BEARING FAILURE OF PSEUDO-DUCTILE THIN PLY ANGLE-PLY LAMINATES

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Abstract

The aim of this work is to investigate the bearing failure of mechanically fastened joints between thin-ply angle-ply laminates with central 0° plies. To achieve this, pseudo-ductile laminates with two different layups $[\pm26_6/0]_{s2}$ and $[\pm25_2/0]_{s4}$ were loaded in a double shear-lap bolted joint configuration in tension. The major focuses of the experiments were to investigate the bearing strength and compare the bearing behaviour between pseudo-ductile laminates with different layups. Constant clamping pressure, edge distance-to-diameter ratio and width-to-diameter ratio were selected across the tests. Although gradual failure was exhibited in both layups, the $[\pm26_6/0]_{s2}$ laminate has shown a higher bearing strength and larger deformation at the hole edge compared to the $[\pm25_2/0]_{s4}$ laminate. The damage mechanisms of both layups were also similar, in the sequence of compressive damage at the hole edge, splitting in angle plies, tensile fracture and tear-out failure.

1. Introduction

Carbon fibre reinforced plastic composites (CFRPs) have gained much interest in recent years due to their outstanding mechanical properties, but their usage is often limited by their sudden and catastrophic failure. To address the limitation, pseudo-ductile thin ply angle-ply laminates with central 0° plies have been developed and gradual failure has been successfully demonstrated in these laminates in tension [1–4]. For example, a $[\pm26_5/0]_s$ laminate made from Skyflex thin ply prepregs with TR30 carbon fibre has shown a metal-like stress-strain response and has produced an additional pseudo-ductile strain over and above the elastic strain of 2.2% [3]. Pseudo-ductility has also been found in thin ply angle-ply laminates with different grades of carbon fibre prepregs and layups to meet the requirements for different potential applications [3,4]. The basics for achieving the metal-like behavior in these laminates are the same - combining the additional strain from fibre reorientation of thin angle plies, with the fibre fragmentation in the central 0° plies and localised dispersed delamination at the $0/-\theta$ interfaces.

To promote these pseudo-ductile laminates towards future applications, they have been investigated under different loading cases including open-hole tension, cyclic loading and unnotched compression [4–6]. In these tests, the laminates have shown different responses and damage mechanisms compared to conventional carbon fibre laminates. Another crucial but more complex loading case is mechanical fastenening, which is a common method to join composite structures together in many applications. As it involves the presence of the hole and interaction between the laminate and fastener, the load carrying ability of the laminate has been found to be reduced significantly due to damage initiation and accumulation within the laminate from the early stage of loading. Previous studies on jointed composites have shown that the damage modes and bearing strength can be influenced by the configuration of laminates and the design of the joints [7–9]. For example, an insufficient hole edge distance-to-diameter ratio or width-to-diameter ratio can lead to shear-out failure or net-tension failure, which can lower bearing strength and result in catastropic failure. In bearing loading, the damage may be initiated by shear cracks induced by the compressive force from the fastener at the hole edge, and then followed by fibre kinking in the 0° plies and unstable delamination growth. Matrix cracks and delamination are suppressed in the pseudo-ductile thin ply angle-ply laminates, and they have shown different damage mechanisms in compression, therefore the bearing performance of these laminates is worth to be understood.

The aim of this paper is to investigate the bearing strength of thin-ply angle-ply laminates with central 0° plies, as well as to characterise the damage mechanism of these laminates and compare the bearing responses between pseudo-ductile laminates with different fibres and layups.

2. Design and experimental procedures

Laminates with two layups - IM-HM $[\pm 25_2/0]_{s4}$ and SM-SM $[\pm 26_6/0]_{s2}$ have been selected, which have both demonstrated pseudo-ductility in tension according to previous studies [4]. In these two layups, the IM denotes the Skyflex UIN020 prepreg with intermediate modulus MR60 fibres, the HM denotes the North Thin Ply Technology prepreg with high modulus YSH70A fibres and SM denotes the Skyflex USN020 prepreg with standard modulus TC35 fibres. All Skyflex prepreg features the K50 semi-toughened epoxy resin and the NTPT prepreg uses 120 EPHTg-402 type epoxy resin. All prepregs were suggested to have a cure temperature of 120 ^{o}C. The mechanical properties of the cured prepregs are shown in Table 1.

Table 1. The cured ply properties of all three prepregs.

Prepreg Type	E_1 (GPa)	E_2 (GPa)	σ_1 (MPa)	G_{12} (GPa)	υ_{12}	ε_1 (%)	t (mm)	v_f (%)
Skyflex USN020A (TC35 fibre)	110	6.2	1780	3.0	0.32	1.6	0.027	52
Skyflex UIN020A (MR60 fibre)	146	6.6	2800	2.97	0.29	1.9	0.028	50
YSH70A/epoxy (YSH70A fibre)	362	6.0	1810	4.00	0.30	0.5	0.032	50

The two laminates mentioned above were then mounted in a double shear-lap bolted joint test fixture with a single hole diameter of 3.175mm and the entire assembly was loaded in tension in a Instron universal testing machine. Figure 1(a) presents a schematic of the testing fixture. As seen from Figure 1(a), the specimen was sandwiched between two halves of steel cylindrical blocks to provide the lateral support to the specimen during loading. As the bearing strength increases with the amount of lateral support, “finger-tight” clamping force was used in this study. Figure 1(b) presents the specimen geometry and dimensions. In order to promote a more gradual failure in the composite bolted joint, a bearing failure mode is desired. An insufficient width-to-diameter ratio (w/d) can lead to net-tension failure and the shear-out failure can occur if the edge distance-to-diameter ratio (e/d) is too low. Therefore, a w/d ratio of 5 and a edge e/d ratio of 3.5 were selected as these number have been demonstrated to be sufficient in multiple layups [8]. The bearing stress can be calculated as follows:

$$\sigma_{bearing} = \frac{k \times P}{d \times t} \tag{1}$$

Where P is the applied load and k is the load per hole factor: 1.0 for a single bolt joint.

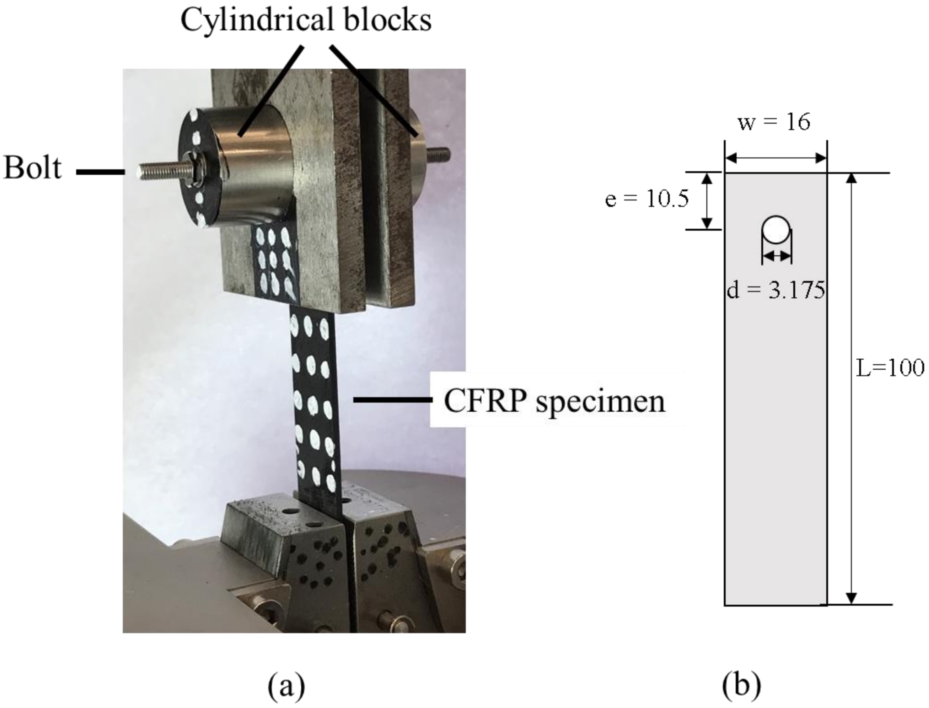

Figure 1. (a) Schematic of the set-up for the bearing testing and (b) an illustration of the specimen geometry. All the units shown in the figure are in mm.

3. Results

The bearing stress was plotted against the displacement of the hole edge and are presented in Figure 2 and Figure 3 for the SM-SM $[\pm26_6/0]_{s2}$ and IM-HM $[\pm25_2/0]_{s4}$ laminates repsectively. The key results are summarised in Table 2. All four specimens for the SM-SM laminate exhibited consistent behaviour – the stress increased gradually with hole deformation, although multiple small stress drops were seen before the ultimate failure. In the initial region, the curve is linear up to an average stress of 432 MPa. At this stage, the hole elastically deformed under the compressive load exerted by the bolt. After the first peak, the response tends to be less stiff and the stress more gradually increases up to the ultimate strength of 609 MPa. All these small load drops represent damage accumulation within the laminates during the loading, but they are still able to carry sufficient load.

The bearing stress-displacement curve for the IM-HM laminate shows similar non-linear behaviour and gradual failure to the SM-SM laminate. It consists of an initial elastic deformation up to an average of 368 MPa, a region of gradual deformation and a final load drop (more than 30%) after the maximum stress of 484 MPa, which corresponds to the ultimate strength. Both the stress at the end of the elastic region and at the ultimate failure for the IM-HM laminate are lower than for the SM-SM laminate. This is due to the bearing failure being a compression dominated failure mode. The high modulus YSH70A carbon fibre material has a lower compressive fracture strain than for the standard modulus fibre, therefore it brings an early failure of the 0° plies in the IM-HM laminate. In addition, the stiffness contribution from the 0° plies in the SM-SM laminate is only 12%, which is much less than the 49% in the IM-HM laminate. This suggests that although the compressive fibre-kinking occurs in the 0° plies of the SM-SM laminate, the delamination supression ability of the thin ply prepreg enables the angle plies to carry a significant amount of further loading. The IM-HM laminate tends to fail sooner as it loses the majority of load carrying ability once the 0° plies fail. The total deformation at the hole edge of the SM-SM laminate is also found to be higher than for the IM-HM laminate, which is attributed to the higher stiffness of the IM-HM laminate and its earlier failure. Both laminates failed in a similar way, with bearing failure at the hole as the primary failure mode. This was then followed by splitting in the angle plies and tensile failure next to the hole, eventually leading to a tear-out type of failure. The details of the damage are worth experimental characterisation in future work, via microscopy and X-ray CT-scanning.

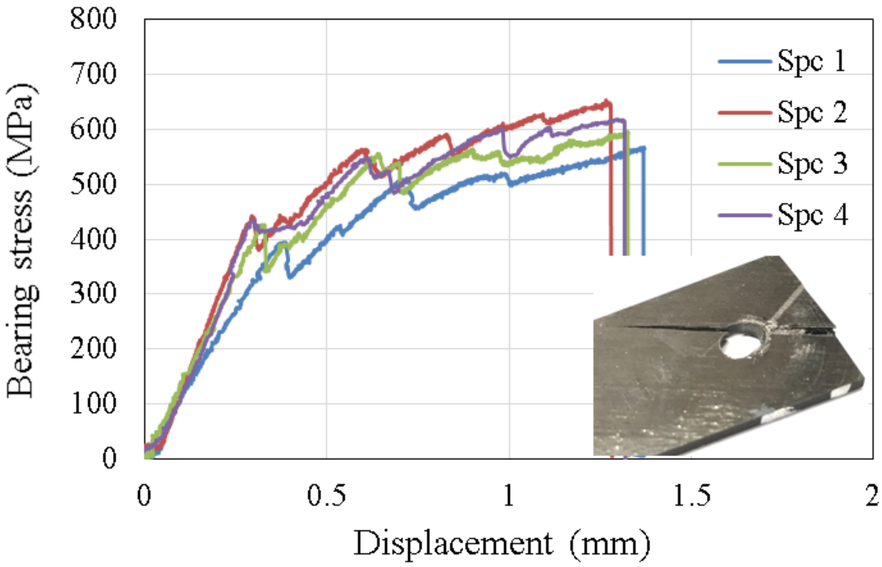

Figure 2. Bearing stress-displacement curves of the SM-SM $[\pm 26_6/0]_{s2}$ laminate. The specimen shown is after the final load drop.

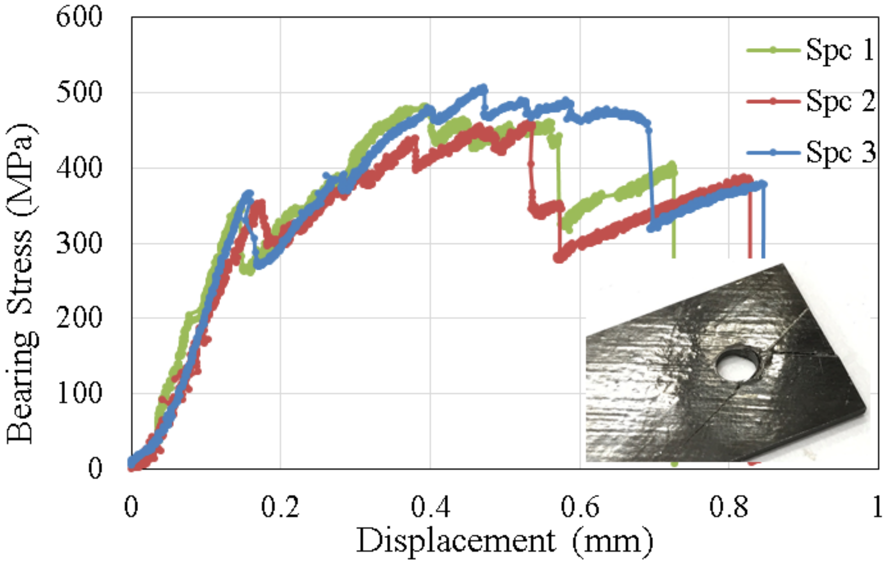

Figure 3. Bearing stress-displacement curves of the IM-HM $[\pm 25_2/0]_{s4}$ laminate. The specimen shown is after the final load drop.

Table 2. Summary of key mechanical properties.

	1st peak bearing stress (MPa)	Ultimate bearing strength (MPa)	Displacement (mm)	Failure mode
SM-SM	432	609	1.38	Bearing, tearout
$[\pm 26_6/0]_{s2}$	(2.0%)	(5.9%)	(5.7%)	
IM-HM	368	484	0.6	Bearing, tearout
$[\pm 25_2/0]_{s4}$	(4.2%)	(4.0%)	(13.0%)	

4. Conclusions

Based on the experimental investigation, the following points can be concluded:

- Gradual failure has been demonstrated in bearing testing for both the pseudo-ductile SM-SM $[\pm 26_6/0]_{s2}$ and IM-HM $[\pm 25_2/0]_{s4}$ laminates.
- The primary failure modes of both laminates are bearing at the contacted hole-edge, followed by splitting in the angle plies, tensile damage and tear-out.
- A higher first peak and ultimate bearing strength has been obtained in the SM-SM laminate compared to the IM-HM laminate. This can be attributed to the higher facture strain of the fibres used in the 0° plies, and the lower total stiffness contribution of the 0° plies in the SM-SM laminates compared with the IM-HM laminates.

Acknowledgments

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