WOVEN FABRIC CARBON FIBRE COMPOSITES HYBRID JOINTS UNDER QUASI-STATIC TESTING

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ABSTRACT: Twill weave carbon fibre reinforced polymer (CFRP) hybrid adhesively bonded-bolted joints was investigated on bearing stress at failure in experimental programmes. The present paper comprises effects of joint type, normalised coupon width (*W*/*d*), laminate orientations and bolt load as specified in designed series. All CFRP hybrid joints exhibited cohesive failure before ultimate failure i.e., net-tension and bearing/net-tension failures. Bearing stress at failure was found to increase with normalized *W*/*d* and small *W*/*d* led to net-tension failure occurrence. Double-lap joints (DLJs) were stronger than single-lap joints (SLJs) due to secondary bending phenomenon in SLJs. Cross-ply presented greater strength than quasi-isotropic lay-up caused by the presence of 0˚ fibres orientation. Clamped condition (applied torque, T = 5 Nm) may change the critical *W*/*d* than finger-tight (FT) case as net-tension failures is likely to occur under clamped condition.

KEYWORDS: *Hybrid Joints; Woven Fabric; CFRP; Failure Modes; Bearing Stress*

1.0 INTRODUCTION

Composite materials offer excellent specific stiffness and strength, compared to traditional engineering materials such as aluminum, steel and concrete. This has led to these materials being increasingly used in most structures applications. Synthetic fibresare widely used as reinforcement of composite material i.e., glass fibre and carbon fibre. Carbon fibre plies are found as thinner and have larger specific strength compared to glass fibre plies as reported from previous study [1]. Formerly, CFRP was widely used in aerospace applications due to its excellent properties. Reduction of crimp by weaving pattern, twill or satin weave offers good drapeability but has slightly unstable configurations compared to plain weave architectures.

In recent years, there has been an increasing interest in hybrid adhesively bonded-bolted joint (hereby written as hybrid joints) compared to conventional joining techniques. Hybrid joints have been introduced as a combination of mechanically-fastened joints (i.e., bolted joint) and adhesively-bonded joints (also known as bonded joints). Currently, there is no available design tools for hybrid joints on standard testing method/set-up. Thus, performance of hybrid joints is fully dependent on mechanical characteristics of composite materials.

Recent literatures have confirmed that hybrid joints exhibit better joint strength compared to both conventional joining techniques. The strength of hybrid SLJs was investigated by Kelly [2] with regards to the effect of laminate stacking sequence. He tested carbon fibre-epoxy laminate with stacking sequence [0/45/90/-45]s and [0/45/90/-45] s2 and found that thicker specimen had higher bearing load capacity and greater stiffness and strength compared to thinner specimen. Chowdhury et al. [3] studied static test on bonded, bolted and hybrid joint on HexPly M18/1/G939 CFRP composites. Generally, bolts in hybrid joints reduced overall bond area due to introduction of hole, thus reducing the peels stress. However, they are able to arrest crack propagation within cohesive adhesive layer and are found to have greater strength than only bonded joints and bolted joints.

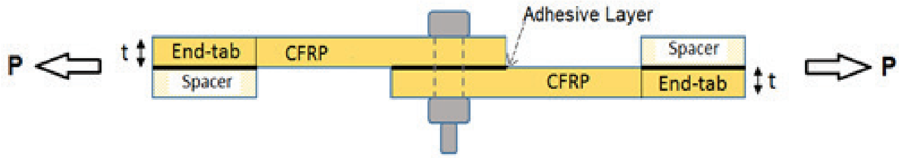
Kelly [4] reported that adhesive layer can transfer the applied tensile loading through the thickness of adhesive layer for hybrid joints cases. Thicker adhesive layer is able to transfer more load by bolt friction in carbon fibre/epoxy hybrid SLJ configurations. From this study, the analysis also revealed that more load was transferred as the overlap length and adhesive modulus increased. On the other hand, a study by Lee et al. [5] investigated the hybrid DLJs with different *W/d* and the adherend thickness on carbon/epoxy. Failure load was found to increase with increment of normalized *W/d* and adherend thickness. The crack initiation and propagation were also studied, by capturing EX-F1 high speed camera. It was found that adhesive layer failed prior to mechanically fastened failure for hybrid joint cases. Woven fabric CFRP bolted SLJs were investigated to study effects of joint geometry and reported that the increase of *W/d* presented higher bearing stress at failure [6].

As research works on woven fabric CFRP hybrid joints are limited, thepresent study is to determine bearing stress at failure on various normalized coupon width *(W/d)*, joint type configurations, lay-up orientation and bolt load as specific in testing series of twill weave

CFRP composite hybrid joints under quasi-static loading. This paper also presents the structures response and associated failure mode of each hybrid coupons.

2.0 METHODOLOGY

The CFRP composite panels were fabricated by combining twill weave carbon fibre and resin system by the wet lay-up techniques under compression molding. Resin system was ready by mixing the epoxy resin SP84 and hardener SP76 with ratio 2:1, respectively. One layer of twill weave carbon fibre was placed on an adjustable aluminum mould smeared uniformly with resin system. The procedures were repeated accordingly to designed lay-up orientation as specified in testing series. After lay-up fabrication process, the wet lay-ups were allowed to set curing period at least twenty-four hours by using hydraulic compression machine prior to demolding. Composite panels were cut accordingly to coupon size by using cooling diamond saw. A diameter of 5 mm hole was drilled at the centreline of overlap region for each joining configuration by using high-speed drilling bits to avoid notch edge defections. Installation of fastening system (the current work used M5 size) with applied clamping torque and adhesive thickness of approximately 0.1 mm was prepared prior to mechanical testing of SLJ and DLJ configurations as given in Figure 1(a) and Figure 1(b) respectively. The coupon geometry of a testing coupon was given in Figure 1(c).



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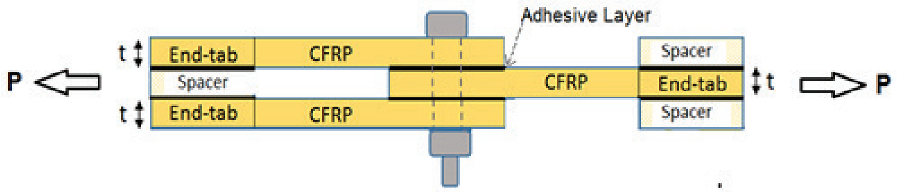

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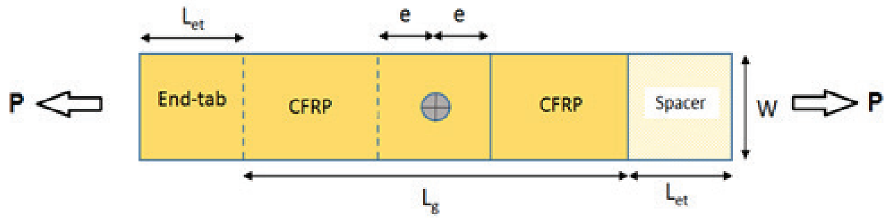


(c)

Figure 1: Hybrid joints coupon geometry; (a) side view of SLJ, (b) DLJ and (c) top view

An experiment framework was investigated to study the bearing stress at failure of twill weave CFRP hybrid joints with four different laminate lay-ups. There are two lay-up types investigated, i.e., cross-ply (CX2, CX4) and quasi-isotropic lay-up (CS2, CQ4) and the stacking sequence of each lay-up is detailed in Table 1. Finger-tight condition which is equivalent to approximately 0.5 Nm and clamped condition with 5 Nm were investigated in this study. Finger-tight condition applied in composite joints is designed as the worst-case scenario, however, 5 Nm of bolt load is frequently used [6]. Joint type configurations consisting of SLJs and DLJs were also incorporated in the current study. As discussed earlier, normalized *e/d* for cross-ply was fixed to 6 and quasi-isotropic lay-up was fixed as 4 to eliminate shear-out failure while normalized *W/d* was ranged between 2 to 5. Coupons were prepared by the designed testing series accordingly to allow the parametric study of different joining variables on bearing stress at failure on twill weave CFRP hybrid joint. Figure 2 shows the photograph of CX4 hybrid SLJ configuration that is ready for mechanical testing.

Table1: Hybrid joint test coupon configurations

Laminate lay-up	Stacking sequences	*e/d*	*W/d*	Joint type	Bolt load
CX2	$(0/90)_S$	6	2,3,4,5	SLJ, DLJ	FT, 5 Nm
CX4	$(0/90)_{2S}$	6	2,3,4,5	SLJ, DLJ	FT, 5 Nm
CS2	$(\pm45)_S$	4	2,3,4,5	SLJ, DLJ	FT, 5 Nm
CQ4	$(0/90/\pm45)_S$	4	2,3,4,5	SLJ, DLJ	FT, 5 Nm

SLJ: Single-lap Joint
DLJ: Double-lap Joint

ASTM Standard D3039B [7] was followed for mechanical testing set-up. All testing coupons were conducted in quasi-static tests by using the Universal Testing Machine (UTM) SHIMAZU AG-I with capacity of

10kN load cell and constant cross-head speed of 0.5 mm/min. At least 3 samples of each designed hybrid joints testing series were carried out and average value of bearing stress at failure were recorded as given in Table 2. In addition, end-tabs were prepared at coupon edges, bonded with aluminum strip prior to testing to provide proper gripping and avoid slippage during mechanical testing as shown in Figure 1(c). Spacers are provided as given in Figure 1(a) and 1(b) to eliminate the occurrence of primary bending.

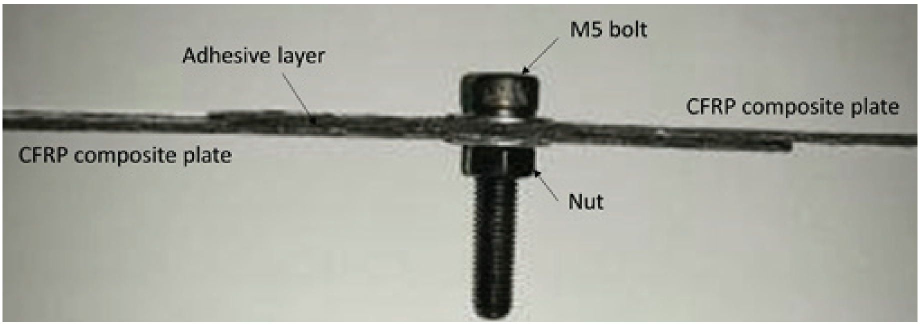
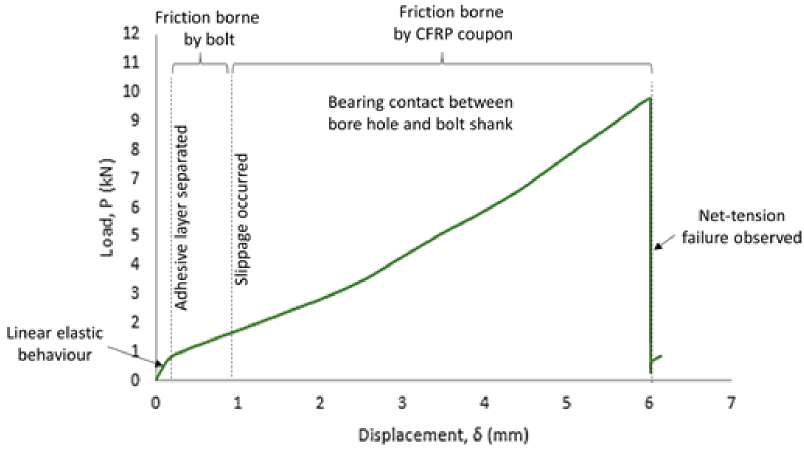


Figure2: Side view of CX4 SLJ hybrid joint

3.0 RESULTS AND DISCUSSION

3.1 Load-displacement Curve

For CFRP joint behavior, cross-ply and quasi-isotropic lay-up showed similar load-displacement profiles for both SLJs and DLJs. Figure 3 shows a representative graph of CX2 hybrid SLJs with clamped condition. From experimental observations, three failure modes were observed, i.e., adhesive failure, net-tension failure and bearing/net-tension failure. Net-tension failures were more prominent in smaller normalized *W/d*, while bearing/net-tension failures occurred in larger *W/d*.



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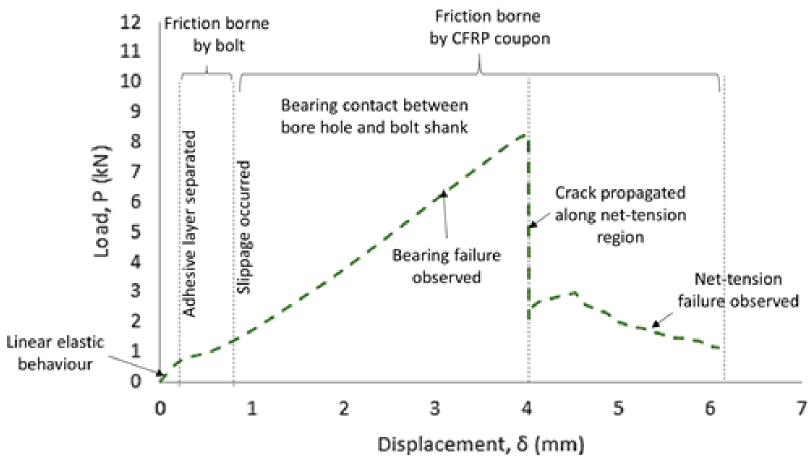


(b)

Figure 3: CFRP joint behaviour for CQ4 lay-up on (a) DLJ and (b) SLJ with clamped condition

From the load-displacement curves as illustrated in Figure 3, it is clearly shown that several stages occur before reaching the ultimate load. The curve initially showed linear elastic behaviour prior to adhesive failures due to splitting of bonded adhesive and adherend layers. As applied load increased, peel stress increased at overlap edges (adhesively joining area) and cracks were initiated and propagated within adhesive layer. This failure is also known as cohesive failure in adhesives. The next stage showed friction load was transferred to adjacent coupon until applied load surpassed bolt load applied ($P>P_{bolt}$). At this point, composite coupon started to slip at shear plane and bearing contact between bolt shalf and bore hole within bearing area took place.

Thereafter, friction load was taken by individual composite joining coupons until ultimate failure.

From the observations for SLJs cases, bolt was tilted due to secondary bending of composite coupon. During testing observation, cracks formation ahead of notch tip can be expected at perpendicular plane to applied loading (screeching sound were heard to indicate matrix cracking and delamination) and fracture catastrophically after a certain distance ahead of notch tip (equivalent to damage zone length of approximately a radius hole size). Different load-displacement profile was reported by Kelly [2], where adhesive bonding failure stage exhibited higher failure load than the bolt failure stage due to ductile toughened adhesive used in his work. The graph shows a dramatic drop when the adherend/coupon was fractured.

Comparing the curve from Figure 3(a) and 3(b), DLJs showed higher peak load than SLJs. This is because of secondary bending in SLJs that exhibited extra tensile stresses as reported by Smith et al. [8]. As observed in Figure 3(b), progressive digging of washer into the coupon is caused by secondary bending of the coupon.

3.2 Effect of Joint Variables on Bearing Stress at Failure

This section discusses effects of *W/d*, lay-up types, joint types and bolt load for CFRP hybrid joints on bearing stress at failure.

3.2.1 Effect of *W/d* Ratio

The effects of normalized *W/d* on bearing stress at failure for CQ4 hybrid joints are shown in Figure 4, under clamped condition. CFRP hybrid DLJs presented trend which transform from net-tension to bearing/net-tension failure mode at critical *W/d* = 5. On the other hand, CFRP hybrid SLJs showed transformation from net-tension to bearing/net-tension failure mode at critical *W/d* = 3. From the observation, it shows that net-tensile failure occurred on smaller *W/d* ratio for SLJs (*W/d*= 2) while DLJs exhibited net-tension failure at *W/d*< 4. Similar trend was reported by Kelly et al. [9] with smaller *W/d* ratio showing net-tension failure while larger *W/d* ratio showing bearing failure for hybrid SLJs. This is due to larger unloaded region in larger *W/d* coupon along net-tension plane to give higher peak load. From Figure 4, it is evident that bearing stress increased with W/d regardless of the type joint and clamp-up condition for each lay-up orientation, similar to the findings reported by Kelly et al. [9] and Lee et al. [5].

3.2.2 Effect of Joint Type

As shown in Figure 4, DLJs is stronger than SLJs in both clamping load for CQ4 lay-up. Generally, all lay-up designation series showed the same trend as CQ4. From the observation, SLJ coupons showed deformation failure that caused the secondary bending. As reported by Smith, et al. [8], extra tensile stress was exhibited due to seconding bending leading to less bearing stress at failure. The secondary bending occurred in SLJs joints due to unsymmetrical loading path. This effect is unavoidable in SLJs configurations. Primary bending has been eliminated by providing spacer of similar coupon thickness during mechanical testing. Secondary bending effect is shown in Figure 5 leading to lower maximum stress. The present results are similar to Li et al. [10] findings that showed stronger DLJs than SLJs.

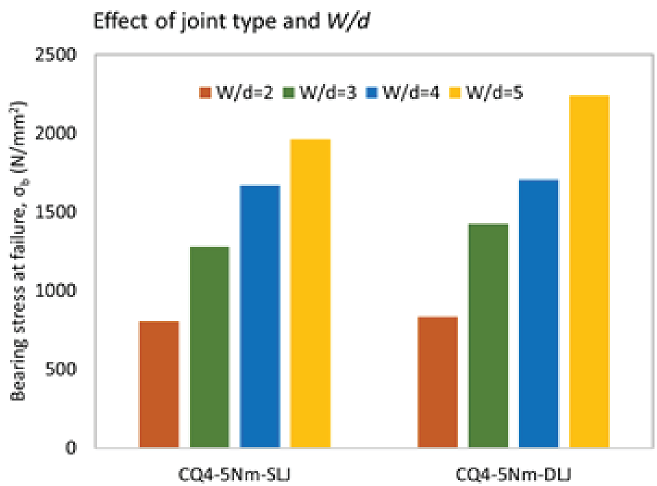


Figure 4: Effect of bearing stress at failure on *W/d* for CQ4 hybrid SLJs and DLJs with clamped condition

Figure 5: Secondary bending effect observed for CQ4 hybrid SLJ

3.2.3 Effect of Lay-up Orientation and Thickness

This section discusses the effects of coupon lay-up orientation and coupon thickness on bearing stress at failure. As illustrated in Figure 6, CS2 lay-up coupons showed the lowest bearing stress. It is because CS2 lay-up coupons do not contain any 0˚ CFRP ply to sustain applied load along fibre direction (longitudinal direction). Comparison of bearing stress at failures on cross-ply lay-up of different coupon thickness, CX2 and CX4 exhibited less significant effect. However, peak load in thicker lay-up i.e., CX4 is higher than CX2. In general, thicker coupons were able to transfer more friction load through coupon thickness and showed higher joint strength. Bearing stress at failure increased with coupon thickness, consistent with the findings reported by Kelly et al. [9].

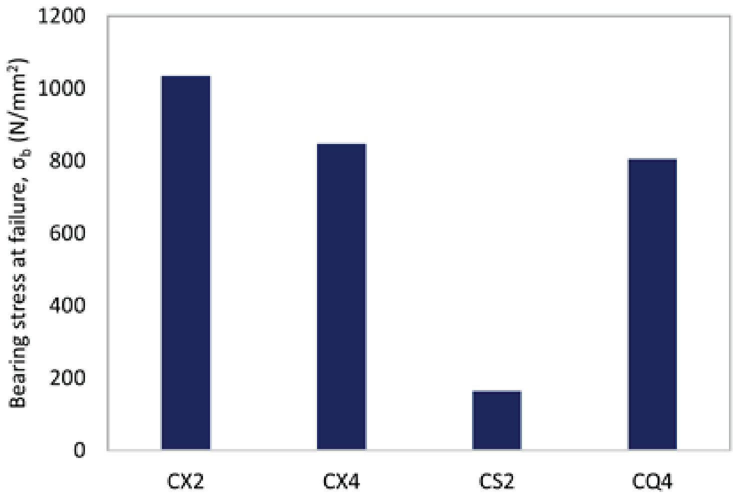
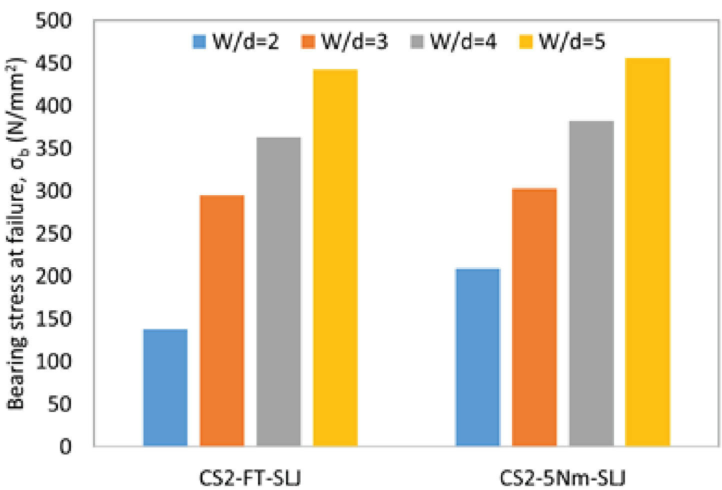


Figure 6: Effect of lay-up orientation and thickness on bearing stress with clamped condition for SLJ, *W*/*d*=2

On the other hand, cross-ply coupons (CX2 and CX4) illustrated higher bearing stress than quasi-isotropic coupons. This is due to the presence of 0˚ plies in cross-ply coupons that play a major role in resisting the applied load while the presence of ±45˚ plies is efficient to resist shear stress as maximum shear stress is given by ±45˚. Due to only ±45˚ in CS2 designation, it was found that the coupon is twisted along its longitudinal plane. Cross-ply lay-up gives larger bearing stress at failure than equivalent quasi-isotropic orientation lay-up.

3.2.4 Effect of Bolt Load

Bolt load was applied by using torque wrench (KTC Digital Torque Wrench GEK 030-C3A). When clamping the bolt, pre-tension load occurred within the bolt shaft to compress the joining coupons. The clamped bolt conditions indicated more uniform stress distribution within overlap region and decrease peel stress at overlap region as stated by Franco et al. [11]. However, both adherends (CFRP coupons) were then separated by bending moment and the joint was fully supported by bolt as reported by Kim et al. [12]. The load transfer is now concentrated near contact area around bolt head and nut after cohesive failure as applied load, P is less than bolt load, P_{bolt}. As $P>P_{bolt}$, slippage occurred at shear plane and friction load is solely taken by individual composite coupons. Most coupons failed in net-tension due to stress concentrations ahead of the notch tip. The load transferred by the bolt increased with the clamp-up condition as illustrated in Figure 7. From this figure, it shows that the effects of bolt load for thinner lay-up, CS2 is less significant than thicker CQ4 lay-up. As described in the previous section, thicker coupons yield more prominent effect of bolt load due to better friction load transfer.



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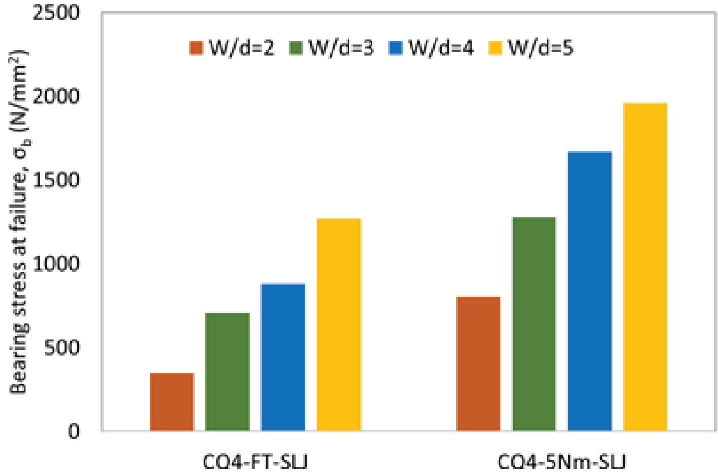

(b)

Figure 7: Effect of bolt load for (a) CS2 and (b) CQ4 SLJ on bearing stress at failure

4.0 CONCLUSION

Most of the testing coupons failed in net-tension failure mode. Bearing stress at failure of normalized coupon width is higher as normalized *W/d* increased as larger unloaded region was found along the net-tension plane, as expected. The DLJs is stronger than SLJs due to secondary bending effects in SLJs. Cross-ply lay-up is stronger than the quasi-isotropic lay-up due to more volume fraction of 0° fibre orientation to sustain applied load. Thicker coupon has better bearing stress at failure due to more load transferred through the coupon thickness than thinner coupons. Testing coupons with bolt load have higher bearing stress at failure as more applied load is required as friction load transfer under clamped condition prior to coupon slippage.

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