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The Effect of Defence Hole System on the Failure Load and Bearing Strength of GFRP Bolted Joint

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Abstract The introduction of an auxiliary holes (or defence hole system) near the main hole has provided several benefits in redistributing the stress flows, hence increasing the failure load. This paper presents the experimental study on the effect of the defence hole system (DHS) on the failure load and bearing strength of the glass fibre reinforced polymer (GFRP) composite bolted joint. A series of bearing tests have been carried out on a double lap bolted joint for a wide range of geometric parameters for the cases of without and with the DHS. It was found that adding the auxiliary hole near the bolt-hole has contributed in improving the failure load up to 34.81% increment, with most of the laminates with the defence hole system have failed at higher failure loads.

Keywords: *defence hole system, composite bolted joint, bearing test, failure load*

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1. Introduction

The use of bolted joints in composite structures are unavoidable in many applications, due to its simplicity in disassembly for repair and maintenance [1], low cost and free from surface treatments [2-3]. Bolted joint is the most efficient type of mechanically fastened joint which comprises of configurations such as pinned, rivet, etc. [4]. 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. Therefore, for the 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.

Over the years, great efforts have been devoted to investigate the stress concentration around the holes in the isotropic [5,6,7] as well as in the orthotropic plates [8,9,10,11], focusing on the optimization of the holes to achieve stress reduction. The work included the use of reinforcement around the hole in an isotropic plate under in-plane loading using a ring of composite materials [12], as well as by increasing the thickness of the laminated composite in the vicinity of the hole [13]. Tosh and Kelly [14] has applied a trajectory fibre steering aligned with the principle stress vectors to increase the strength of a composite specimen containing an open hole and a pin-loaded hole, achieving the strength improvement of 62% and 85%, respectively. In addition, an unique method has been proposed by introducing an auxiliary holes in the low stress regions near the main hole which is known as the defence hole system (DHS). The method allows the flow of the stress trajectories to be redistributed around the main hole, which helps in smoothening the flow of the stress trajectories.

A considerable amount of studies in the literature have investigated the optimization of the size, shape, and the distance of the auxiliary hole from the main hole in the isotropic plate. On the other hand, relatively limited literatures have been published to demonstrate the use of DHS in the orthotropic plate. Akour et al. [15] has investigated the effect of position, size and shape of the DHS using both photoelasticity and numerical methods, and has revealed that the elliptical DHS could reduce up to 31.7% of the stress concentration. In addition, Rhee et al. [16] observed that the size optimization and location of the auxiliary holes has minimized stress concentration in the orthotropic composite. In addition, by introducing four coaxial defence holes on either side of the circular main hole could lead to a 24.4% reduction in stress concentration in the rectangular isotropic plate and a 31% reduction in the orthotropic counterpart [17].

Nonetheless, the question remains on how the introduction of DHS in the bolted (or pinned) joint could significantly improve the stress reduction, hence increasing the failure load and bearing capacity of the bolted joint assembly of reinforced composites. Therefore, this study presents an experimental analysis on the effect of the DHS on the failure load and thus, the bearing strength of the single-bolt, double-lap composite bolted joint.

2. Experimental Materials and Methods

2.1. Materials and Specimen Preparation

The glass fibre reinforced polymer (GFRP) composite laminates were fabricated using a vacuum bagging processing technique. This technique delivers a uniformly distributed pressure on the entire surface of the laminate, which helps in removing the excess resin, entrapping air and efficiently integrating the laminate. Eight plies of glass fibre plain weave fabric of 800g/m^2 was impregnated with a two-part epoxy resin with the mixing ratio of 2:1 by weight (epoxy CP 216Z2 PART A: hardener CP 216Z2 PART B). The resin contains the main compound of Diglycidyl Ether of Bisphenol-F, providing a low viscosity property that enables the material to react with a full range of epoxy curatives. All the plies principal direction were aligned in the same direction as $[0]_8$.

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 was connected to the vacuum bagging setup. On the other hand, the curing was performed using a Grieve WRC 566-500 oven capable of providing continuous vacuum supply to the bagging during curing. The curing included one dwell section for 120 minutes at 80±10°C. This cure cycle entails 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 from the beginning of the cure until the removal of laminate panel, as the temperature was cooled to room temperature.

The laminates with the final thickness of 5.2 mm were then cut to size using a jig saw with a tungsten carbide blade, followed by a final finishing to eliminate the edge delamination. The holes were drilled in the undersize and then a reamer was used to achieve the required bolt-hole diameter and the auxiliary hole diameters. In order to minimize the damage at the hole edge, a block of dummy composite plate was attached underneath the laminates during the drilling.

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 5.2 mm, 8 mm and 140 mm, respectively. In addition, a second group of laminates was prepared with the defence hole system. Similar to the previous joint without the DHS, the values of W/D and E/D were varied as 2, 3, 4 and 5 and 1, 2, 3, 4 and 5, respectively. For each geometric configuration (W/D and E/D), two additional parameters of auxiliary holes were introduced, with the defence hole diameter (DHD) at a distance from the bolt-hole (DS) were selected relative to the bolt-hole diameter. Two values for DHD were selected as 0.625D and 0.75D, while three values of DS as 1.5D, 2D and 2.5D. The geometry of the laminates with and without the DHS is illustrated in Figure 1. In addition, Table 1 specifies six different configurations of the laminates with the DHS in reference to the laminates without the DHS.

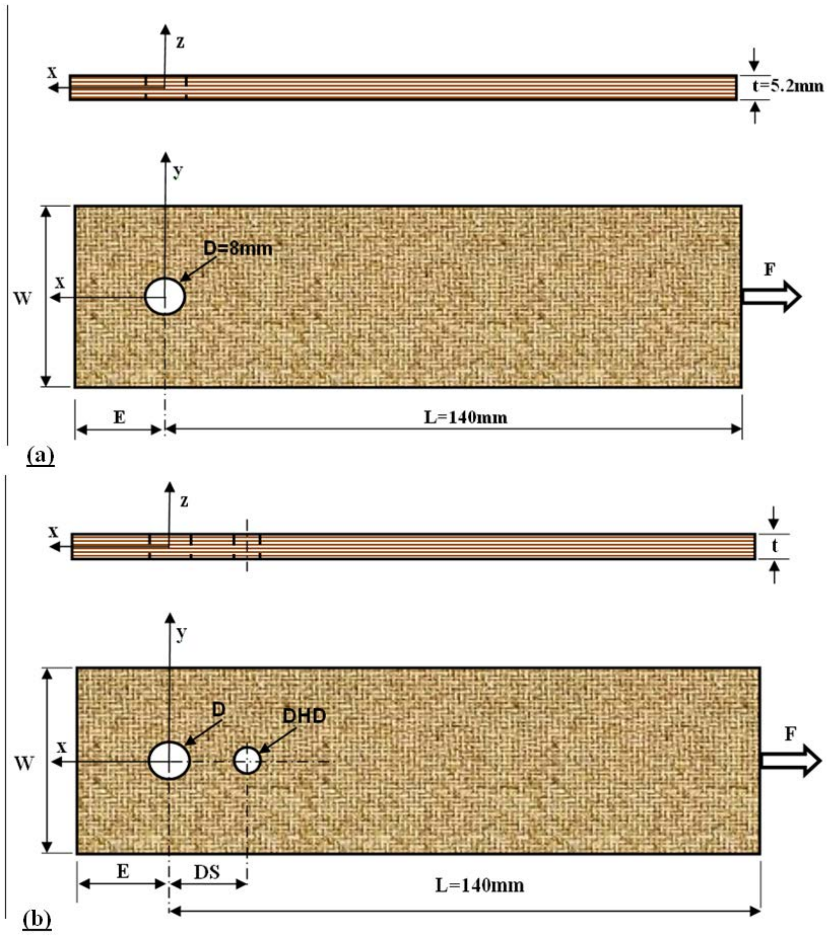

Figure 1. The geometry of the laminate test coupons; (a) without the DHS, and (b) with the DHS

Table 1. Configuration of the laminates with the DHS

Symbol	Configuration
A	DS=1.5D, DHD=0.625D
B	DS=1.5D, DHD=0.75D
C	DS=2D, DHD=0.625D
D	DS=2D, DHD=0.75D
E	DS=2.5D, DHD=0.625D
F	DS=2.5D, DHD=0.75D

2.2. Bearing Test

The bearing test was conducted to investigate the effect of the DHS on the single-bolt, double-lap bolted composite joints for both cases according to ASTM standard D 5961/D 5961M-10 procedures A [18]. The test was carried out using INSTRON 3367 universal testing machine with the loading capacity of 30 kN, in tensile loading at a rate of 0.5 mm/min. The bolt displacement was continuously monitored via the data acquisition system during the tests. The composite specimen was connected to two steel plates with the aid of finger tightened bolt, which represents the lowest bolt torque [19]. Two steel washers were inserted between the composite specimen and the steel plates. For all tests, the principal fibres direction of the composite specimen was aligned with the load direction. The schematic of joint configuration for the test is illustrated in Figure 2.

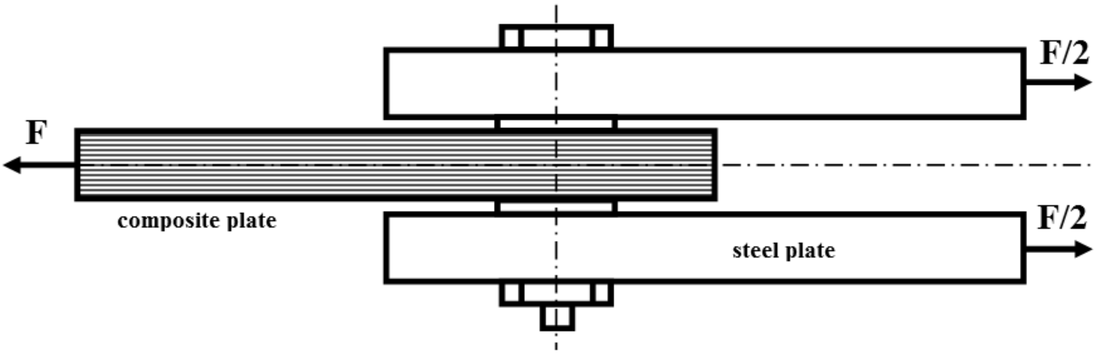

Figure 2. Schematic of the composite bolted joint for the bearing test

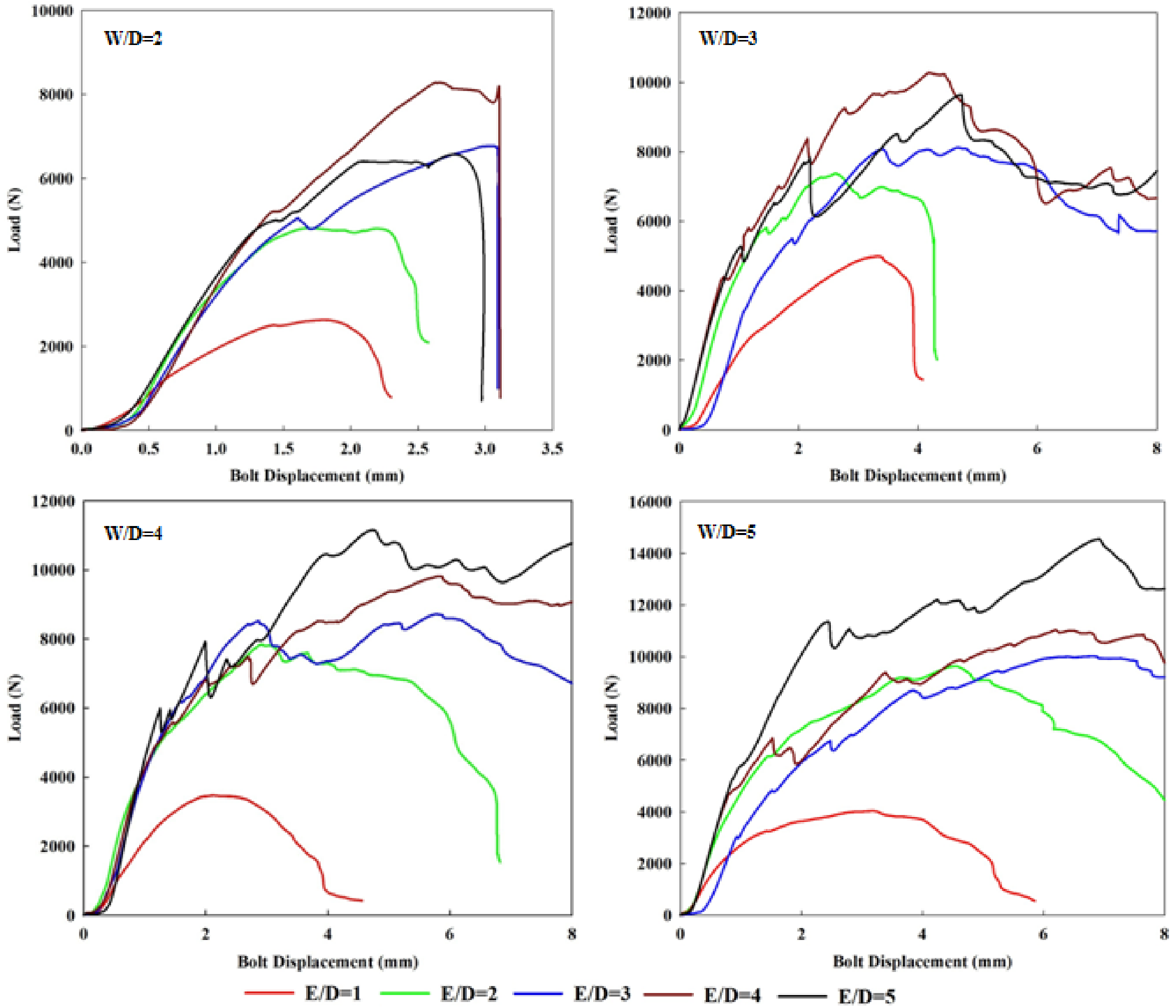

Figure 3. Load-displacement curves for the bolted joints with different configurations

3. Results and Discussion

3.1. Failure Load of the Laminated Bolted Joint without the DHS

Figure 3 shows the load-displacement curves for the bolted joint of the laminates without the DHS for different width to diameter (W/D) and edge to diameter ratios (E/D). A linear response was observed at the early stage of the test until a reduction in chord modulus due to matrix failure, followed by the first unloading of the curve indicating the first fibre failure, by which is known as the first ply failure (FPF). The FPF has occurred from approximately 1 mm of the bolt displacement for the laminates with small W/D to 2.4 mm for those of the laminates with large W/D. The laminates still possessed a load bearing capacity, and continued in sustaining more load prior to the final failure or the ultimate failure load, known as last ply failure (LPF). From these curves, it was observed that the bolt displacements at the ultimate failure load varied from 2.1 mm for the small W/D to 6.9 mm for the large W/D configurations.

Results of the failure loads for the laminates without the DHS for different W/D and E/D ratios are summarized in Figure 4. 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 before 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, which allowed for the larger bolt-displacement up to the final failure. For the laminates with W/D=2 and E/D=1, the minimum failure load was achieved for both of the first and the last failure loads. This was attributed to the high stresses in the net-tension and shear-out area for the narrow and small edge laminates, respectively. 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.

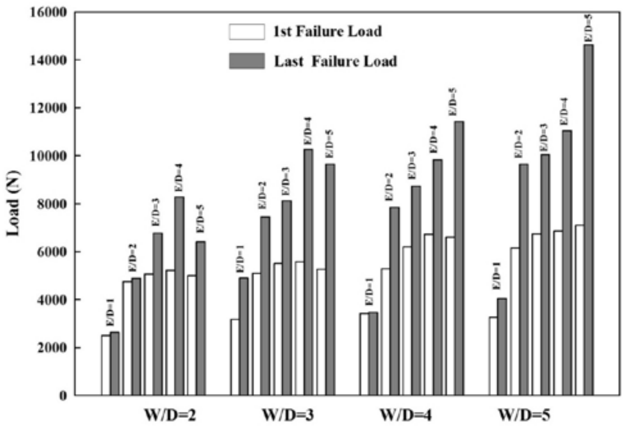

Figure 4. The failure loads experienced by the laminates following the bearing tests

It was found that between the tested ranges of W/D ratios, the results demonstrated that there was a marked increase in the failure load when the E/D ratio has increased from 1 to 2. On the other hand, a lower load rise was achieved for the other E/D ratios (E/D≥ 2). It was anticipated that laminates with small edge distance (E/D=1) experienced high shear stresses which give rise to shear failure mode at low failure load.

3.2. Failure Modes

In general, there are three basic failure modes that could occur in the bolted joints. They are known as net-tension, shear-out, and bearing failure modes, as well as the combinations of the two. These different modes could be easily distinguished from the load-displacement curves following the bearing test.

As mentioned previously, 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 have failed abruptly, which was indicated by the sharp load drop, 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 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 considerable values of the bolt displacements. This failure mode is the more desirable mechanism 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 5 indicates the typical response curves of the laminates illustrated by the photo of the failure modes.

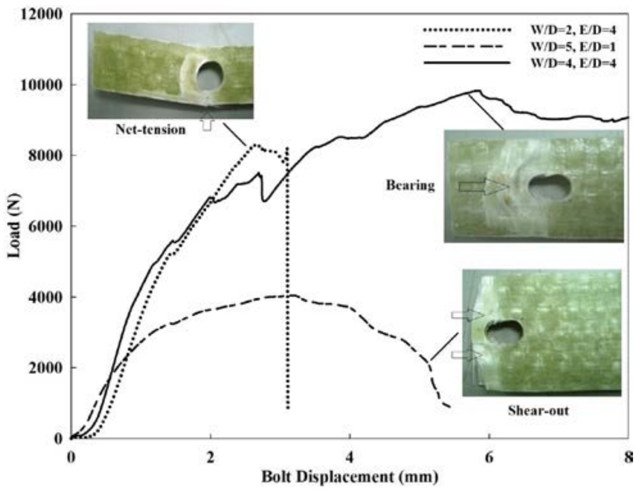

Figure 5. Failure modes based on the different responses when the bolted joints were subjected to bearing test

It was observed that a critical point of E/D and W/D could be specified, whereby beyond these values the failure mode has indicated obvious changes from the net-tension or shear out to bearing failure [20,21,22,23]. 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 as in Table 2. The results have 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 2. Failure mode of the laminates without the DHS for all 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

S=shear-out, N= net-tension, B= bearing, B-S= bearing shear-out failure mode.

3.3. Failure Load of the Laminated Bolted Joint with the DHS

The bearing test was carried out to assess the effect of the auxiliary hole (i.e. DHS) on the failure load of the laminates with different geometries. Note that, for the purpose of the assessment, the first fibre failure load in the load-displacement curve was referred for further analysis.

Figure 6 shows the comparison of the failure loads for the laminates with different geometric parameters. The results have indicated that in general, most of the laminates with the DHS failed at high failure loads compared to those laminates without the DHS, except for the small geometric laminates (i.e. W/D=2 and E/D=1) with the defence hole diameter of DHD=0.75D at a distance DS=1.5D, as well as with the DHD=0.75D at a DS=2D, causing a slight decrease in the failure loads. Significant increments of the bearing strength were observed for the laminates with the DHS configurations in relative comparison to those of the counterparts without the DHS. The benefits of introducing the auxiliary hole were becoming more apparent when the geometries of the joint configuration of E/D were increased. Similarly, the laminates with larger W/D could also sustain more loads before the first ply failure.

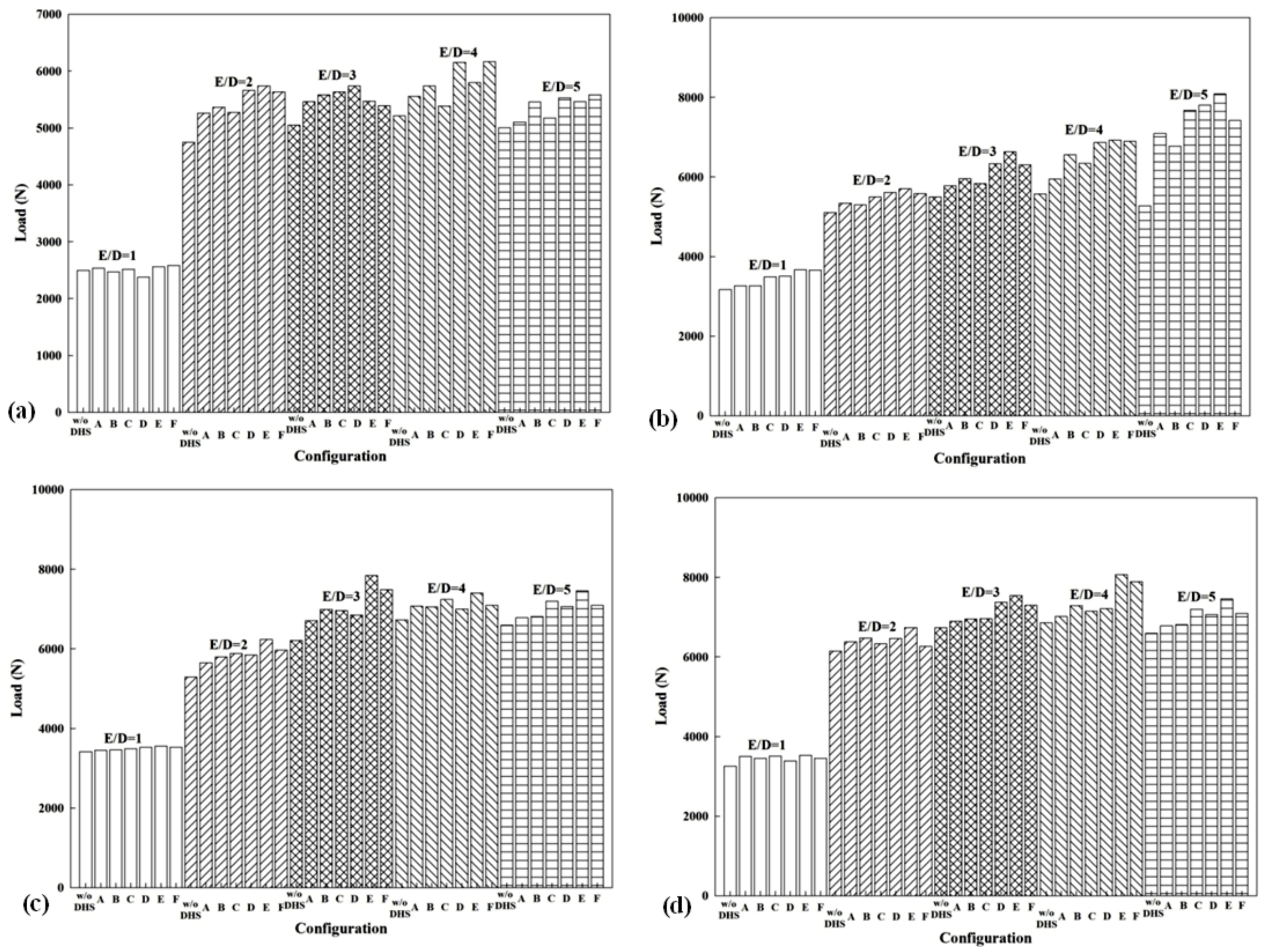

Figure 6. Failure loads of the composite bolted joints with (a) W/D=2; (b) W/D=3; (c) W/D=4; and (d) W/D=5

However, it is rather difficult to clearly observe the benefits of load increment due to the change in configuration of the DHS. Therefore, these results were further analyzed in Table 3, emphasizing the percentage of load increments in comparison to the laminates without the DHS, and were listed for each W/D and E/D ratios. For the laminates with small geometry (i.e. W/D=2 and E/D=1), insignificant reductions in the failure load were observed for the defence hole system of DHD=0.75D at DS=1.5D (configuration B) and DHD=0.75D at DS=2D (configuration D). This uncommon case may be attributed to the high stress concentration for various stress components (σ_x, σ_y and τ_{xy}) at the small area around the bolt-hole in those three regions of net-tension, shear-out and bearing planes.

Table 3. Load increment (in %) for all laminates.

Symbol	Configuration	Load increment (in %)			
		W/D=2	W/D=3	W/D=4	W/D=5
		E/D=1			
A	DS=1.5D, 0.625D	1.48	2.89	0.97	6.94
B	DS=1.5D, 0.75D	-1.03	2.79	1.32	5.69
C	DS=2D, 0.625D	0.7	9.02	1.95	7.07
D	DS=2D, 0.75D	-5	9.62	3.04	3.83
E	DS=2.5D, 0.625D	2.4	13.59	3.91	7.67
F	DS=2.5D, 0.75D	3.31	13.29	3.09	5.53
		E/D=2			
A	DS=1.5D, 0.625D	9.78	4.48	6.36	3.68
B	DS=1.5D, 0.75D	11.51	3.68	8.67	5.1
C	DS=2D, 0.625D	9.98	7.23	10.02	3.02
D	DS=2D, 0.75D	16.11	9.07	9.47	4.95
E	DS=2.5D, 0.625D	17.3	10.48	15.2	8.82
F	DS=2.5D, 0.75D	15.69	8.58	11.37	1.89
		E/D=3			
A	DS=1.5D, 0.625D	7.46	4.77	7.48	2.34
B	DS=1.5D, 0.75D	9.52	7.66	11.24	3.09
C	DS=2D, 0.625D	10.34	5.71	10.81	3.23
D	DS=2D, 0.75D	12	13.13	9.33	8.6
E	DS=2.5D, 0.625D	7.67	17.04	20.87	10.7
F	DS=2.5D, 0.75D	6.24	12.71	17.13	7.73
		E/D=4			
A	DS=1.5D, 0.625D	6.17	6.22	4.81	2.27
B	DS=1.5D, 0.75D	9.22	14.94	4.57	5.96
C	DS=2D, 0.625D	3.26	12.14	7.11	4.11
D	DS=2D, 0.75D	15.31	18.84	3.9	4.98
E	DS=2.5D, 0.625D	10.13	19.48	9.09	15.01
F	DS=2.5D, 0.75D	15.48	19.14	5.14	13.17
		E/D=5			
A	DS=1.5D, 0.625D	1.94	25.67	2.73	2.73
B	DS=1.5D, 0.75D	8.27	22.14	3.22	3.22
C	DS=2D, 0.625D	3.28	31.29	8.34	8.34
D	DS=2D, 0.75D	9.5	32.39	6.61	6.61
E	DS=2.5D, 0.625D	8.38	34.81	11.59	11.59
F	DS=2.5D, 0.75D	10.34	28.89	7.08	7.08

Generally, for larger laminate dimensions (i.e. E/D≥2), introducing the defence hole at a large distance (DS=2.5D) provided the most advantageous in the load increment, while a lower load increment was achieved by the small defence hole distance (DS=1.5D). The maximum load increment was obtained by laminates with a defence hole diameter of DHD=0.625D at a distance of DS=2.5D (configuration E). This indicates that for wide and long edge distance laminates, the maximum failure load increment was achieved by varying the defence hole parameters from the main hole. As a result, the highest load increment of 34.81% was obtained for the laminate with the configuration of W/D=3 and E/D=5 with the DHS design of DHD=0.625D at distance of DS=2.5D. The increment in failure load for such bolted design would delay the catastrophic failure and provide higher bearing strength to the configuration. Accordingly, a lower use of the material could be utilized for the particular design loading, reducing the weight of the joint structure while keeping the main benefit of high strength-to-weight ratio of the composite.

4. Conclusions

The bearing tests for double-lap, single-bolt joints in the GFRP composite structure for the laminates with and without the DHS have been carried out to determine the effect of introducing the auxiliary hole on the failure load and thus, the bearing strength. Experimental results showed that the laminates with the defence hole system have failed at higher failure loads compared to those without the defence hole system, except for two configurations with small geometric parameters (i.e. W/D=2 and E/D=1), which caused a slight decrease in the failure load. For the larger laminates, the optimum load increment was achieved at the defence hole system of DS=2.5D, but the benefit of the DHS was lessened with the reduction in the DS. For the laminates with wider and longer edge distance, the maximum load increment was achieved for the DHS of diameter DHD=0.625D at distance of DS=2.5D. The highest load increment of 34.81% was obtained for the laminate with the configuration of W/D=3 and E/D=5.

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