [10] values of $w/d = 6$ and $e/d = 6$ were used to ensure bearing failure was achieved.

The samples were prepared by cutting the laminates oversize using a dedicated composite cutting machine with a diamond coated blade and then machining to final specification using a computer aided precision milling machine with carbide cutters, thus ensuring high quality edges and geometric accuracy. All joints had a nominal length $L = 135$ mm and all holes were drilled undersize using a standard tungsten carbide drill bit and then reamed to a final diameter of 6 mm using a straight edged reamer.

For both materials, five repeats of tests to failure were carried out. To investigate the progression of damage, further samples were tested to certain distinct points on the bearing stress–strain curves. The specimens were then sectioned at a specific plane within the laminate (see Fig. 1c) and examined using a scanning electron microscope (SEM). The planes were marked prior to testing and then exposed using a diamond coated wafering blade. The sectioned material was mounted and cast in epoxy resin, and finished by grinding with watered silicon carbide paper and polishing with diamond suspension fluid.

Finally, on further specimens, strain gauges were used to investigate surface strains. Three-element gauges with gauge lengths of 2 mm were arranged around the hole as shown in Fig. 1d. The gauges on the rosette were orientated along the loading direction, transverse to the load and at 45° to the load.

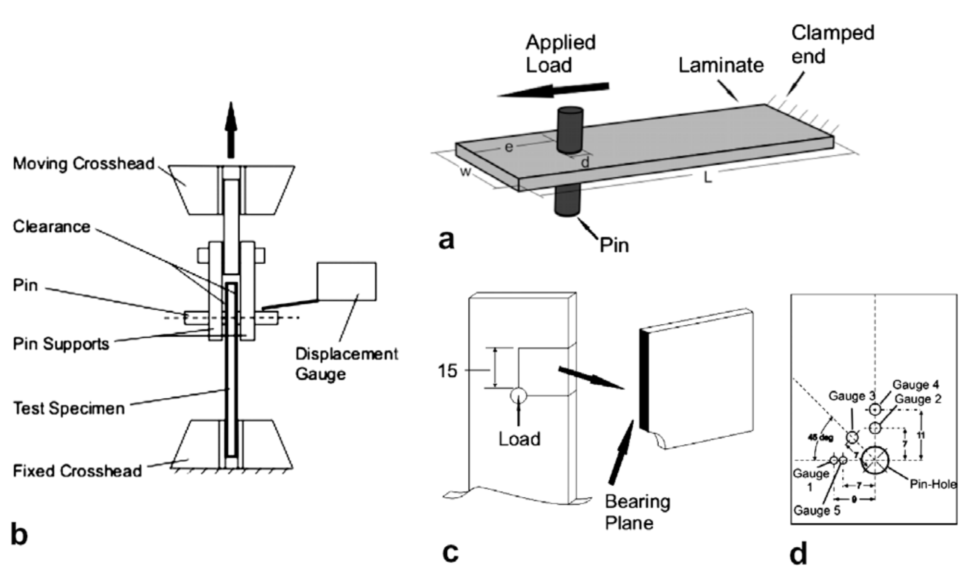

Fig. 1. (a) Pin-bearing test configuration and typical joint geometry. (b) Schematic showing salient features of the experimental set-up. (c) Plane of interest examined during SEM. (d) Location of strain gauges used to investigate surface strains. All dimensions in mm.