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Experimental Investigation on Mechanical Behaviour of GFRP Countersunk Composite Bolted Joints

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Abstract - *Composite structures are constructed using the mechanical joints comprising of either bolted, bonded or hybrid joints. For heavy loading cases, bolted joints are preferred. The main objective of this work is to investigate the influence of geometric parameter (edge distance to diameter ratio), fastener parameter (washer type and the effect of bolt pre-tightening) on the strength of counter sunk bolted joints in GFRP composites. The mechanical properties ultimate strength, toughness and fracture strain of developed GFRP laminates have been determined experimentally. Taguchi's design of experiments is used to determine the optimal joint using Minitab. The experimental results revealed that, optimal joint (for ultimate load) was obtained when e/d ratio = 5, tightening torque = 5 N-m along with thick washer and for toughness optimal joint was obtained when e/d ratio = 4, tightening torque = 5 N-m along with thick washer. Mixed failure modes were observed for most of the cases with higher e/d ratio which reduces the sudden catastrophic failure. For lower e/d ratio shear out mode of failure was witnessed.*

Key Words: *Mechanical Joints, Geometric Parameter, Fastener Parameters, Failure Modes*

1. INTRODUCTION

Recent research trend is converged towards the optimization studies with objectives such as reduction in weight, reduction of cost, improvement in strength, maximizing the functional requirement parameters. In this connection, composite materials are gaining more attraction. Therefore, the use of composite materials has increased. The composite materials offer advantages such as low weight to strength ratio, high stiffness to weight ratio, low coefficient of thermal expansion, low coefficient of friction, superior damping and impact characteristics and many more. Due to low weight and fuel savings offered by the composite materials, they are extensively used in aircrafts and defence vehicles. Shortly the automobile sector may adopt the composites in order to obtain the fuel saving [1].

Due to limitations of manufacture and maintenance, bolted joints are quite commonly used in composite structures. However, the drilling of holes cuts the fibre and causes local stress concentration, resulting in reduction of load carrying capacity. To ensure safety and increase weight saving efficiency, the joint structures must be designed seriously, and their mechanical behaviour should be studied carefully. The failure mode and strength are important properties for composite bolted joints [9].

The main failure modes of multi-bolt joints include net-section failure, bearing failure and shear out failure as shown in Fig. 1. The bearing failure is a progressive process, while net-section failure and shear out failure occur immediately and catastrophically. The latter two failure modes may reduce the load carrying capacity or cause instant failure of the whole structure. That is the reason why bearing failure mode is preferred in joint structural design and the other two modes should be avoided [9].

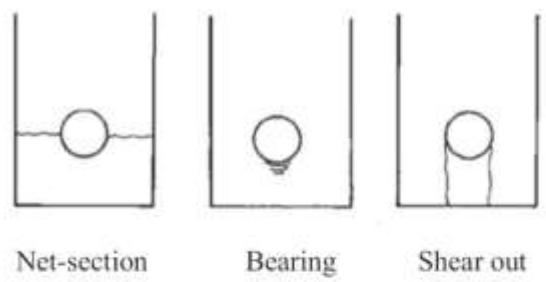

Fig -1: **Failure modes of composite bolted joints [9].**

2. LITERATURE REVIEW

L.V.Awadhani et al., [1] studied the effect of geometric parameter (edge distance to diameter ratio) on the behaviour of composite joints. Analysis revealed that, the failure mode changes with variation in e/d ratio. With increase in edge distance, failure mode changes form cleavage or net tension to bearing failure. Peak load increased with increase in edge distance of bolt. From results it was concluded that, strength of composite bolted joints increases with increase in edge distance; which was also stated by Song Zhou et al., [2].

The tightening torque plays an important role in enhancing the strength and load carrying capacity of a composite joint. Ioannis K. Giannopoulos et al., [3], Jae-Il Choi et al., [4] and F.Esmaeili et al., [5] investigated the effects of bolt torque tightening on the strength and fatigue design of bolted fibre reinforced polymer laminates. They observed that with increasing pre-tightening torque, the joint static strength increased along with fatigue life and also the numerical simulations and experimental results revealed that fatigue life of composite joint was improved by increasing the clamping force due to compressive stresses created around the hole.

Type of washer used on the joint reveals that load carrying capacity of composite bolted specimens, bolt strength can be enhanced by using washers effectively, which has been reported by U.A. Khashaba et al., [6], Liyong Tong [7] and Shriram Dravid et al., [8].

Countersunk bolts on composite joints is a new idea in which researchers have tried to analyse the effect of parameters on mechanical performance of composites. This has been reported in Maajid Chishti et al., [10] and Yunong Zhai et al., [11].

The main objective of the present work is to investigate the effect of considered parameters on mechanical performance, to determine the optimal joint and to study the failure mechanism of developed FRP counter sunk composite bolted joints. The e/d ratio, tightening torque and the washer thickness are chosen parameters for single-lap, single bolt composite joint.

Table -1: Parameters and levels

Level / Parameter	1	2	3
e/d	3	4	5
Tightening torque(N-m)	5	10	15
Washer thickness(mm)	Nil	2 (Thin)	3 (Thick)

3. EXPERIMETAL PROCEDURE

3.1 Materials and specimens

The configuration and dimension of composite specimen used in tensile test is shown in Fig.2. The design was based on ASTM D5961. Bi-directional Glass fibres are taken as reinforcement and epoxy resin as matrix material. The epoxy resin and corresponding hardener used for fabrication were LAPOX L12 and K6. The high temperature curing resin and hardener were taken at a ratio of 10:1 by weight percentage. Hardened steel bolt, nut and washers were selected to reduce the effect of torque loosening. The fabrication of the composite plates is done by using compression moulding technique followed by oven heating at a temperature of 180^{0}C for about 3hrs. Then specimens of suitable dimension were cut using a diamond cutter.

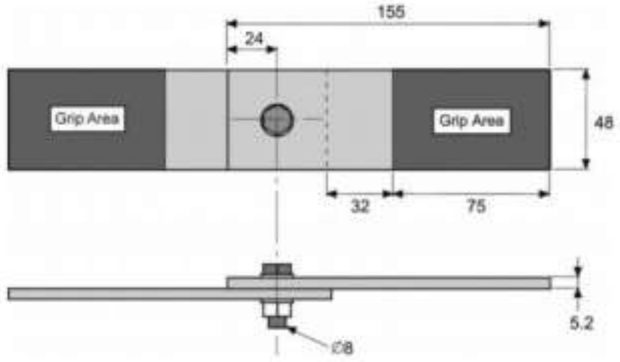

Fig -2: Tensile test specimen

3.2 Experimental tests

3.2.1 Water absorption test

The water absorption ability test was carried out according to ASTM D570 (Prescribed standard for conducting water absorption test in composites) for the developed composite specimen by immersing it in distilled water at room temperature for 24 hours. Water absorption test is used to determine the amount of water absorbed under specified condition. The data sheds light on the percentage of voids present in the developed composite specimen.

For the water absorption test, the specimen is initially weighed at dry state. The material is then submerged in distilled water at room temperature for about 24 hours. Specimen is removed, patted dry with a tissue, and weighed. Water absorption is expressed as increase in weight percent (Vo).

$$V_o = \frac{W_2 - W_1}{W_1} \times 100 \quad \text{Eq. 1}$$

Where, W_1 & W_2 are the weight composite specimen before and after immersion respectively.

Table -2: Water absorption test results

Particulars	**Values**
Before immersion (W_1 in g)	75.25
After immersion (W_2 in g)	75.289
Percentage of water absorption (%)	0.0518

3.2.2 Density test

Density of the developed composite specimen was determined by burn off test.

$$V_f = \frac{w_f/\rho_f}{\frac{w_f}{\rho_f} + \frac{wm}{\rho m}} \times 100 \quad \text{Eq. 2}$$

Where,

W_f = weight of fiber (g)

ρ_f = density of fiber (2.6g/cm^3)

W_m = weight of matrix (g)

ρ_m = density of matrix (1.15g/cm^3)

V_f = volume fraction of fiber

From the obtained volume fraction, density of the composite can be obtained by using the formula

$$\rho = (V_f * \rho_f + Vm * \rho m) - V_o \quad \text{Eq. 3}$$

Where,

V_m = volume fraction of matrix

V_o = void percentage

Table -3: Density test results

Particulars	Values
Fibre volume fraction (%)	69.95
Matrix volume fraction (%)	30.05
Density (kg/m3)	2164.27

3.2.3 Tensile test

Tensile properties of angle-ply [0^0/90^0] composites were determined experimentally according to ASTM D5961. Tests were performed on single lap composite specimen consisting of two regions: a central region called gauge length, with in which failure is expected to occur, and two end regions which are clamped into a grip mechanism connected to a test machine. In tensile test, a uniaxial load at a loading rate of 2mm/min was applied through both the end. The ultimate tensile strength and toughness were determined from the load–displacement curve of the testing machine.

3.2.4 Taguchi technique

The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of this method is designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied. Instead of having to test all possible combinations.

Classical experimental design methods are too complex and are not easy to use. A large number of experiments have to be carried out when the number of process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments using Minitab. Orthogonal arrays are special standard experimental design that requires only a small number of experimental trials to find the main factors effects on output. For three parameters and three levels L9 orthogonal array was selected from the array selector as shown in Table 4.

Table -4: Taguchi L9 Orthogonal Array

Levels / Parameters	A	B	C
1	**1**	**1**	**1**
2	**1**	**2**	**2**
3	**1**	**3**	**3**
4	**2**	**1**	**2**
5	**2**	**2**	**3**
6	**2**	**3**	**1**
7	**3**	**1**	**3**
8	**3**	**2**	**1**
9	**3**	**3**	**2**

4. RESULTS AND DISCUSSIONS

4.1 Tensile Test

Quasi static tensile tests were conducted for the developed composite bolted joints at a crosshead speed of 2mm/min until the specimen failed. The composite specimens were tested in the Instron servo hydraulic universal testing machine (UTM). The graph stress vs strain was generated from load vs displacement data obtained from the test results. Stress–strain curve is plotted for the determination of ultimate tensile strength, fracture strain and toughness. The test results are summarized in Table 5. Fig 3.1 to 3.9 shows the stress strain curves for test case 1 to 9 along with their respective failure modes.

The graphs consist of three distinctive regions. Region 1 consists of stiffness degradation due to the nonlinear composition of the considered composite joint. This results in unstable crack propagation along the transverse direction of the hole through the matrix region. The crack propagates along the matrix region through the interphase to the fibres. Once the failure reaches fibres, the fibres starts taking the load. As a result, the initial failure stops and increase in the load value can be observed in region 2. Region 3 encloses specimen failure area staring from ultimate point to the fracture point.

Table -5: Test results for counter sunk condition

Test case	e/d	Torque (N-m)	Washer	Ultimate strength (MPa)	Fracture strain	Toughness (MJ/m³)
1	3	5	Thick	61.37	0.455	5.736
2	3	10	Thin	42.66	0.245	1.1129
3	3	15	Nil	48.11	0.462	5.1702
4	4	5	Thin	61.09	0.309	5.6401
5	4	10	Nil	52.4	0.462	4.958
6	4	15	Thick	52.88	0.268	4.537
7	5	5	Nil	57.29	0.223	4.497
8	5	10	Thick	63.9	0.229	4.836
9	5	15	Thin	60.89	0.223	4.1718

*S=Shear out, N=Net tension, B=Bearing failure

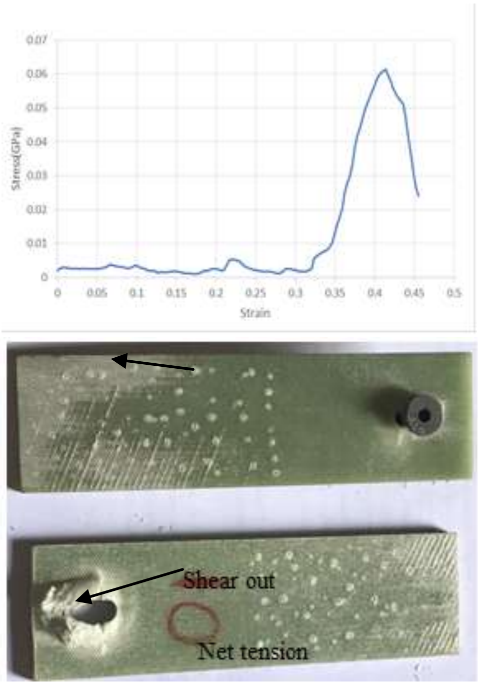

Fig -3.1: e/d = 3, torque = 5 N-m, washer = thick

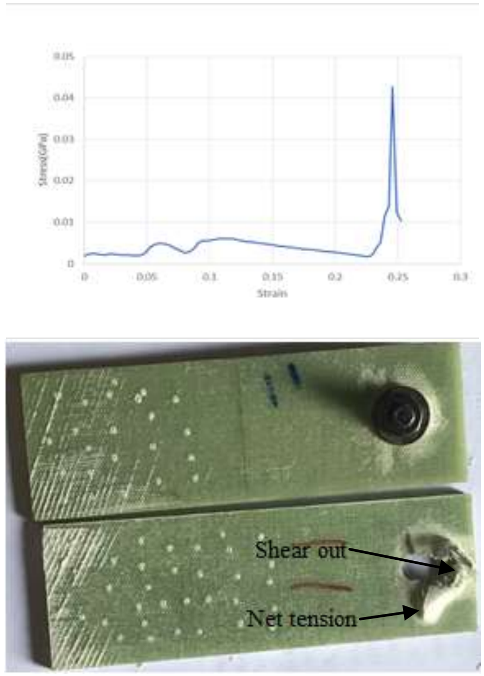

Fig -3.2: e/d = 3, torque = 10N-m, washer = thin

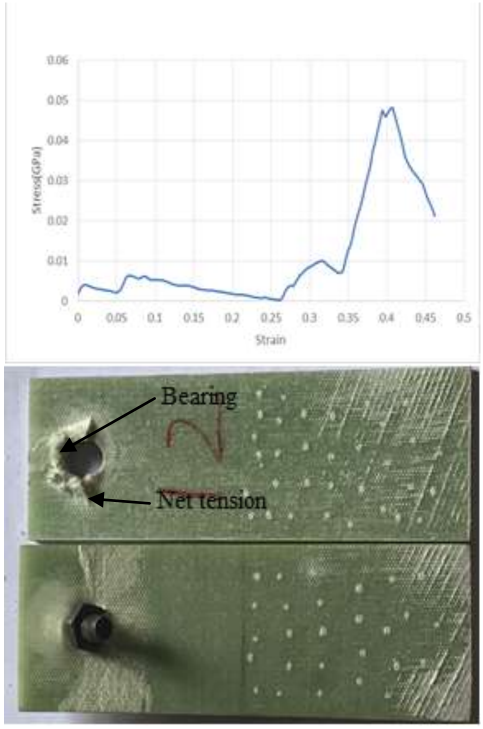

Fig -3.3: e/d = 3, torque = 15 N-m, washer = without

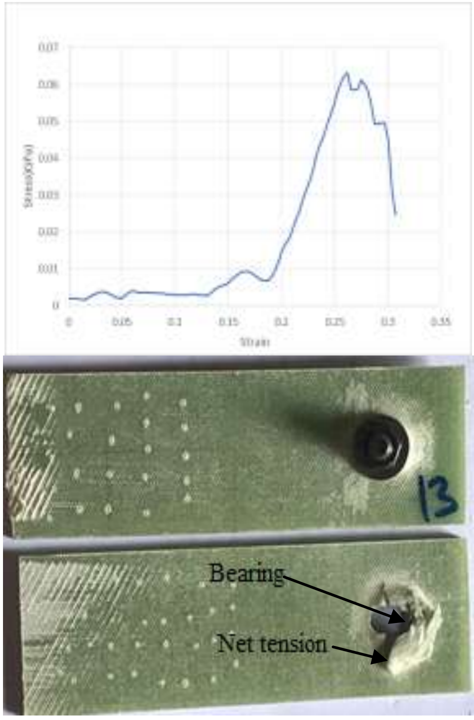

Fig -3.4: e/d = 4, torque = 5 N-m, washer = thin

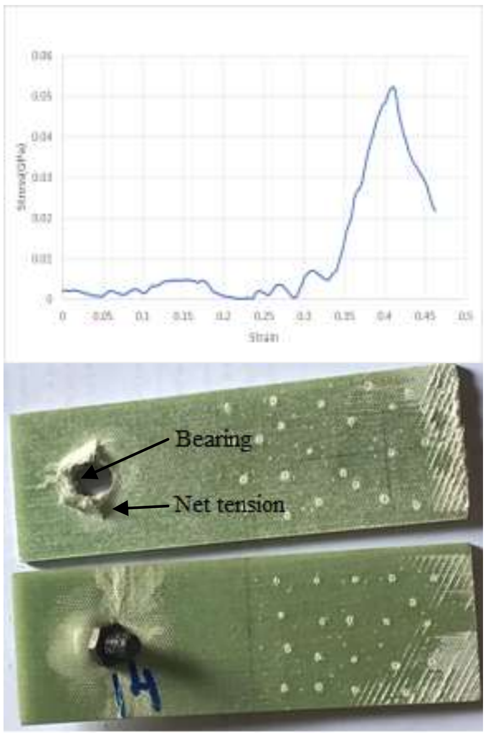

Fig -3.5: e/d = 4, torque = 10 N-m, washer = nil

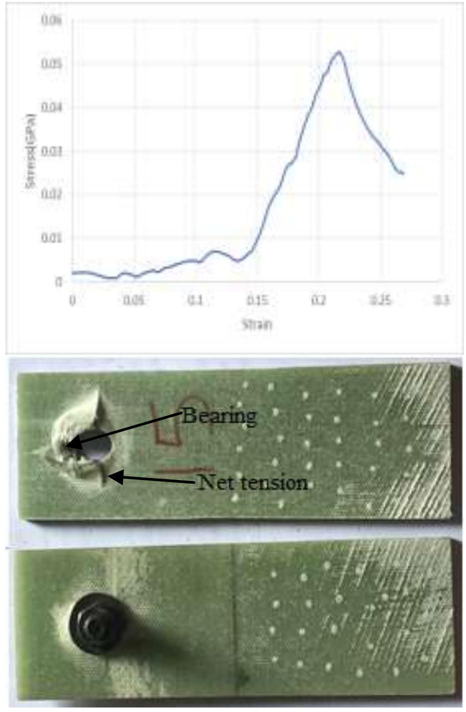

Fig -3.6: e/d = 4, torque = 15 N-m, washer = thick

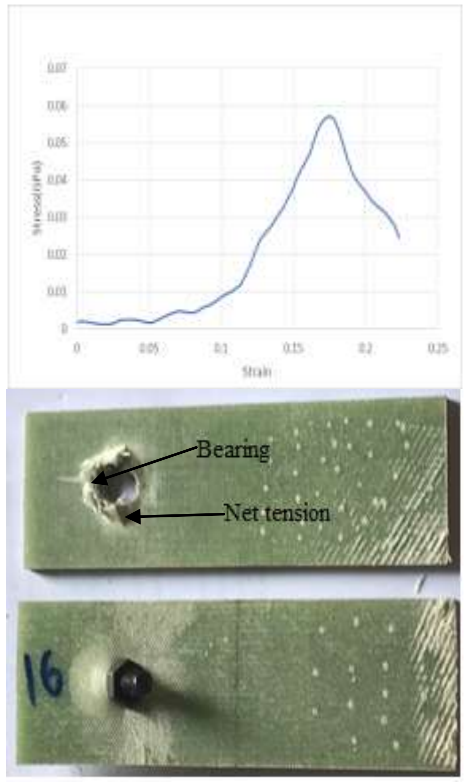

Fig -3.7: e/d = 5, torque = 5 N-m, washer = nil

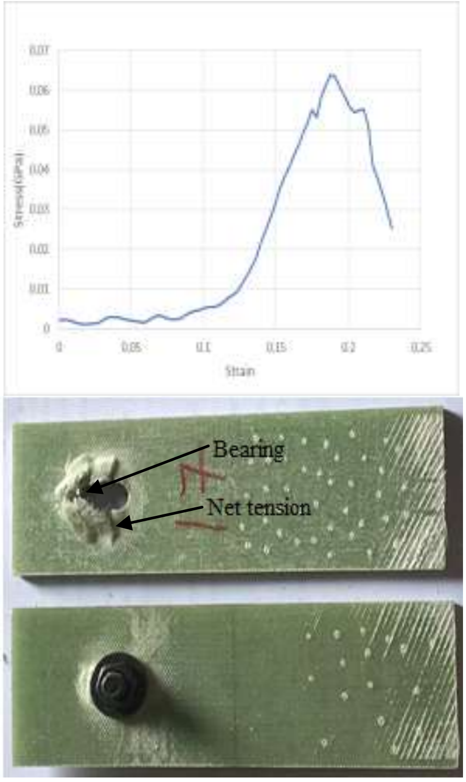

Fig -3.8: e/d = 5, torque = 10 N-m, washer = thick

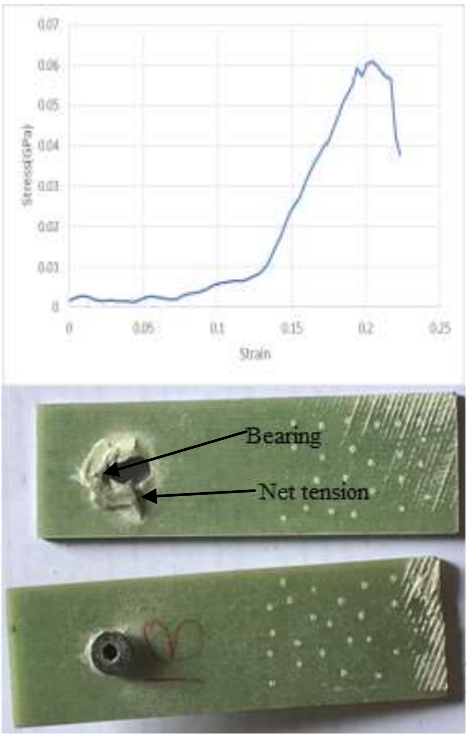

Fig -3.9: e/d = 5, torque = 15 N-m, washer = thin

4.3.1 Effect of geometrical factor (e/d)

In the conditions tested herein, with increase in e/d ratio, overlap length of the composite joints were increased. As a result, the slope of the stress strain diagram (stiffness of the joint) increased with increase in e/d ratio. The stress strain diagrams behave in a nonlinear fashion due to mixed failure mode. Investigation revealed that, the failure mode changes with variation in e/d ratio. With increase in edge distance, failure mode changes from shear out or net tension to bearing failure. Peak load also increases with increase in edge distance of bolt.

4.3.2 Effect of fastener parameter (Tightening torque)

In the counter sunk condition, the transverse compressive strength of the laminate was found to be reduced due to change in geometry of the bolt hole. As a result, pre tightening levels cannot exceed 5N-m. The lower pre-tightened torqued specimens had a longer displacement to failure. This feature is advantageous to damage tolerant designs.

The pre-tightening levels cannot exceed the maximum transverse compressive strength of the laminate to prevent initial crack formation.

4.3.3 Effect of fastener parameter (washer)

For bolted joint cases tested herein, the joints comprising of washers exhibited higher load carrying capacity. Since absence of washer in the joint led to earlier fibre tear and failure.

4.3.4 S/N ratio for counter sunk bolts

a) Ultimate load

Table -6(a): Response Table for Means

Levels	e/d	Tightening Torque	Washer
1	9.192	10.525	9.370
2	9.888	9.545	10.422
3	11.223	10.23	10.512
Delta	2.032	0.980	1.142
Rank	1	3	2

In the Table 6(a), mean S/N ratios for each levels of parameters are shown. It consists of ranks assigned to each parameter based on delta value (highest mean value – lowest mean value). Rank 1 is assigned to parameter with higher delta value, rank 2 to the 2nd highest and so on. Optimum process parameter is the combination of the one's that yields the maximum mean value within the considered parametric level for each parameter.

Within the joints tested herein comprising of counter sunk bolts for ultimate load, e/d ratio has the highest effect on determining the joint performance of the developed joint, followed by washer effect and tightening torque.

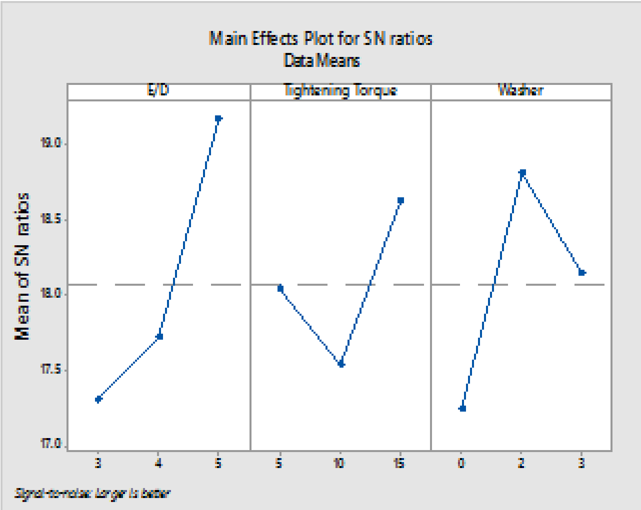

Fig -4(a): S/N ratio plot for counter sunk condition

Typical main effect plots and response table of parameters with respect to counter sunk condition for ultimate load is shown in fig 4(a) and Table 6(a). It can be concluded that e/d ratio has maximum effect on ultimate strength of the counter sunk joint followed by washer and tightening torque. From the results of response table for means, it's evident that for the counter sunk condition optimal joint is obtained when e/d ratio is 5, tightening torque is 5 N-m and thick washer is used.

Regression equations for counter sunk bolt condition

Edge distance to diameter ratio (e/d) =

4.000 - 1.000 Ultimate Load_10.65 - 1.000 Ultimate Load_12.01 + 0.00000 Ultimate Load_13.08 + 0.000000 Ultimate Load_13.20 + 1.000 Ultimate Load_ 14.30 + 1.000 Ultimate Load_15.20 + 0.000000 Ultimate Load_15.25- 1.000 Ultimate Load_15.32 + 1.000 Ultimate Load_15.95 Eq. 4(a)

Tightening torque =

10.00 - 0.000000 Ultimate Load_10.65 + 5.000 Ultimate Load_12.01 + 0.0 Ultimate Load_13.08 + 5.000 Ultimate Load_13.20 - 5.000 Ultimate Load_14.30 + 5.000 Ultimate Load_15.20 - 5.000 Ultimate Load_15.25 - 5.000 UltimateLoad_15.32 + 0.0 UltimateLoad_15.95 Eq. 5(a)

Washer =

1.667 + 0.3333 Ultimate Load_10.65 - 1.667 Ultimate Load_12.01 - 1.667 Ultimate Load_13.08 + 1.333 Ultimate Load_13.20 - 1.667 Ultimate Load_14.30 + 0.3333 Ultimate Load_15.20 + 0.3333 Ultimate Load_15.25 + 1.333 Ultimate Load_15.32 + 1.333 Ultimate Load_15.95 Eq. 6(a)

b) Toughness

Table -6(b): Response Table for Mean

Levels	e/d	Tightening Torque	Washer
1	4.006	5.291	4.875
2	5.045	3.635	3.641
3	4.501	4.626	5.036
Delta	1.039	1.656	1.395
Rank	3	1	2

Within the joints tested herein comprising of counter sunk bolts for toughness, tightening torque has the highest effect on determining the joint performance of the developed joint, followed by washer effect and e/d ratio.

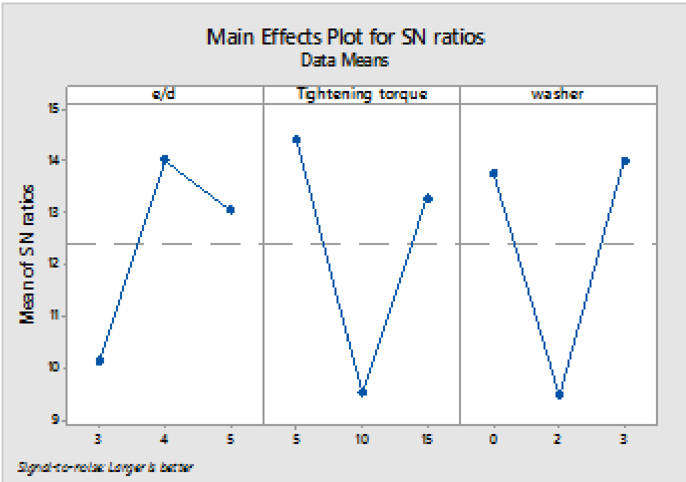

Fig. 4(b) S/N ratio plot for counter sunk condition

Typical main effect plots and response table of parameters with respect to counter sunk condition for toughness is shown in fig 4(b) and Table 6(b). It can be concluded that tightening torque has maximum effect on toughness of the counter sunk joint followed by washer and e/d ratio. From the results of response table for means, it's evident that for the counter sunk condition optimal joint is obtained when e/d ratio = 4, tightening torque = 5 N-m and thick washer is used.

Regression equations for counter sunk bolt condition

Edge distance to diameter ratio (e/d) =

4.000 - 1.000 Toughness_1.112 + 1.000 Toughness_4.171 + 1.000 Toughness_4.497 + 0.000000 Toughness_4.537 + 1.000 Toughness_4.836 + 0.000000 Toughness_4.98 - 1.000 Toughness_5.170 + 0.000000 Toughness_5.640 - 1.000 Toughness_5.736 Eq. 4(b)

Tightening torque =

10.00 + 0.000000 Toughness_1.112 + 5.000Toughness_4.171 - 5.000 Toughness_ 4.497 + 5.000 Toughness_4.537 + 0.000000 Toughness_4.836 + 0.000000 Toughness _4.958 + 5.000 Toughness_5.170 - 5.000 Toughness_5.640 - 5.000 Toughness_5.736 Eq. 5(b)

Washer =

1.667 + 0.3333 Toughness_1.112 + 0.3333 Toughness_4.171 - 1.667 Toughness_4.47 + 1.333 Toughness_4.537 + 1.333 Toughness_4.836 - 1.667 Toughness_4.958 - 1.667 Toughness_5.170 + 0.3333 Toughness_5.640 + 1.333 Toughness_5.736 Eq. 6(b)

5. CONCLUSIONS

The quasi static tests were carried out on single lap, single bolted composite joints in tension. Following conclusions were drawn from the present investigation.

- The developed composite specimens exhibited excellent resistance to water absorption rate due to presence of very low percentage of voids.
- Firstly, stiffness degradation as a result of unstable crack propagation through the matrix region was observed. This was due to nonlinear composition of the developed joint leading to "bearing failure".
- Secondly, delamination between the layers was observed. This was attributed to different strains in the 0^o and 90^o layers.
- After delamination, the ''net-tension'' failure mode was observed for 90^o layers. This followed by other modes for 0^0 layers. 90^0 layers had the minimum strength compared to 0^0 layers.
- Mode of failure changed according to geometry. It was observed that for low e/d ratio, specimens failed by shear out failure. As distance of bolt from edge increased failure mode changed from shear out to bearing failure.
- From quasi static loading for the composite bolted joints tested herein, with increase in pre-tightening torque, the joint strength increased as a result of increase in the contact pressure between the specimen and fastener.
- The distance of the edge from the bolt hole has a significant effect in changing the failure modes from shear out to bearing. The strength of the GFRP composite joint can be increased by increasing the distance from the edge.
- Mixed failure mode was observed for most of the cases due to higher e/d ratio which reduces the occurrence of sudden catastrophic failure occurrence. For lower e/d ratio, shear out mode of failure was witnessed.
- For the counter sunk condition, optimal joint was obtained when e/d ratio = 5, tightening torque = 5 N-m along with thick washer and for toughness optimal joint was obtained when e/d ratio = 4, tightening torque = 5 N-m along with thick washer.

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