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SPECIFIC BEARING STRENGTH OF BOLTED COMPOSITE JOINT WITH DIFFERENT GLASS FIBER REINFORCEMENT

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ABSTRACT

Bolted joints are vastly used in many applications and constitute an integral part of structural components. The reliability of the bolted joints depends mainly on the local laminate bearing strength, which is significantly influenced by various parameters. This paper presents the experimental study on the effect of different reinforcement and geometrical designs of glass reinforced composite on the bearing strength of a double-lap, single bolt joint under tensile load. Four different types of glass fibre reinforcements were prepared, consisting of chopped strand with weight of 600 g/m^2, plain weave of 800 g/m^2 and 290 g/m^2 and 2/2 twill weave of 200 g/m^2. The composite coupons were designed with a series of width to bolt diameter (W/D) and edge distance to bolt diameter (E/D) ratios, varied as 2, 3, 4 and 5 and 1, 2, 3, 4 and 5, respectively. A bearing test was conducted according to the ASTM standard D5961/D5961M-10 to determine the specific bearing strength of the laminates. It was found that the plain weave of 800 g/m^2 single-bolted laminates provided highest specific bearing strength compared to other composites. The critical point of the geometric parameters by which the failure mode changes from shear-out and net-tension mode to bearing mode was also identified. The laminates with large geometric parameters failed mainly in the desired bearing failure. The analysis specifically considers the significant influence of the geometrical and material parameters on improving the structural performance of the composite bolted joints.

Keywords: composites, bolted joint, bearing test, failure modes.

INTRODUCTION

The use of bolted joints in composite structures are unavoidable in many applications, due to its simplicity in disassembly for repair and maintenance, low cost and free from surface treatments [1]. Structures can be connected using bolted joints in single or double-lap configurations with a single or multi-bolts. These joints require holes to be drilled in the structure, thus causing high stress concentration which subsequently reducing the strength of the structure. For a reliable design in the bolted joints, the work should take into account on how the catastrophic failure of the joint could be avoided; for an instant, the failure load could be increased by reducing the stress concentration around the bolt-hole.

The reliability of the bolted joints depends mainly on the local laminate bearing strength, which is significantly influenced by different parameters including geometric, fastener, design and material parameters [2-5]. Içten and Karakuzu [6] has observed that the bearing strength of a pin loaded carbon–epoxy composite plate was significantly influenced by different fibre orientation. The 0° composite plate could experience the maximum bearing strength, while the minimum strength was observed for the 45° composite plate. In addition, the bearing strength was found to decrease with increasing the fibre orientation angle from 0° to 45°.

Similar result was also observed for $[0°]_8$ laminate, where the highest bearing strength was achieved with the shear out failure mode [7]. From the same work, the net tension failure mode was seen in the bolted joints with fibre orientations of $[90°]_8$. But, when the 45° ply was stacked together with 0° ply as in $[0°/0°/45°/45°]_s$, the bearing strength and failure load of the joint have been improved in comparison to $[0°/0°/30°/30°]_s$ and $[0°/0°/45°/135°]_s$ [8]. In other work, Pakdil [9] has also found that the orientation of $[0°/0°/45°/45°]_s$ provided the highest bearing strength and failure load in comparison to other stacking sequences of $[0°/0°/30°/30°]_s$, $[0°/0°/90°/90°]_s$ and $[0°/0°/60°/60°]_s$, which the latter presented the weakest joint.

In addition, several studies have been comprehensively investigated the effects of geometric parameters on the bearing strength [2, 6, 8, 10]. The bolted composite joint typically comprise of a thickness (t), width (W), edge distance (E), and hole diameter (D). The effects of edge distance to hole diameter ratio (E/D) and width to hole diameter ratio (W/D) have been considerably investigated. In a recent study, the optimum geometric parameters for both the bearing strength and failure modes have been analysed with respect to E/D and W/D of a single bolt, single lap composite joint [11]. Earlier study has found that the bearing strength has increased with the E/D and W/D ratios for different ply orientations of single-bolted glass reinforced epoxy composite plates [12]. However, Yilmaz and Simazçelik [13] showed that providing sufficiently large end distance (E) and width (W), tension and shear out failures could be suppressed, achieving full bearing strength potential.

Nonetheless, increasing W/D and E/D ratios beyond a certain value has an insignificant effect on the ultimate load capacity. Okutan *et al.* determined these values as 2 and 3 for E/D and W/D, respectively for a pin-loaded woven glass fibre reinforced epoxy laminate [14]. At this point, a transition in failure modes was observed.

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On the other hand, it was found that the failure mode of the woven fabric laminate with different densities was a bearing mode for specimens with W/D > 2 and E/D > 2, and maximum bearing strength at W/D=4 and E/D=4 for all densities [15].

Over the years, it was observed that the investigative work on the bearing strength behaviour of the laminates with different woven linear densities was limited. In a particular study, Atas [16] examined experimentally the bearing characteristics of pinned joints in an orthogonal fabric and a non-orthogonal fabric with small weaving angles. The weaving angles between interlacing yarns have caused undesirable damages and thus, reduced the load carrying capacity of the laminates. But, the condition could be improved by orientating the stacking sequence in different directions with respect to the symmetry plane in order to take the advantage of the weaving design.

To a certain extent, this study presents the investigation on the effect of different fabric designs of glass reinforced composite on the failure load and bearing strength of a double-lap, single bolt joint under tensile loading. The explicit correlation between the bearing strength and failure modes is examined. The analysis specifically considers the significant influence of the geometrical changes on the bearing strength and desirable failure modes.

METHODOLOGY

Materials and specimen preparation

The glass reinforced polymer composite laminates were fabricated using a vacuum bagging processing technique. Four different types of glass fibre reinforcements were prepared, consisting of chopped strand with weight of 600 g/m2, plain weave of 800 g/m2 and 290 g/m2 and 2/2 twill weave of 200 g/m2. A two-part epoxy resin was used as a matrix material with the mixing ratio of 2:1 by weight (epoxy resin of CP 216Z2 PART A: hardener of CP 216Z2 PART B). Eight plies were laid up in the same orientation [0]8, except for the chopped strand laminate, prepared at a random orientation.

Vacuum debulking was performed during the layup using a JK-VP-3C single stage vacuum pump of Shanghai Jingke Scientific Instrument with ultimate vacuum of 5 Pa, with an Airtech-Airflow 65R hose and VV 401 Airtech vacuum port were connected to the vacuum bagging setup. The curing cycle was performed using a Grieve WRC 566-500 to include one dwell section for 120 minutes at 80±10°C. This cure cycle entailed heating and cooling rates of 1.7°C/min. A primary vacuum pump connected to the vacuum bag, supplied a vacuum pressure of -1 bar to extract the air throughout the curing process.

Following the debagging, the laminates with the final thickness of 5.2 mm were cut to size using a jig saw with the blade of a tungsten carbide grit edge. Subsequently, a tungsten carbide sanding block was used to refine the cutting edge and to reduce the edge delamination. The laminates were drilled in undersize holes, and the reamer was used to achieve the final diameters. The composite coupons were designed with a series of width to bolt diameter (W/D) and edge distance to bolt diameter (E/D), varied as 2, 3, 4 and 5 and 1, 2, 3, 4 and 5, respectively, while keeping the thickness (t), the bolt-hole diameter (D), and the free length (L) constant at values of 5.2mm, 8mm and 140mm, respectively. The geometry of the experimental specimens for single-bolted glass reinforced epoxy composite is illustrated in Figure-1.

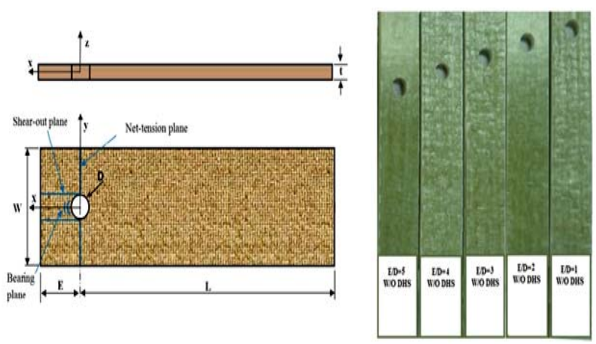

Figure-1. The geometry of the experimental specimens for single-bolted glass reinforced epoxy composite.

Bearing test

A bearing test was conducted according to the ASTM standard D 5961/D 5961M-10 procedures A [17]. The experiments were carried out using an INSTRON 3367 universal testing machine with 30 kN loading capacity in tensile loading at a rate of 0.5 mm/min as shown schematically in Figure-2.

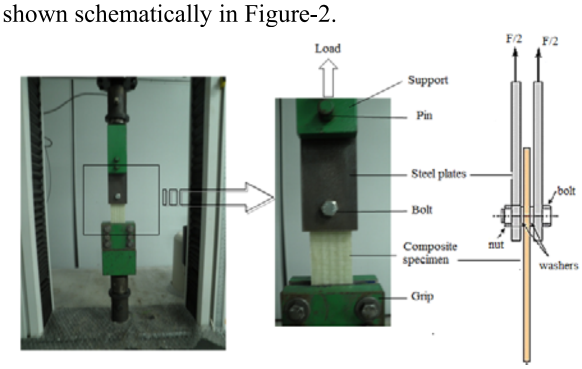

Figure-2. Experimental setup for bearing test of single-bolted glass reinforced epoxy composite coupons.

A steel bolt was inserted into the bolt-hole with two steel washers located between the composite specimen and the steel plates. The upper end of the steel plates was connected to a special fork with the aid of two pins attached to the machine crosshead, with the other end remained fix at the grips. The steel bolt was hand-tightened, which represents the lowest bolt torque. The load was applied until the final failure or when the bolt displacement reached 8 mm, which was equal to the bolt-hole diameter.

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The load-bolt displacement curve was obtained through the data acquisition system utilizing Bluehill 2 Software, and the bearing stress was subsequently calculated as follows:

$$\sigma_b = \frac{F}{D.t} \tag{1}$$

where F, D, and t represent the failure load (N), bolt-hole diameter (mm), and composite plate thickness (mm), respectively. Subsequently, the bearing strain, ϵ_b can be derived by dividing the bolt displacement over the bolt-hole diameter:

$$\epsilon_b = \text{(Bolt displacement)}/D \tag{2}$$

Given the variation in the densities of the laminates, the specific bearing strength [MPa/(g/cm^3)] was evaluated for each laminate by normalizing the bearing strength with the specified density using the following equation:

$$sp\sigma_b = \frac{\sigma_b}{\rho} \tag{3}$$

where ρ is the density of the composite material (g/m^3), and were determined according to the ASTM D 792 standard [18].

RESULT AND DISCUSSION

Bearing strength of different glass reinforcements

Load versus bolt displacement curves for all laminates were plotted as shown in Figure-3. It was observed that the material responses have started with a linear trend and subsequently, as the displacement progressed, substantial load drops were evidently observed. These load drops were attributed to the qualitative indication of the first fiber failure. The laminate then continued to sustain more loads as the other lamina remained intact. An offset line to the linear part of the curve was plotted with the offset distance at 0.02 of the bolt-hole diameter.

As a result, three values of the failure load can be extracted from the load-displacement curves. The first value represented the first failure load identified by the first drop in the load, indicating the first fiber failure (F1st). The second value was obtained by intersecting the offset line with the load-displacement curve at a point (F2%). Finally, the third value was attributed to the maximum load value of the final failure, representing the ultimate load (Fu).

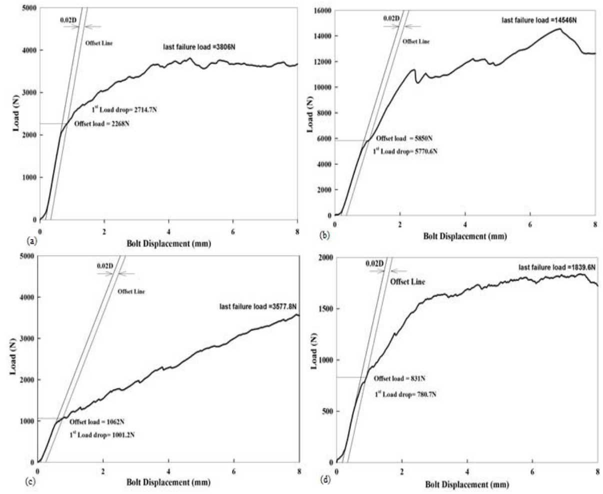

Figure-3. Load-displacement curves for single-bolted laminates with different glass reinforcements.

The results were further computed from Figure-3 for the variation (in %) of the ultimate failure loads with respect to the 2% offset load. The data indicated that the variations were 40.4%, 59.78%, 70.3% and 54.8% for chopped 600, plain weave 800, plain weave 290 and twill weave 290, respectively. While, the variation (in %) of the ultimate failure loads with respect to the first failure loads were calculated as 28.6%, 60.3%, 72% and 57.5% for those of chopped 600, plain weave 800, plain weave 290 and twill weave 290, respectively. While in the terms of the bolt displacement, the ratio (%) of the bolt displacement at the ultimate failure load to the bolt displacement at 2% offset load were computed as 81.2% (chopped 600), 84.7% (plain weave 800), 90.5% (plain weave 290) and 87.9% (twill weave 290). Also, the ratio (%) of bolt displacement at the ultimate failure loads to the bolt displacement at the first loads were found to be 71.6% (chopped 600), 85.3% (plain weave 800), 92% (plain weave 290) and 88.7% (twill weave 290).

From the above findings, it was found that the variations between the ultimate failure load as well as the displacement with respect to the 2% offset and the first failure load (and displacement) is almost the same, except some variations were observed for those of the chopped laminate.

The specific bearing strengths of the bolted joint composite laminates were further analyzed as shown in Figure-4. Among the laminates, it was found that the specimen with the plain weave of 800 g/m2 glass fibre has attained the highest specific bearing strengths (sp σbu), with percentage increment of 58.6%, 37.3% and 54.7% than those laminates of chopped 200g/m2, plain weave 200g/m2 and twill weave 290g/m2, respectively. While, the laminate also achieved higher first specific bearing strength (sp σb1st) of 25.6%, 55.7% and 51.6% in comparison to those of chopped laminates, plain weave 200g/m2 and twill weave 290g/m2, respectively. In addition, for the 2% offset specific bearing strength (sp

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σby), the laminate has experienced much higher properties compared relatively to those other counterparts, achieving 38.7% (to chopped 200g/m2), 53.7% (to plain weave 200g/m2) and 49.2% (to twill weave 290g/m2). These results can be attributed to the fact that the particular laminate consisted of the highest fibre volume content in comparison to other composite specimens.

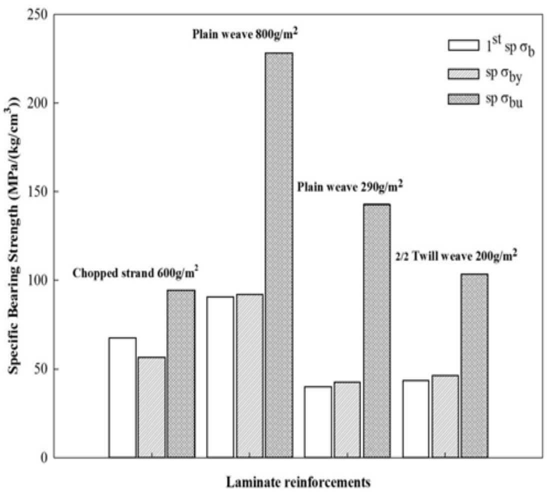


Figure-4. Specific bearing strengths of the bolted joint composite laminates of chopped strand 200g/m2, plain weave 200g/m2 and twill weave 290g/m2.

Effect of geometrical designs of composite bolted joint

Results of the failure loads for the single-bolted laminates with different W/D and E/D ratios are summarized in Figure-5. Note that, the first failure load was indicated by the first drop in the load-displacement curve (i.e. first fibre failure) and the last failure loads represented the ultimate load that the laminate could sustain prior to the final rupture. It has been observed that the laminates were able to further uphold the load of about 1.4% to 51.4% after the first fibre failure. The laminates with large geometries (W/D and E/D) were found to retain more loads after the first failure. For the narrow laminates with small edge distances (i.e. W/D=2 and E/D=1), the minimum failure load was achieved for both of the first and the last failure loads. However, the widest laminates with the longest edge distance (i.e. W/D=5 and E/D=5) have experienced maximum failure load for both types of the failure loads. It was found that between the range of the tested W/D ratios, the results demonstrated that there was a marked rise in the failure load when the E/D ratio has increased from 1 to 2.

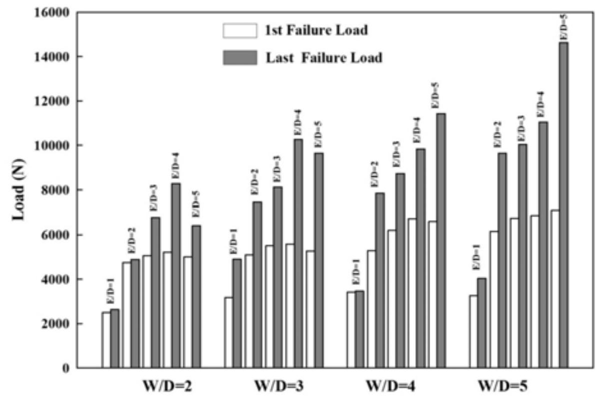
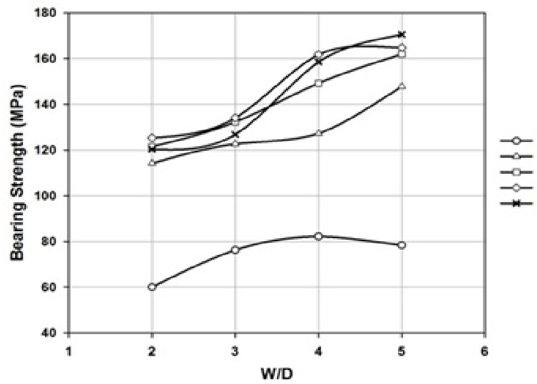


Figure-5. Failure loads for the single-bolted laminates with different W/D and E/D ratios.

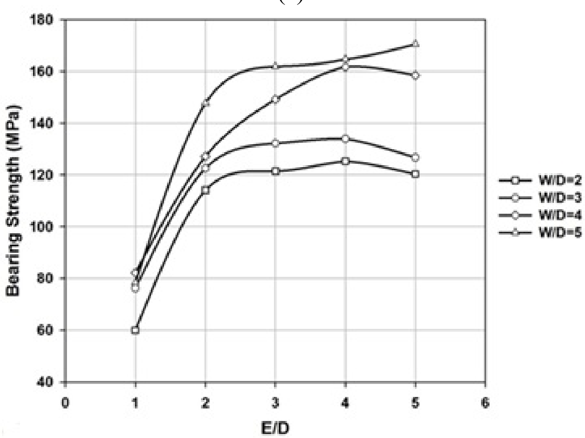
The effect of width and laminate edge distance of the laminates on the bearing strength is shown in Figure 6. For laminates tested at all range of E/D ratios, the small width ratio (W/D=2) provided the smallest bearing strength. This indicated that the narrow specimens had high stresses in the net-tension area which led to the tendency of net-tension failure. Generally, bearing strength increases as the width ratio increases. On the other hand, it was observed that the laminate would reach the ultimate bearing strength value at E/D≥3 for all W/D ratios. Bearing strength increased with the E/D ratio, but beyond E/D=3 the bearing strength progressed almost constantly or changed with slight differences. The small edge distance ratio (E/D=1) provided the smallest bearing strength but highest shearing stresses, which indicates that specimens with a small edge distance are prone to shear-out failure.

Failure modes

Generally, there are three basic failure modes that could occur in the composite bolted joints subjected to loading. They are known as net-tension, shear-out, and bearing failure modes, as well as the combinations of two different modes. These different modes could be easily distinguished from the load-displacement curves following the bearing test. As mentioned earlier, the first portion of the load-displacement curve represented the linear proportion of the load with displacement (or stress vs. strain). Following the linear part of the curve, some specimens failed abruptly, which was indicated by the sharp load drop, and causing the net-tension failure mode to occur. In some specimens, a gradual decrease in the load took place (i.e. for W/D=5, E/D=1); this will initiate a different failure, known as shear-out failure mode. Both failure modes were catastrophic and were considered as non-safe failure modes. The third mode was a bearing failure mode, occurred when the specimens continued to hold the loading for large values of the bolt displacements. This failure mode is a more desired mode for the design of the composite bolted joint and occurs gradually in compression action to the composite opposite to the bolt shank, providing a prior warning before the final failure of the structure. Figure-7 indicates the response curves of the laminates illustrated by the photo of the failure modes.



(a)



(b)

Figure-6. The effect of (a) W/D and (b) E/D on bearing strength of single-bolted laminates.

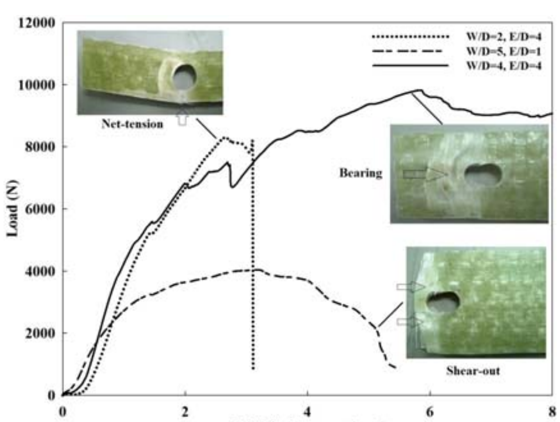


Figure-7. The relation of load-displacement curve with specific failure modes with of single-bolted laminates.

It was observed that a critical point of E/D and W/D could be quantified, whereby beyond these values the failure mode changes from the net-tension or shear out to bearing failure. It was also found that this critical point has a significant relation to the geometric parameters (E/D and W/D). Therefore, the details of the failure modes for different joint configurations have been highlighted in a failure map for the laminates without the DHS, in Table-1. It was clearly indicated that the laminates with W/D ≥3 and E/D ≥3 failed noticeably in the bearing failure mode. On the hand, the laminates with small W/D ratios have failed in the net-tension mode except for those laminates with the small edge distance ratio (E/D ≤2). Whilst, all the laminates with small edge distance ratios (E/D ≤2) have shown signs of shear out failure.

Table-1. Failure mode of the single-bolted laminates for the tested ranges of W/D and E/D.

W/D	E/D				
	1	2	3	4	5
2	S	B-S	N	N	B-N
3	S	B-S	B	B	B
4	S	B-S	B	B	B
5	B-S	B-S	B	B	B

CONCLUSIONS

The study presented the experimental work on the effect of different reinforcement and geometrical designs of glass reinforced composite on the failure load and bearing strength of single-bolted laminates under tensile loading. It was found that the plain weave of 800g/m2 laminate has attained the highest specific bearing strength compared to the other glass laminates. The finding has further established that the laminates with small geometric parameters obtained small bolt-hole elongation before exhibiting the final failure, whereas those with large geometric parameters obtained a large bolt-hole elongation and demonstrated warning signs before the final failure. Narrow laminates obtained the smallest bearing strength, which led to the net-tension failure mode. Bearing strength has increased with the increase in the edge distance until the optimum bearing strength at a laminate's edge distance for all width ratios. The critical point of the geometric parameters by which the failure mode changes from catastrophic failure (shear-out and net-tension mode) to safe failure (bearing mode) was obtained. Laminates with large geometric parameters failed in the bearing failure mode, whereas narrow laminates failed in the catastrophic mode.

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