Investigation of geometrical and composite material parameters for tension-absorbing bolted joints

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ABSTRACT

In the event of an aircraft crash landing, the fuselage cross-section tends to ovalise. This leads to tension loading of the passenger and cargo floor cross-beams. In past research activities, this has been identified as an opportunity to absorb energy, through a novel design of the frame to cross-beam attachments [1]. These specialised attachments are referred to as "tension-absorbing" joints. They are designed to protect the bolt from early failure and provide guidance for it to push through, and crush, the composite adherends over a considerable distance, leading to a substantial amount of energy absorption. In the present work, material and geometrical parameters of these joints are investigated experimentally to provide data for a design database. A simplified version of the joint is tested, in which a pin is pulled through a 2 mm thick composite laminate using a specialised experimental rig. The bearing strength and energy absorption capabilities are investigated under quasi-static loading, for 4 mm and 12 mm diameter pins and three different stacking sequences. Two different specimen widths are employed to determine the extent of damage progression towards the specimen edge. Digital Image Correlation (DIC) is used to measure the pin displacement. It is found that symmetric layups with a repeating unit of $[45/-45/90/0]$ inhibit off-axis pin movement, providing for a consistent test, and that the wider specimen is required to avoid the damage reaching all the way to the specimen edge. For both pin diameters, an interspersed stacking sequence results in higher values of peak load, mean crushing load and specific energy absorption than a blocked layup.

1 INTRODUCTION

Composite materials enable the production of large structures with tailored material properties, high strength-to-weight ratio, excellent corrosion and fatigue resistance, good vibration attenuation effects, and potentially high energy absorption in crash or impact events. Bolted joints are of prime importance in a crash event because they are the sites where damage and failure typically initiate. Under high-rate loading, standard composite joints typically fail initially in bearing, whereby small amounts of composite crushing occur, and ultimately by bolt failure or bolt pull-through [1]. Such behaviour results in relatively minor levels of energy absorption. However, a novel "tension-absorbing" joint proposed in [2], works in such a way that the bolt is protected against failure, and guided to push through, and crush, the composite adherends over a considerable distance, leading to substantial amounts of energy absorption. This joint concept was first proposed for aircraft cabin overhead luggage racks, and it was concluded that fibre reinforced plastics can give high energy absorption, with a constant level of crushing force, in this "extended" bearing mode of failure [3].

In the present work, material and geometrical parameters of these joints are investigated experimentally to provide data for a design database. A simplified version of the joint is tested, in which a pin is pulled through a 2 mm thick composite laminate using a specialised experimental rig. The bearing strength and energy absorption capabilities are investigated under quasi-static loading, for 4 mm and 12 mm diameter pins and three different stacking sequences. Two different specimen widths are employed to determine the extent of damage progression towards the specimen edge. Digital Image Correlation (DIC) is used to measure the pin displacement and surface-ply strains.

2 PROBLEM DESCRIPTION

An initial study was performed to select the specimen geometry and layup. Specimen dimensions, illustrated in Figure 1(a), were chosen, considering the geometrical constraints imposed by the Zwick 100 kN servo-hydraulic universal straining frame gripping system. The narrow specimen has the advantage of efficient use of material, but it was unclear whether damage would progress to the specimen edge, so the wider specimen was also tested. A metallic pin was pulled through the material via a specially-designed fixture, see Figure 1(b). Three different stacking sequences, shown in Table 1, were selected to investigate their effect on pin off-axis movement and surface ply peeling. Furthermore, for each stacking sequence, "interspersed" and "blocked" versions were tested, in which plies of the same orientation were kept apart, or grouped together respectively, see Table 1. Two pin diameters (D) were considered, 4 and 12 mm, and the thickness (t) of all specimens was 2 mm. Two repeats of each test configuration were performed.

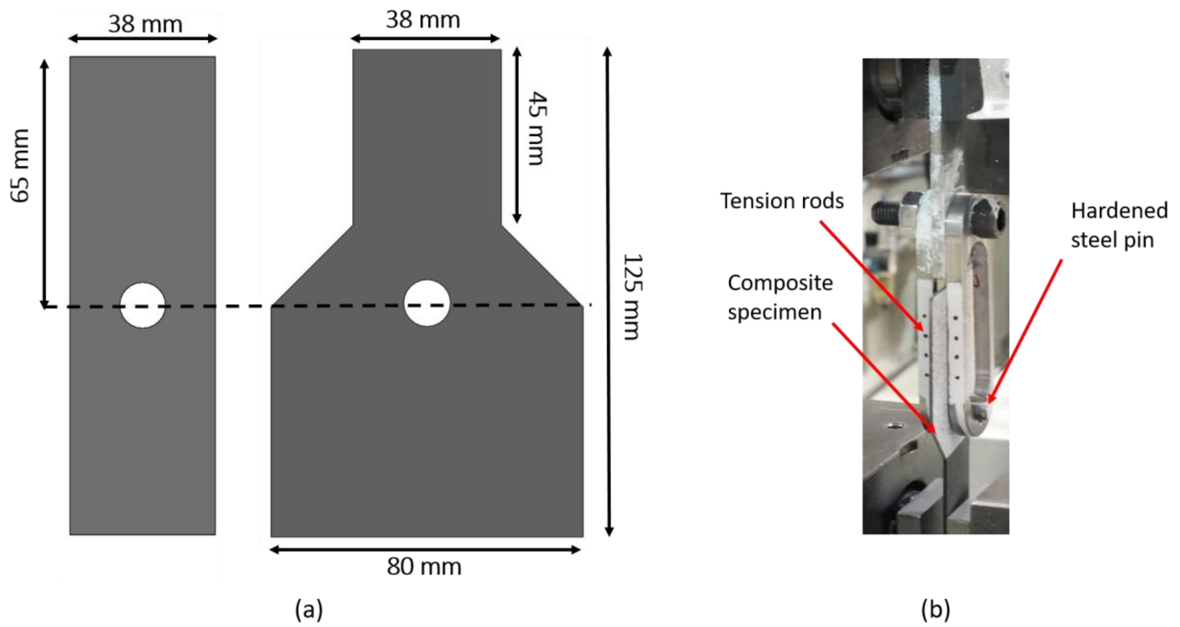

Figure 1: (a) Geometries investigated (b) Test setup

Layup No.	Stacking Sequence	
	Interspersed (IP)	**Blocked (BK)**
1	$[45/90/-45/0]_{2s}$	$[45_2/90_2/-45_2/0_2]_s$
2	$[0/45/90/-45]_{2s}$	$[0_2/45_2/90_2/-45_2]_s$
3	$[45/-45/90/0]_{2s}$	$[45_2/-45_2/90_2/0_2]_s$

Table 1: Stacking sequences

HexPly® IM7/8552 (EU version: 134 gsm) carbon-epoxy was selected, as it is widely used in industry and its mechanical properties, including damage and failure, have been characterised and published in the open literature, at quasi-static and dynamic rates. The following performance parameters were devised for comparison of specimens:

- Maximum bearing force and strength ($F_{\max}$ and $\sigma_{\max}$), where:

$$\sigma_{\max} = \frac{F_{\max}}{D \cdot t} \tag{1}$$

- Mean crushing force and stress (F_{mean} and σ_{mean}), where:

$$\sigma_{mean} = \frac{F_{mean}}{D \cdot t} \tag{2}$$

- Specific energy absorption (SEA), which is the area under the force-deflection curve divided by the mass of the destroyed material. For materials with brittle fibres, it has been estimated that the width of destroyed material is 20% larger than the pin diameter, so SEA is given as [4]:

$$SEA = \frac{1}{1.2 \rho t D s_m} \int_0^{s_m} F \cdot ds \tag{3}$$

where ρ is the material density and s_m is the maximum pin displacement.

3 RESULTS

3.1 Typical force-displacement response

Figure 2(a) and (b) show typical force-displacement responses for blocked and interspersed ply stacking sequences respectively. Bearing response is plotted up to 20 mm pin displacement, beyond which the bearing load levels is approximately constant.

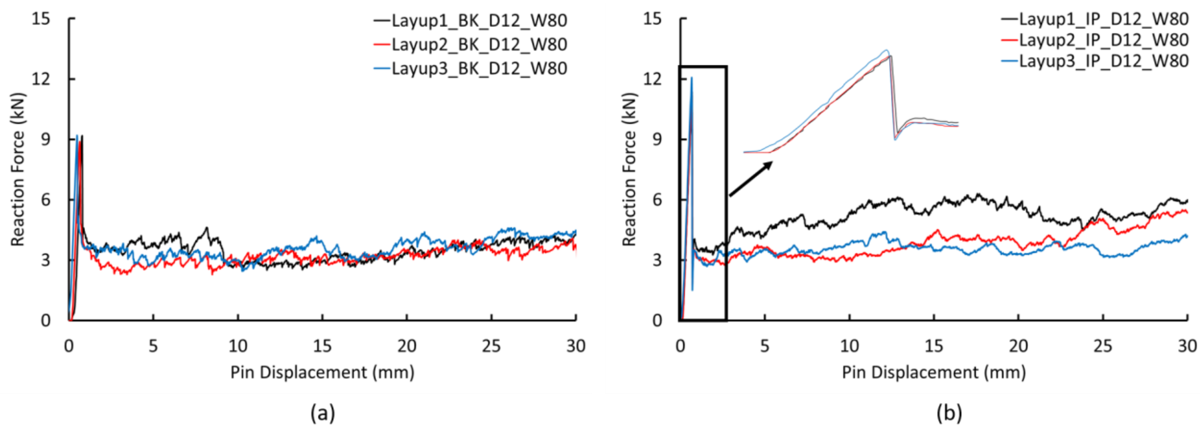

Figure 2: Force-displacement response for different layup specimen of thickness 2 mm, width 80 mm and tested with pin diameter 12 mm for plies grouping (a) blocked and (b) interspersed

The response can be divided into four phases:

Phase 1: Initial pin displacement without any significant load on the laminate. This corresponds to the adjustment of the fixture to load the pin in the loading direction.

Phase 2: Linearly increasing load with pin displacement, the slope of which gives the stiffness of the pin bearing joint.

Phase 3: Non-linear load variation due to initiation of damage, culminating in the maximum load ($F_{\max}$), beyond which a catastrophic load drop occurs

Phase 4: Steady crushing of the laminate, with mean crushing force (F_{mean}) calculated by taking the mean load between 5 and 30 mm of pin displacement.

3.2 Effect of stacking sequence and specimen geometry

Several researchers have performed open-hole tension and compression tests on IM7/8552 [5-9] using "Layup 1" (see Table 1) so "Layup 1" was selected and tests were performed with the narrow specimen, shown in Figure 1(a). As shown in Figure 3, for this layup, the pins (4 and 12 mm) were observed to move off-axis (i.e. in a direction different from the loading direction), and the surface ply or plies tended to peel off with relative ease. The absence of lateral constraint by the test setup and the presence of the 45° surface ply, is expected to be the cause of this pin off-axis movement. For the blocked ply stacking sequence *two* surface plies on the front and back surface tended to peel off, resulting in a significant reduction in thickness which is effective in energy absorption.

In an attempt to reduce the spread of damage across the width of the specimen and the pin off-axis movement "Layup 2", which has a 0° ply on the surface, was tested. Figure 4 shows that, for this lay-up, with a small diameter pin (4 mm), the pin tended to move in the loading direction and the spread of damage across the full width of the specimen was avoided for both interspersed and blocked stacking sequences. For larger (12 mm) diameter pins, a similar failure behaviour was observed but the specimen ultimately failed in net tension instead of bearing. This was due to the small width-to-diameter ratio (w/d = 3.1) which is significantly less than the value (w/d = 6) recommended to ensure bearing failure [10]. The disadvantage of "Layup 2" is that placing 0° plies on the surface means the load bearing plies can easily delaminate without contributing much to energy absorption. Furthermore, this stacking sequence is not recommended by the Composite Material Handbook [11].

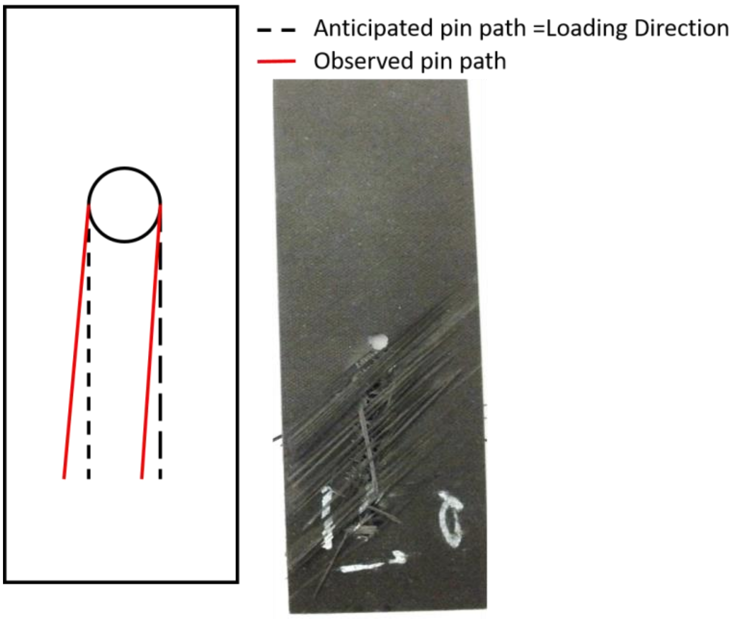

Figure 3: Pin off-axis movement and surface ply peeling in interspersed ply stacking of “Layup 1”

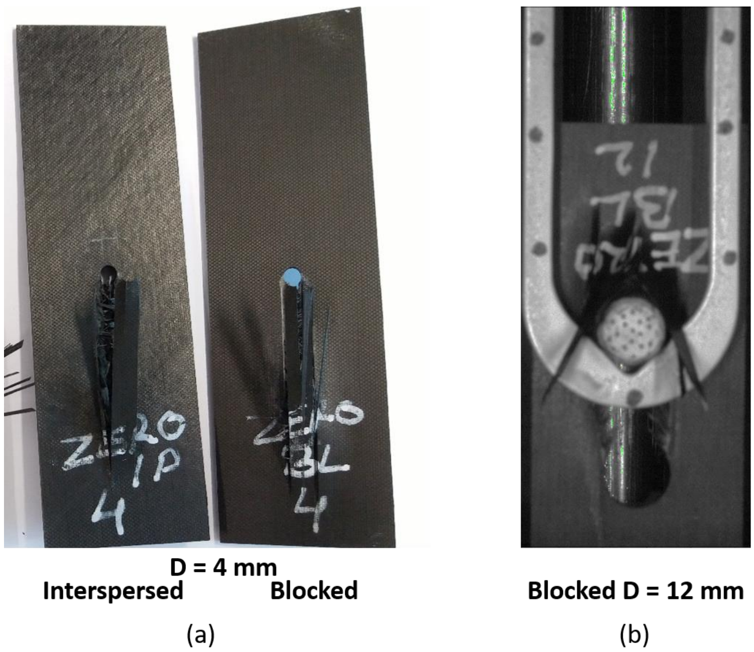

Figure 4: (a) Failure behaviour of “Layup 2” specimens tested with D = 4 mm for both interspersed and blocked ply grouping and (b) specimen tested with D = 12 mm for blocked ply grouping

To address all these issues “Layup 3” was tested, which has a 45° ply on the surface followed by a -45° ply underneath. This layup addressed both the issues i.e., pin off-axis movement and spread of damage towards the specimen edge, for tests conducted with D = 4 and 12 mm, see Figure 5. However, as shown in Figure 6(a), the narrow specimens failed ultimately in net tension instead of bearing. To address this issue the wider specimen shown in Figure 1(a) was tested. Figure 6 shows that the wider geometry resulted in bearing failure for all layups. In terms of performance parameters, no significant difference was observed between the narrow and wide specimens, as can be seen in Figure 6(e) which is for interspersed “Layup 3” specimens with D = 12 mm.

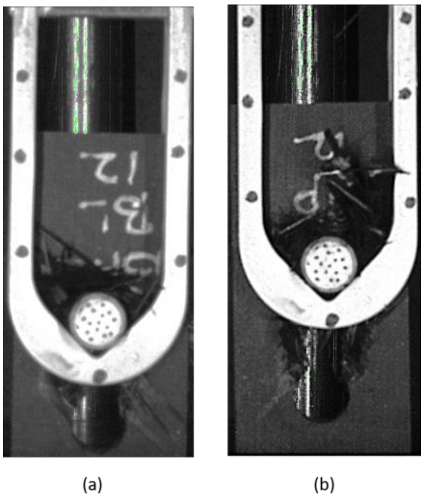

Figure 5: Failure of "Layup 3" specimens with D = 12 mm, (a) blocked and (b) interspersed

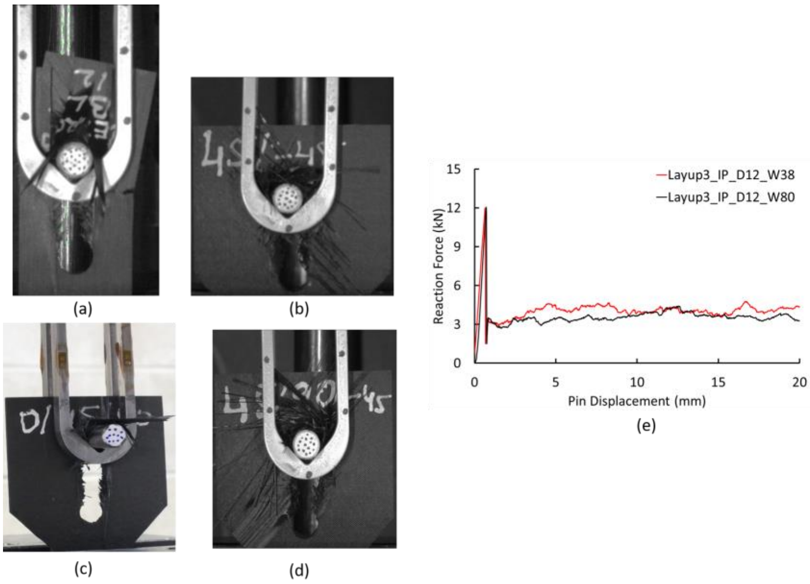

Figure 6: (a) Net-tension failure observed in narrow specimen. Wider specimen tested with D = 12 mm for (b) Layup 1, (c) Layup 2, (d) Layup 3, (e) force-displacement response for specimens with different widths having interspersed Layup 3

3.3 Effect of pin diameter, and blocked versus interspersed lay-ups

The effect of pin diameter on maximum bearing stress, mean crushing stress and specific energy absorption (SEA) is shown in Figure 7 and Figure 8 for blocked and interspersed layups respectively. For all the laminate stacking sequences, maximum bearing stress decreases with increasing pin diameter. For example, in case of blocked layups (Figure 7), σ_{max} decreases by 13%, 15% and 21%, when the pin diameter is increased from 4 to 12 mm for Layup 1, Layup 2 and Layup 3 respectively. Interspersed layups show higher maximum strength values than blocked layups. Examination of the failure modes reveals that blocked laminates have delamination as their dominant mode of failure, which is a low energy phenomenon, whereas interspersed laminates fail in quasi-brittle fibre fracture, fibre matrix cracking, fibre kinking and delamination, resulting in higher strength.

Figure 7(b) and Figure 8(b) also demonstrate a reduction in mean crushing stress with increasing pin diameter for all layups. For example, in case of blocked laminates, a decrease of 53%, 48% and

41% is observed when the pin diameter is increased from 4 to 12 mm for Layup 1, Layup 2 and Layup 3 respectively. A similar trend was also observed for interspersed stacking sequences and has been observed previously by Bergmann [12]. This trend is attributed to the size effect associated with varying pin diameter, a higher stress concentration factor being present for the 4 mm diameter pin compared to the 12 mm diameter pin.

The SEA also showed a decreasing trend with increasing pin diameter for all layups. For example, for blocked Layup 1 tests with 4 mm pin diameter, SEA = 150 kJ/kg, and this decreases to 66.7 kJ/kg (-55.5%) for tests conducted with 12 mm pin diameter.

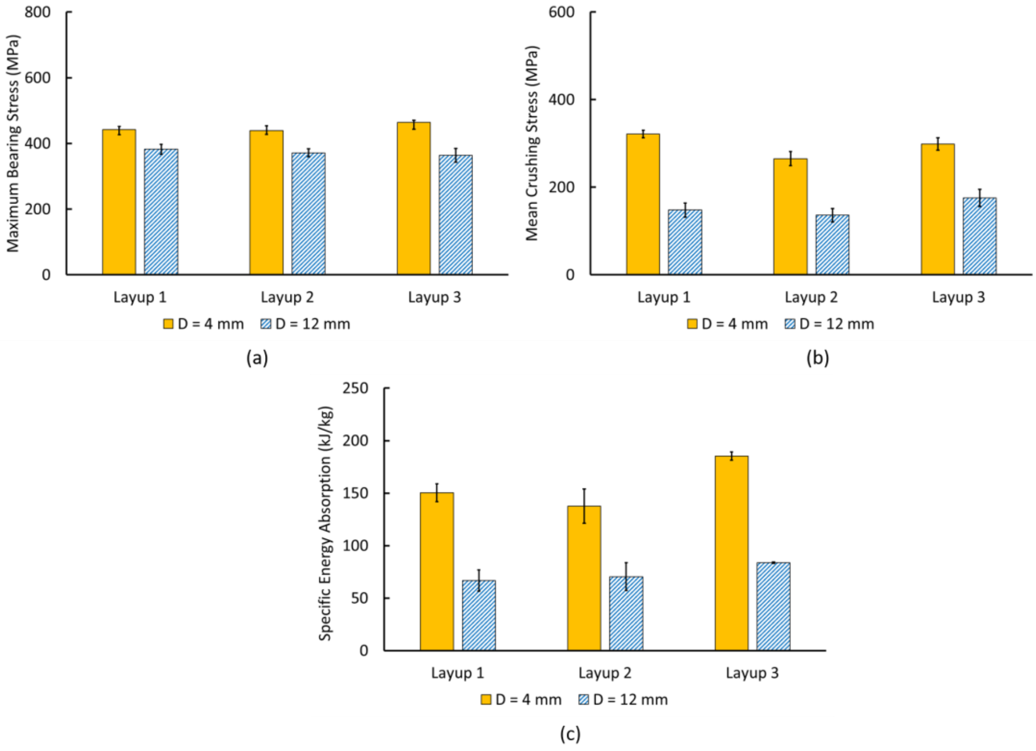

Figure 7: Effect of pin diameter on (a) maximum bearing stress, (b) mean crushing stress and (c) energy absorption for blocked ply layups

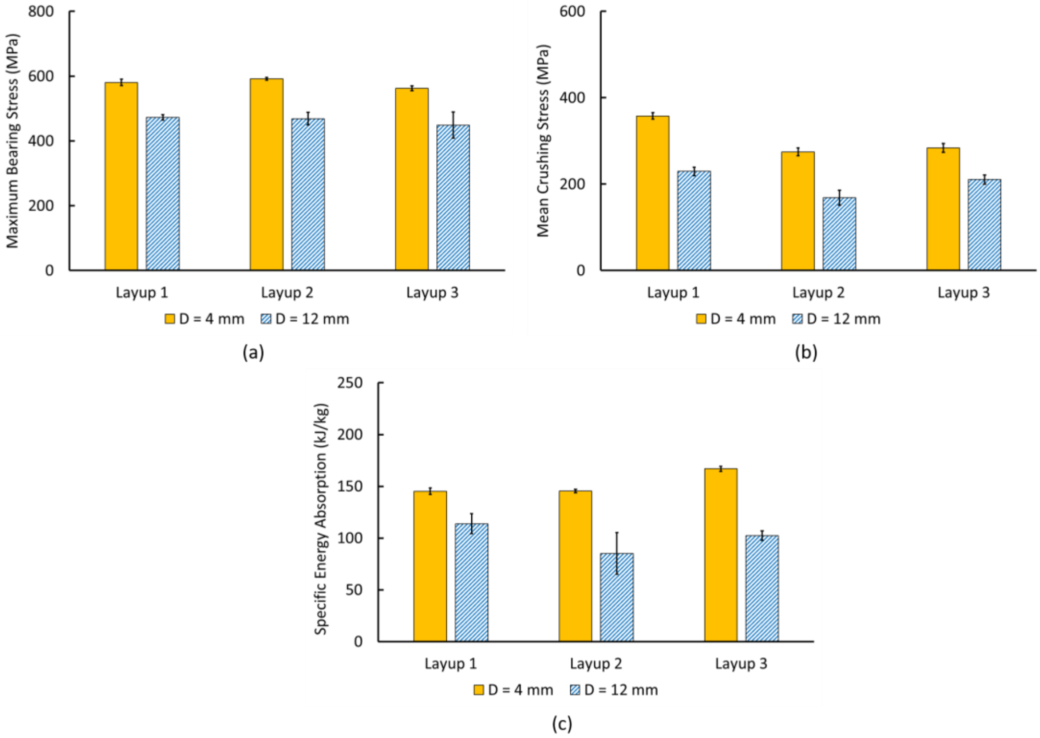

Figure 8: Effect of pin diameter on (a) Maximum bearing stress, (b) mean crushing stress and (c) energy absorption for interspersed ply layups

4. CONCLUSIONS

In this study, the effect of pin diameter, specimen geometry and stacking sequence on the energy absorption performance of laminates crushed by a pin was investigated. A quasi-isotropic layup $[45_n / 90_n / -45_n / 0_n]_{ms}$, where n = 2 and m = 1 for blocked plies and n = 1 and m = 2 for interspersed plies, was initially selected but this configuration resulted in off-axis pin movement and spread of damage towards the edge of the specimen. To address these issues two other stacking sequences were considered. The second layup ($[0_n / 45_n / 90_n / -45_n]_{ms}$) resolved these issues but the placement of a 0° ply on the surface of the laminate resulted in a decrease in energy absorption as these main load-bearing plies were easily delaminated. Furthermore, this stacking sequence is not recommended in design handbooks. For specimens having stacking sequence $[45_n / -45_n / 90_n / 0_n]_{ms}$, pin off-axis movement and spread of damage to the specimen edge were avoided, but net tension failure occurred with the narrow specimens and the largest bolt diameter. To avoid this, a wider specimen geometry was devised. In terms of peak and mean loads changing the geometry did not have any influence. So, a wider specimen geometry is selected as the baseline to perform future pin bearing tests.

Maximum bearing strength, mean crushing stress and specific energy absorption decreased with increasing pin diameter. For each lay-up, blocking of plies resulted in lower strength, crushing stress and specific energy absorption. In future work, a comprehensive experimental study will be conducted to develop a complete design database for tension absorbing joints, using the wider specimen geometry and Layup 3 as the baseline stacking sequence.

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