VOL. 11, NO. 3, FEBRUARY 2016 ISSN 1819-6608

ARPN Journal of Engineering and Applied Sciences

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EXPERIMENTAL INVESTIGATION OF WOVEN FABRIC CFRP BOLTED JOINTS: PARAMETRIC STUDY

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ABSTRACT

Present paper comprises a wide ranging experimental study of mechanically fastened woven CFRP using double-lap joint (DLJ) configurations. Details of the bolted joint materials and its configurations are given. This is followed by an account of the sample preparation process and a description of the range of joint types and variables investigated. Mechanical testing set-up and test method are then described. Experimental results relating to damage observations and ultimate strength are then presented. This is followed by discussion on the relationships between the bearing stress at failure and the hole size of specimens, the level of clamp-up and different joint type.

Keywords: woven fabric CFRP, bolted Joints, bearing stress.

INTRODUCTION

Experimental studies by previous researchers mostly consider single-bolted connections and investigate bearing strength, failure modes and failure mechanisms. The geometry of the bolted joint problem, which is used in further discussion, is given in Figure-1. A vast body of work exists, addressing the effect of varying single joint geometry (such as laminate thickness, hole diameter, *W/d* and *e/d* ratios) in each lay-up system (other dimensions are constants) as this has a great influence on ultimate bearing strength.

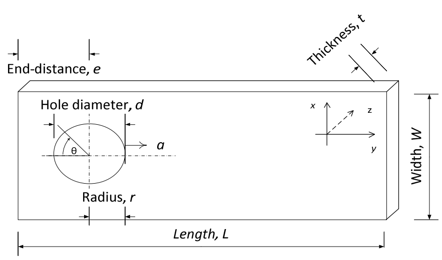
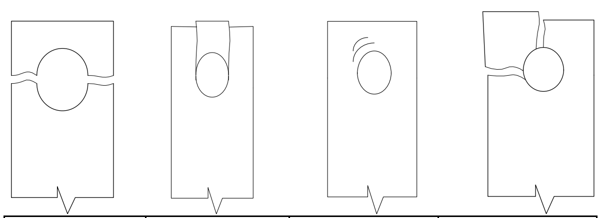


Figure-1. Geometry dimension used in bolted joint problems.

Three distinct failure modes can occur in composite bolted joints as shown in Figure-2. Net-tension failures are given by sudden crack propagations to failure due to relatively small area of sample cross-section. Shear-out failure occurs in small end-distance to hole centre or in highly orthotropic laminates such as cross-ply lay-up. Bearing failure is given as compressive failure close to contact region at the hole edge, exhibiting more ductile failure behaviour. Failures may also exist due to secondary failure modes, such as mixed net-tension and shear-out failure known as cleavage failure.



(a) net-tension failure	(b)Shear-out failure	(c)Bearing failure	(d)Cleavage failure

Figure-2. Failure modes in mechanically fastened composite joints.

In woven fabric composite system, there is a limited amount of experimental work reported with bolted joints. Early work with this system such as Okutan *et al*. (2001), Aktas and Dirikolu (2004) and Karakuzu *et. al*. (2006) has considered pin joint (not clamped) looking at how strength and failure modes relate with geometrical parameters such as hole diameter, *d*, laminate thickness, *t*, width, *W*, and edge distance, *e*. Due to low bearing compressive strength of woven system compared to non-woven counterparts, critical *W/d* is increased and dependent on woven system investigated. The effect of stacking sequence on bearing strengths in woven fabric systems has been investigated by Ujjin *et al*. (2004) and Aktas *et al*. (2009).

Esendemir (2008) and Kontolatis (2000) investigated the effects of geometrical parameters on the failure mode and failure loads of bolted joints in woven glass-epoxy plates for different clamping loads. As observed in the non-woven counterpart, the bearing strength of woven glass/epoxy laminate is increased by increasing *W/d* and *e/d*. Endensier (2008) also found that as clamping load increases, the ultimate bearing strength

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showed a significant increase and the failure modes became net-tension in most cases. Nassar *et al.* (2007) investigated experimentally the effect of bolt-torque in single-lap, woven glass-epoxy composite joints with protruding head bolts. His microscopic study showed that no significant delamination occurred at the holes with fully-torqued bolts whereas delamination was observed at holes with finger-tight bolts. Kontolatis (2000) used a similar GFRP woven fabric system as used by Belmonte *et. al.* (2001) in double-lap bolted joints with a clamping torque of 5 *N m* using protruding bolt. He found that net-tension failures occurred with *W/d*=4. These initiated from the stress concentration at the hole edge perpendicular to the loading axis. Mixed mode of bearing and net-tension failures occurred with *W/d*=5 and sufficiently large *e/d* =4.

EXPERIMENTAL SET-UP

Bolted joints components

Seven sets of CFRP woven fabric lay-up systems are studied in current work. Together these laminates represent a sub-set of those tested by Belmonte *et al.* (2004) in their investigation of open-hole behaviour. The materials comprised four plain weave (PW) and three five-harness satin weave (5HS) continuous carbon fibre reinforcements. The PW and 5HS woven fabric laminates used are based upon Toray T300 high strength carbon fibres and are manufactured from Primco prepregs with a layer thickness of about 0.2 mm. The epoxy resin system, which controls the matrix dominated properties, such as the transverse strength, is Vantico MY750. All sets of CFRP woven fabric systems were fabricated by St. Bernards Composite Ltd.

The laminates produced have been ultrasonically scanned to identify any internal defects, mainly associated porosity or delamination, and marked with waterproof marker pen to highlight the presence of the defects. Defects were more prominent in the thicker panels of five harness satin with less porosity observed in thinner panels. During the sectioning of the panels, care was taken to avoid the areas containing defects.

Composite/steel joints were investigated. A high yield strength stainless steel (with σ_y = 720 N/mm^2) of thickness 3 mm was used. This was chosen because the high yield strength prevents bearing failure in the steel and this means that it can be reused. A range of size of steel plates and hole sizes (a total of 16 sets) was prepared corresponding to the different joint geometries tested.

The fastener systems used in this joint configuration system are steel washers and steel bolts. Bolt fasteners and washers with 5 mm holes are commercially identified as M5 and those for use with 10 mm diameter holes are designated M10. In this study, high grade stainless steel bolts with protruding hexagon bolt head, in accordance with standard in DIN 913, were used. The fastener systems are able to provide lateral constraint through joint thickness which is expected to improve the joint behaviour by contributing to a higher bearing strength. This study used a consistent size of washer (and associated clamping area) and bolt type throughout all joints in the test matrix to avoid any effects from variations in these test parameters. A4 stainless steel washers are used for the two bolt sizes as specified in DIN 125A, M5 (outer diameter, d_{wo} = 10 mm and inner diameter, d_{wi} = 5 mm) and M10 (d_{wo} = 21 mm and d_{wi} = 10 mm). Protruding fasteners are chosen rather than countersunk fastener because they offer higher bearing strength. On the contrary, singularity stress is exhibited at the head tip in countersunk fasteners. Service limit state (SLS) in mechanically-fastened joints requires the composite plate to fail before the fastener systems.

Cutting of composite panels

The available CFRP panels are measured and exact measurements are drafted in CAD program (SOLIDEDGE). This program is easy to use and is able to optimize the number of plates produced as required. For each cut edge, a 3 mm gap was needed to allow for the width of the cut and this was taken into account during drafting stage. Thicker lay-ups with significant region of internal defects from C-scan are drafted particularly carefully to ensure the coupons are free from defects.

CFRP panels were sectioned with a water-cooled diamond saw to produce the required number of coupons. A slow cutting speed was used to achieve a better finish. The coupons are numbered and labelled according to the respective series using a designated code. Following cutting, the plate width and thickness are then measured and recorded for future reference. A total of 624 coupons were prepared.

Holes of diameter 5 mm or 10 mm were introduced into each coupon using low helix and high speed steel drill suitable for drilling thermoset polymer. A sharp angled point to the drill bit is required to reduce the end pressure and to minimize matrix burning and break away during laminate exit. A steel jig was used to achieve the required end-distance (of *e/d* ratio) and to hold the specimen in place while drilling. Drilling process was conducted as carefully as possible and all holes were inspected visually to ensure there was no hole break-out.

Bolted lap joint configurations

The two assemblies of bolted lap-joint tested were the single-lap bolted joint (SLJ) and the double-lap bolted joint (DLJ) as illustrated in Figures 3 and 4, respectively. The bolted joint system used in practice is determined from the applications, environment, cost, site location, etc. Single-lap joint is commonly used in aerospace application to reduce weight penalty, but is subjected to bolt tilting and failure due to secondary bending phenomenon. Primary bending in SLJ can be alleviated by providing spacer of similar plate thickness at

VOL. 11, NO. 3, FEBRUARY 2016 ISSN 1819-6608
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the end edge of the plates. On the other hand, bolted double-lap joints usually exhibit higher strength because of the lack of bending. The bolt was a good fit to the specimen hole (effectively a perfect-fit), so the effect from clearance was negligible. Care was taken on CFRP bore hole to be free from contacting with bolt thread.

Two steel washers are provided below the bolt head and above the nut respectively in both joint types. The bolt head should be large enough to reduce the pre-load relaxation. The installation torques studied was a finger-tight condition and a clamped condition of 5 N m (see next section). Finger-tight condition (equivalent to about 0.5 N m) is always used in composite joint design in many applications as worst case scenario for safety factor. Two fastener diameters were used enabling any hole-size effect to be investigated.

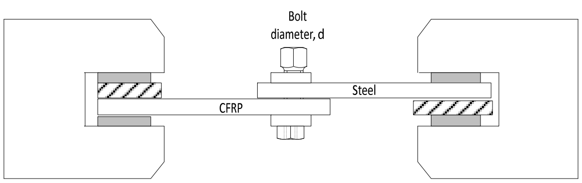

Figure-3. Schematic of single-lap joint configuration used in present study.

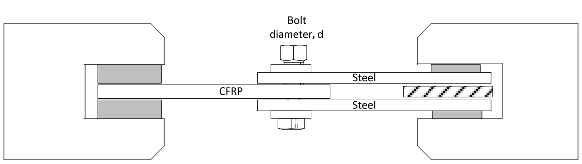

Figure-4. Schematic of the double-lap joint configuration used in present study.

Finger-tight conditions and clamp-up of 5 N m are investigated in this study to investigate the change in failure behaviour with clamp-up torque. Torque wrench of suitable torque limits (0 - 20 N m) is used to provide a sufficient and accurate amount of clamp-up. The torque wrench is calibrated prior to first use as indicated in manufacturer's guidelines. Clamp-up is applied slowly to ensure that joints are not over-clamped. All joint assemblies were tested immediately after clamp-up to eliminate the effects from bolt relaxation.

Test matrix

Laminates of zero or low numbers of 45º plies have a low shear strength and the stress concentrations at the hole edge is sensitive to edge distance. According to Collings (1977), critical *e/d* for cross-ply CFRP laminates is given as 5 (transition from shear-out failure to bearing failure). In this study, *e/d* ratio is chosen as 6 for cross-ply and 4 for quasi-isotropic laminates. On the other hand, critical *W/d* is given as 3 in cross-ply lay-up but 4 in quasi-isotropic stacking sequence. Therefore, plates of 2 <*W/d* < 5 are provided for quasi-isotropic lay-up and 2 <*W/d* < 3 for cross-ply lay-up. This combination of *e/d* and *W/d* is chosen to eliminate shear-out and to study the net-tension/bearing transition range of joint geometries.

The test matrix is shown in Table-1. Each laminate series is tested in both single-lap joint and double-lap joint geometry. A detailed diagram for one lay-up is shown in Figure-5. As indicated above, the main aim in current work is to study net-tension failure, for any given lay-up (material type and thickness). The end distance is fixed and the joint width is varied accordingly. Cross-ply lay-up systems have *W/d* ratio between 2 and 3. For the quasi-isotropic systems, *W/d* ratio is varied in the range of 2 - 5. Furthermore, two different hole sizes (*d* = 5 mm, *d* = 10 mm) and two clamp-up conditions (FT (≈ 0.5 N m) and T = 5 N m) were studied.

Table-1. Range of test parameters investigated for CFRP DLJ and SLJ tests.

Laminate	Thickness, *t* (mm)	*e/d*	*W/d*	Hole size, d (mm)	Clamp-up torques
PX2	0.51	6 (fixed)	2 - 3	5, 10	FT, 5 N m
PX4	1.03	6 (fixed)	2 - 3	5, 10	FT, 5 N m
5X2	0.81	6 (fixed)	2 - 3	5, 10	FT, 5 N m
5X4	1.60	6 (fixed)	2 - 3	5, 10	FT, 5 N m
PQ4	1.02	4 (fixed)	2 - 5	5, 10	FT, 5 N m
PQ8	2.03	4 (fixed)	2 - 5	5, 10	FT, 5 N m
5Q12	4.62	4 (fixed)	2 - 5	5, 10	FT, 5 N m

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	W/d	Hole diameter	Preload torque
PQ4 (*e/d* fixed *t* fixed) (DLJ/SLJ)	2	*d* = 5 mm	Finger-tight
			T = 5 N m
		d = 10 mm	Finger-tight
			T = 5 N m
	3	*d* = 5 mm	Finger-tight
			T = 5 N m
		d = 10 mm	Finger-tight
			T = 5 N m
	4	*d* = 5 mm	Finger-tight
			T = 5 N m
		d = 10 mm	Finger-tight
			T = 5 N m
	5	*d* = 5 mm	Finger-tight
			T = 5 N m
		d = 10 mm	Finger-tight
			T = 5 N m

Figure-5. Range of tests carried out on PQ4 laminate (16 different *W/d*, hole diameter and clamp-up combinations for each joint type).

Mechanical testing

The tensile testing of the bolted lap-joint systems is described next. The aim of the testing was to determine the load-displacement response, the ultimate strength and associated failure mechanisms. In general, at least three specimens for each test matrix joint were tested and the average bearing stress at failure was recorded. However, due to limited panel size available, some joint systems of certain lay-up have only two coupons. The numbers seem sufficient as most test configurations showed good reproducibility.

ASTM Standard D3039B was referred to in designing the test set-up for measuring quasi-static tensile strength properties of bolted joints. Quasi-static tensile loading on bolted joints was carried out using INSTRON 1175 upgraded to 5550, which is located in Mechanical Testing Laboratory, University of Surrey. The cross-head speed used was 0.5 mm/min and the load cell capacity was 100 kN. Data required from the test are applied load and displacement which is obtained from PC data log recorded every second. For larger hole size (*d*= 10 mm) coupons, a servo-hydraulic fatigue machine was used due to the capability of this machine to accommodate the largest coupon width of 50 mm. Samples of double-lap joint and single-lap joint assemblies installed experimentally are displayed in Figure-3 and Figure-4 respectively.

EXPERIMENTAL RESULTS

Bearing stress at failure as a function of *W/d* and material types

The bearing stress at failure of all specimens (double-lap joints and single-lap joints) increased as a function of *W/d*, as expected. As indicated already, joints with low *W/d* typically failed in net-tension mode and joints with larger *W/d* failed in bearing mode (followed by bolt pull through in the single-lap joint). Net-tension failures at low *W/d* were sudden and catastrophic. At intermediate *W/d* net-tension failure was preceded by local bearing damage (more obvious in finger-tight). At larger *W/d*, there was a full bearing failure in some laminates with peak-load corresponding to a through-thickness compression fracture of the laminate at the washer edge.

 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Table-2. Maximum bearing stress at failure in different lay-up.

Lay-up	**Bearing stress at failure** (N/mm²)							
	Double-Lap joint				**Single-Lap joint**			
	***d* = 5 mm**		***d* = 10 mm**		***d* = 5 mm**		***d* = 10 mm**	
	FT	**T=5*N m***	**FT**	**T=5*N m***	**FT**	**T=5*N m***	**FT**	**T=5*N m***
PX2	513*	992*	413	622*	404*	778*	281*	365*
PX4	525*	717*	480	557*	496*	670*	444*	519*
5X2	495*	664*	364*	488*	428*	648*	332*	428*
5X4	468*	605*	435*	441*	491*	600*	411*	470*
PQ4	614	1005	544	789	505	789	435	547
PQ8	656	905	570	706	581	676	528	591
5Q12	-	-	610	576*	-	-	560	548

*Coupons observed to fail in net-tension mode

Table-2 shows the highest bearing stress at failure achieved in each laminate for 5 mm and 10 mm holes in the finger-tight and clamped condition. There are a number of aspects of behaviour apparent from the results in the table. With regard to the magnitude of the bearing stresses at failure achieved they are greater than the base-line tensile strengths of the laminates, reported in Belmonte *et al*. (2004). True bearing failure was seen more readily in the quasi-isotropic lay-ups compared to the cross-ply lay-ups for the range of joint geometries investigated here. This reflects a combination of the stress state around the hole and the relative values of the tension and (constrained) compression strengths. It is likely that testing the cross-ply at larger *W/d* (*W/d* >3) could lead to further increase in strength and a change in failure mode. It is apparent that the bearing stress at failure of the joints with the 5 mm diameter holes exceed those of the joints with 10 mm diameter holes. This is a consequence of the greater role of the friction load transfer in the joints with the smaller hole size.

Figure-6 shows the bearing stress at failure as a function of joint width for clamped PQ8 DLJ and SLJ geometries with the bolt hole size of 10 mm. The trends are as expected with the DLJ moving from net-tension to bearing failure and the SLJ moving from net-tension to bearing/bolt pull through. Cross-ply and quasi-isotropic lay-up in DLJs demonstrated transition from net-tension to bearing failures at *W/d* = 3 and *W/d* = 4, respectively, with finger-tight conditions. In clamped condition, this value is increased to *W/d* = 5 in quasi-isotropic lay-up (Figure-6a) but all lay-up in cross-ply gave net-tension mode (note that maximum is *W/d*=3). However, transition to bearing/pull through failures in SLJs with similar lay-up is given at *W/d* = 4 (Figure-6b).

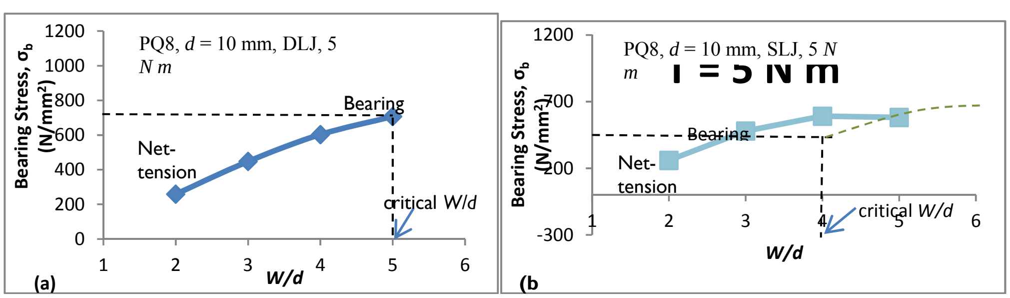

Figure-6. Bearing stress at failure as a function of *W/d* for PQ8 showing transition from net-tension to bearing failures (a) DLJ (b) SLJ.

As indicated previously, for most configurations a minimum of three composite plates coupons are tested and average values of bearing stress at failure are taken for each joint configurations investigated. Full datasets of experimental work on bearing stress at joint failure are given in Appendix A. Plain weave fabric system shows higher bolted joint strength as compared to five-harness satin fabric system. Similar trends are also observed by Belmonte (2004) for open-hole strength and are attributable to the higher fibre volume fraction of plain

VOL. 11, NO. 3, FEBRUARY 2016 ISSN 1819-6608
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weave, even though plain weave exhibited higher degree of crimp as compared to equivalent five-harness satin fabric. The higher fibre volume fraction in PW fabric is attributed to the ability of the fabric to nest the fibres tighter.

The effect of the joint parameters on bearing stress at failure is discussed in more detail in sub-section below. It is apparent from the overall results that clamped joints are stronger than finger-tight, the 10 mm bolt gives weaker than joints with the M5 bolt and double-lap joint are stronger than single-lap joint.

Effect of hole size

This section considers the effect of hole size at constant *W/d* ratios [note that a larger hole size gives a larger *d/t* ratio]. Figure-7 shows the bearing stress at failure as a function of normalised joint width for PQ4 laminates, at two different hole sizes, in clamped condition. Similar trends were seen in other sets of results. There is a reduction in bearing stress with larger hole size regardless of failure modes. The stress concentration effect is independent of the hole diameter at a constant *W/d*. Although there is less frictional load transfer in larger *d/t* ratio specimens, the bearing stress at failure are significantly lower. Hence there is a hole size effect associated with the larger volume of highly stressed material for the larger hole size. This agrees with Belmonte's (2004) findings (and with numerous other researchers) on the open-hole and bolted joints problem.

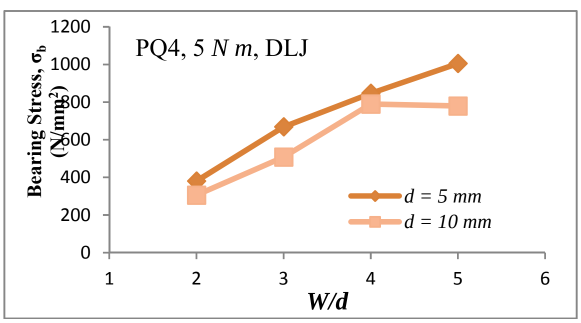

Figure-7. Bearing stress at failure as a function of normalised joint width for PQ4 laminates at two different hole sizes.

Effect of bolt loads

As expected, the failure load increased with bolt load. This is because the clamp-up provides lateral support and requires larger applied load, *P* to overcome friction. Applied bolt tightening significantly increased the critical *W/d* ratio values. For example in PQ4 lay-up, critical *W/d* is found to be 4, for the finger-tight conditions, and increased to 5 for clamped condition. This is because the constraint (as a result from clamp-up) restrained the movement of washers and bolt leading to higher strength and produced net-tension mode.

Figure-8 compares the effects of finger-tight conditions and clamped torque of 5 N m in PQ4 and PQ8 lay-up at 5 mm hole size. The effect from clamp-up is more apparent in thin laminates than thicker laminates. This is likely to be because the load transfer through friction is less in thicker laminates. Hence for the thicker laminates, there is less difference in bearing stress at failure between clamped and finger-tight conditions.

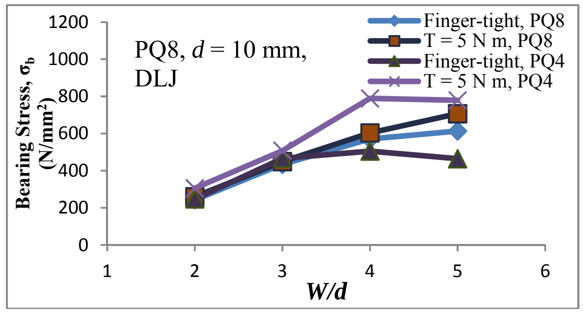

Figure-8. Bearing stress at failure as a function of normalised joint width for PQ8 and PQ4 laminates at two different clamp-up conditions.

Effect of joint type

Figure-9 shows the bearing stress at failure as a function of normalised joint width for PQ4 laminate for different joint types and bolt loads. In double-lap joint, cracks are initiated and propagated uniformly through the thickness. On the other hand, single-lap joint configuration, secondary bending is observed and fractures initiates at bottom plane (on most tension side of specimen) and propagate through the thickness to top plane (the less tension side). This is shown in Figure 10. Although secondary bending is associated with strength reduction, the tensile failures in the SLJs did not show consistently lower strengths than the DLJs. It may that this failure mechanism might be stronger than double-lap joint configuration due to redistribution of stresses to adjacent lay-up if current lay-up had failed. However, only certain lay-up and joint geometries showed these characteristics, especially in thicker plates.

In single-lap joints, with *W/d* ratio found to ~ 4 for quasi-isotropic and *W/d* ~ 3 for cross-ply) the washer edge is found to dig into the CFRP specimen due to bolt bending and tilting. Apart from showing bearing failure as exhibited in double-lap joint, the single-lap joint is prone to show washer bending in composite plate. On the other hand, joints with smaller *W/d* ratio showed net-tension failure mode in both joint configurations.

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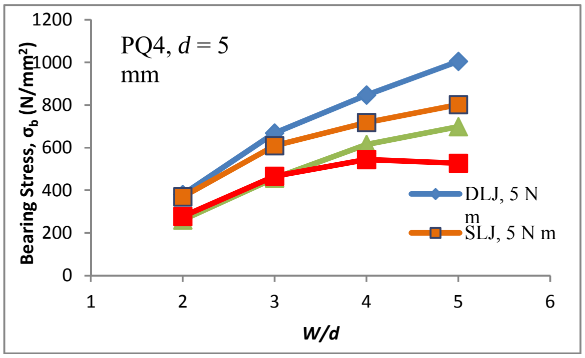

Figure-9. Bearing stress at failure as a function of normalized joint width for PQ4 laminate for different joint types and clamp-up condition.

Figure-10. Crack propagation through thickness elevated from bottom plane and top plane in single-lap joint.

CONCLUSIONS

An extensive experimental study has been carried out on the bearing stress at failure of bolted joints assembled using woven fabric CFRP based on two fabric types and of two lay-ups. Joint geometries were chosen to give failure in net-tension or bearing. The trends of the experimental data were consistent with previous studies in the literature, although investigations of fabric systems are limited. Clamped joints were stronger than pinned joints. DLJs were stronger than SLJs. There was a hole size effect whereby joints with holes of diameter 10 mm were weaker than those with a hole diameter of 5 mm.

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