Experimental study on tensile strength of hybrid composite lap joints

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CFRP-Carbon fiber reinforced plastics, GFRP-Glass fiber reinforced plastics, laminates, hybrid lap joint.

ABSTRACT

With the growing use of composite materials in different fields, including aerospace, marine, architecture, automotive, sports and recreation, the need to join dissimilar composite materials has arisen. In this study, the work is aimed at fabrication and testing of Fiber reinforced plastic (FRP) hybrid lap joints. We emphasize on analysing joint strength, efficiency of different Fiber reinforced materials (Carbon fiber, Glass fiber, Carbon+Glass fiber). We find the joint strength of GFRP-128.03Mpa, CFRP+ GFRP-478.42Mpa, CFRP-578.47Mpa. A finite element analysis has been carried out using ANSYS in order to obtain stress distribution of the hybrid composite lap joint. With the results of the finite element study and experimental Comparison, joint strength of different composite materials are compared, and design suggestions were made based on these results.

1. Introduction

A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone. The use of light weight, high strength composite structures for applications including building, aeronautics, aerospace, automotive, sports and packaging has recently increased. Joining is a critical step in the manufacture of components from polymers and polymeric composites. As the requirements for the component increase, so do the requirements for joining, especially in structural applications. Most polymer composites are joined using either adhesive bonding or mechanical fasteners[5]. The use of adhesives is very desirable because drilling holes is not needed. However, the strength of the adhesive joint is lower than mechanical fasteners and it depends on the adhesive area i.e. if the adhesive area is more the joint strength is high [3]. On the other hand, mechanical fasteners provide advantages like better strength, easy to design, and they can be easily taken apart. The main limitations are, increased weight, the presence of large stress concentrations around the fastener holes, and leakage problems. Either of these two joining techniques are not perfect. A hybrid joint, combination of adhesive bonding and mechanical fastening, is able to combine the advantages of both joint types and also improves the joint strength, efficiency. With regard to aircraft structure assembly, hybrid joining could be interesting because it could reduce the load transferred by the fasteners in order to improve the fatigue life, while ensuring static strength under extreme loads. The idea is to design the hybrid joint in order to share the load between the adhesive and the fasteners in a suitable way.

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2. Design of Hybrid Lap Joint

The dimensions of the hybrid joint are considered according to the standard ASTM D31638. The laminates were 25 mm wide and 100 mm long, two such laminates are joined with an overlap length of 40mm. An adhesive layer, 0.2mm thickness, is applied in between the laminates. The total length of the joint is 160 mm long. Two bolts were placed in overlap region along the length with a row pitch length as 16mm and margin 12mm. The bolt diameter (4mm) is chosen to be larger than the thickness of the laminate which is 3mm.

Table 1
Dimensions of the joint.

Width of laminate	25 mm
Length of laminate	100 mm
Thickness of laminate	3 mm
Plate overlap	40 mm
Diameter of bolt	4 mm
Diameter of bolt head	8 mm
Pitch	25 mm
Margin	12 mm
Row pitch	16 mm

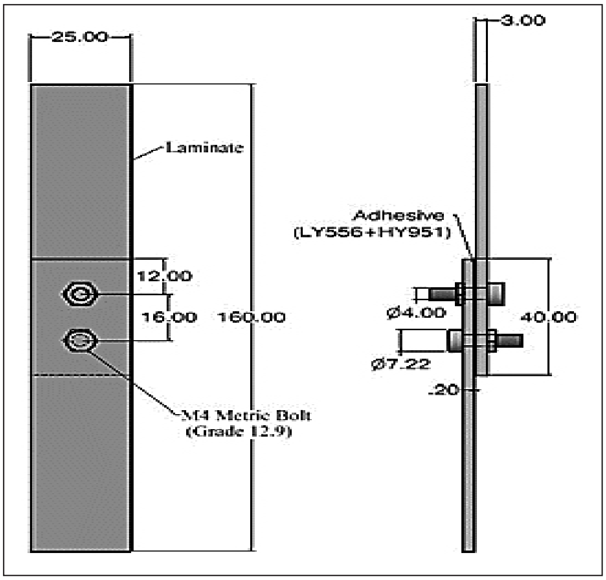
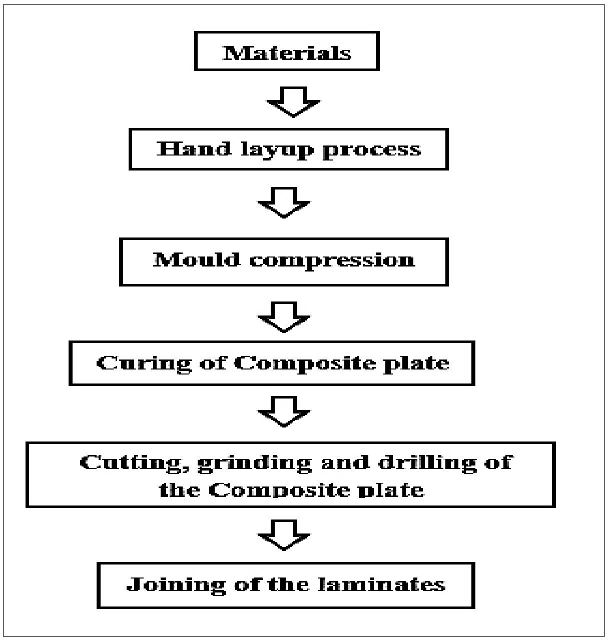


Fig. 1. Hybrid lap joint Dimensions.



The reinforcement used for fabrication of the laminates is E-Glass fabric (Woven type, plain weave), Carbon fabric (Woven type, plain weave) and epoxy resin (LY556+HY951) which acts as matrix material. The following table shows the properties of fiber materials used in the project.

Table 2
Properties of fiber materials used.

Material	Poisson ratio	Youngs modulus (Mpa)	Tensile strength (Mpa)
E-Glass (400gsm)	0.22	79000	2000
Carbon (400 gsm)	0.3	230000	3450
Epoxy resin	0.28	3436	60-90

Once all the materials are prepared, the fibers are put in the mould. It is important to mention that the resin and hardener are to be mixed in the proportions, usually given by the supplier, and it is 10:1. The portions can be either measured by weight or by volume fraction. The impregnation of resin is done by using rollers and brushes. The impregnation helps in forcing the resin inside the fabric. The composite plate fabricated by this process are then cured under standard atmospheric conditions. This process is simple to use and results in low cost tooling with the use of room-temperature cure resins. Three different laminates are prepared namely GFRP(Glass fiber reinforced plastic), CFRP(Glass fiber reinforced plastic), mixed (CFRP+GFRP).

Fig. 2. Hand layup process.

After the layup process the mould containing composite layers is mounted in a hydraulic or mechanical moulding press. This is to ensure that there are no presence of gaps/air bubbles in between the layers. Good surface finishes are obtainable, contributing to lower part finishing cost[5].

The cured composite plates are machined in to laminates as per the required dimensions. A circular (HSS) cutting tool is used for the cutting purposes with a cutting speed of 15m/s and feed rate 50mm/min. For drilling holes, poly crystalline diamond (pcd) tool, 4mm diameter, is used with cutting speed and feed rate as 60m/min and 0.0508 - 0.0889mm/rev respectively. These parameters are followed to limit defects introduced into work piece and tool wear.

The laminates are joined by adhesive joint and bolted joint. Surface treatments prior to the application of adhesives are recommended to achieve maximum mechanical strength. Bond strength can be significantly improved by surface treating the adherends prior to bonding by increasing surface roughness. For the adhesive joint, epoxy resin (LY556 + HY951) is used as adhesive. High tensile bolts (M4, Grade 12.9) are used for the bolted joint. Washers are used to prevent the penetration of bolt heads into the laminate. (Ref. Fig. 3, 4, 5).

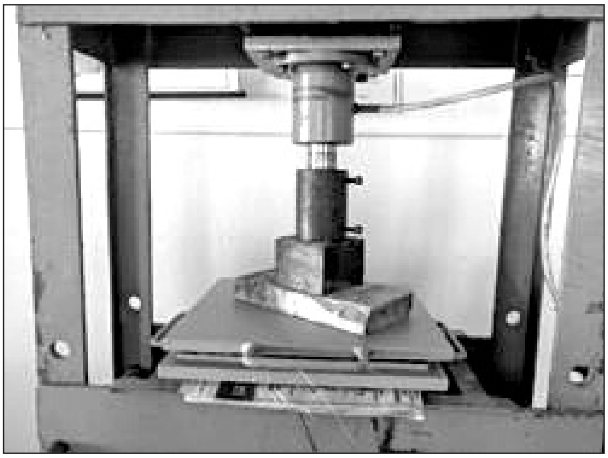


Fig. 3. Mould under hydraulic compression.

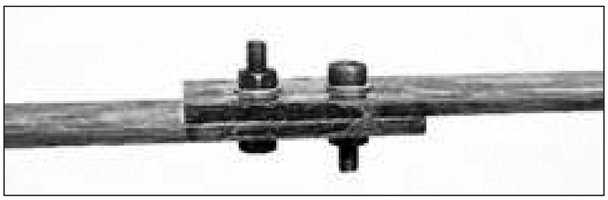


Fig. 4. CFRP hybrid lap joint.

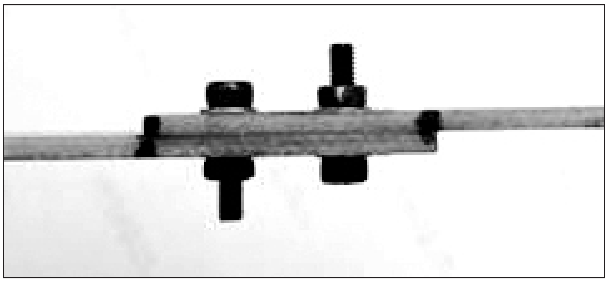


Fig. 5. GFRP hybrid lap joint.

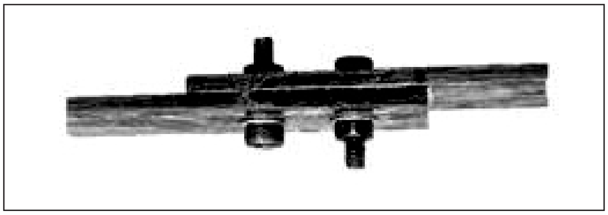


Fig. 6. CFRP+GFRP hybrid lap joint.

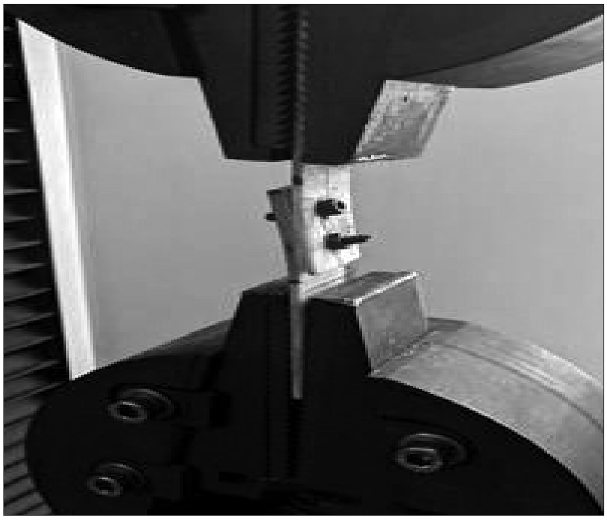


Fig. 7. Tensile test of the joint.

The hybrid joints are tested for the joint strength, for this purpose the universal testing machine is used. The specimens were tested on the testing unit with a load cell capacity of 100kN. The tensile test is done following ASTM D3163. A typical test speed for standard test specimens is 2 mm/min (0.05 in/min). An extensometer or strain gauge is used to determine elongation and tensile modulus. (Ref. Fig. 6, 7).

2.1. Defining the hybrid lap joint in Ansys

The hybrid lap joints were modelled and analysed using Ansys work bench, a finite element modelling software. The stresses such as von-mises stress and maximum shear stress were found. The breaking load of the joints obtained from the tensile test is applied as one of the boundary conditions in Ansys. For the applied load, the stress distribution is analysed on each hybrid lap joint and emphasized for the joint failure stress which is already known from the experiment.

The hybrid joint is modelled in Ansys by the steps mentioned below.

1. Ansys ACP
2. Mechanical model
3. Static Structural

Ansys composite Prep-Post or ACP is a component system in Ansys workbench which is used to create and transfer layered composite model to solver input file. The material properties which can be linear/nonlinear, isotropic/orthotropic are defined and a CAD geometry is designed for the analysis. Meshing the geometric model is key to get accurate results in finite element analysis. For the current analysis, the statistics of the mesh for each composite laminate is as showed below.

- Nodes-2037
- Elements-634
- Element order- Quadratic
- Element size- 2.2mm

A stack-up fabric (ply) is created with a defined stacking sequence. The orientation must be given for every ply in the stack-up. For example, a GFRP laminate consists sequence of E-Glass fabric plies.

Two such laminates are created in separate ACP components, and later combined in static structural along with the bolts which are modelled in a mechanical model. In static structural the displacements, strains and stresses of the hybrid joint are determined for the applied boundary conditions. Defining correct Contacts, boundary conditions is key in order to avoid errors in the output solution.(Ref. Fig. 8.)

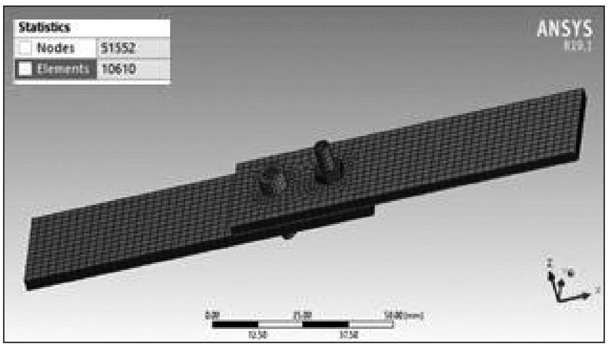


Fig. 8. Modelled hybrid lap joint in Ansys.

3. Results

For each hybrid lap joint, three samples were tested and the average strength and efficiency are calculated. The results obtained from the tensile test of the different hybrid lap joints are analysed and compared.

The following are the formulae used for the hybrid lap joint to estimate the overall joint strength and efficiency.

1. Shear strength of the bolt:

$$\tau_{bolt} = \frac{F}{\frac{\pi}{4} d^2 \times 2}$$

The area for the Shear strength of the bolt is doubled because two bolts are used per pitch length.

2. Tearing of the plate:

$$\sigma = \frac{F}{(p - d)t}$$

3. Shear strength of the laminate:

$$\tau_{laminate} = \frac{F}{2 \times m \times t}$$

The area for the Shear strength of the bolt is doubled because of the double shear of the plate.

4. Crushing strength of the plate:

$$\sigma_c = \frac{F}{2 \times d \times t}$$

The area for the Crushing strength of the plate is doubled because two bolts are used per pitch length.

5. Efficiency of the joint

$$\eta = \frac{\text{Stress at joint failure } (\tau_{bolt}, \sigma, \tau_{laminate}, \sigma_c)}{\text{Tensile strength of the material (Mpa)}}$$

Where
F is the breaking load on the joint
P - Pitch of the bolted joint
d - Diameter of the bolt(mm)
t - Thickness of the plate (mm)
σ – Tearing strength of the plate
$\tau_{\_bolt}$ - Shear strength of the bolt
$\tau_{\_laminate}$ - Shear strength of the laminate
η - Efficiency of the joint
m - Margin(mm)
σ_c - Crushing strength of the plate

The mode of failure for the GFRP hybrid lap joint is tearing failure of the laminate across the hole, shown in figure 9, CFRP+GFRP hybrid lap joint is crushing of the laminate, shown in figure 11, and for the CFRP hybrid lap joint is shearing failure of the bolts which is shown in figure 10. The joint strengths and efficiencies are calculated for each joint and the values are mentioned below.

- The Average strength of GFRP hybrid lap Joint = 128.03Mpa
- The Average strength of CFRP+GFRP hybrid lap Joint = 478.42Mpa
- The Average strength of CFRP hybrid lap Joint = 578.47Mpa
- The Average Efficiency of CFRP+GFRP hybrid lap Joint(η_avg) = 73.28%
- The Average Efficiency of CFRP hybrid lap Joint (η_avg) = 58.4%
- The Average Efficiency of GFRP hybrid lap Joint(η_avg) = 62.92%

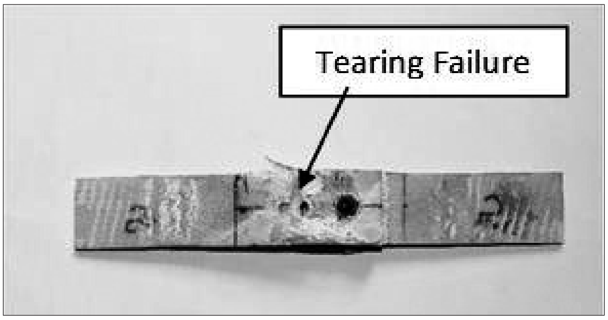


Fig. 9. Failure of GFRP joint.

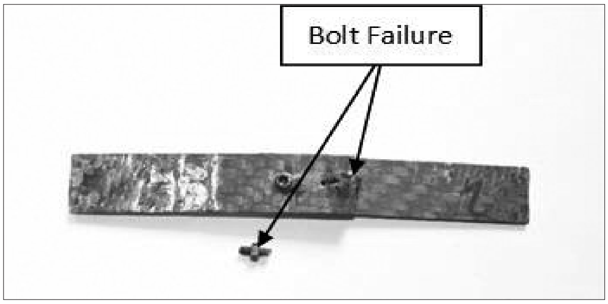


Fig. 10. Failure of CFRP joint.

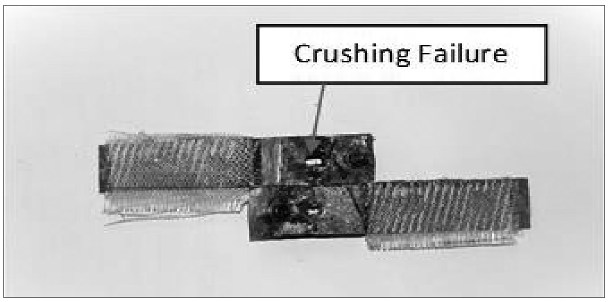


Fig. 11. Failure of CFRP+GFRP joint.

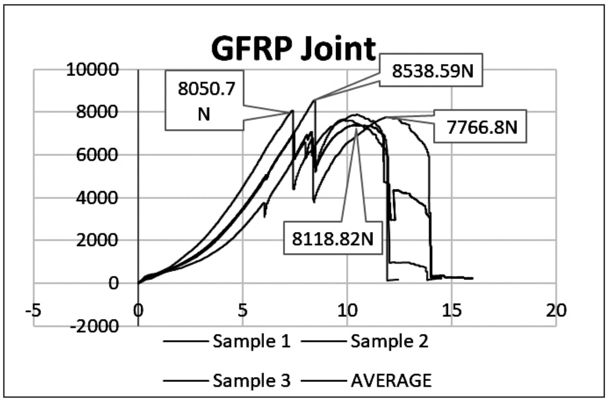


Fig. 12. Load vs displacement of GFRP joint.

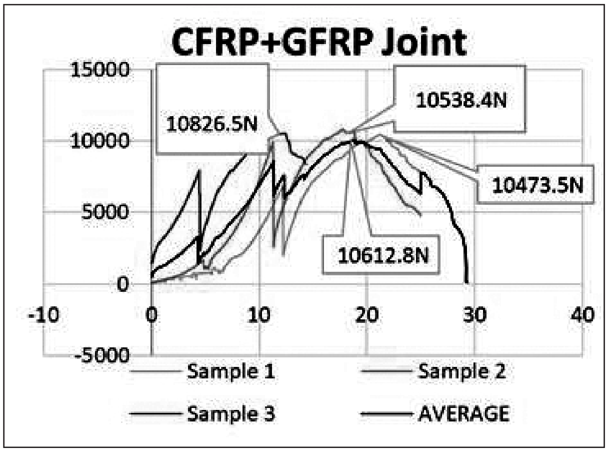


Fig. 13. Load vs displacement of CFRP+GFRP joint.

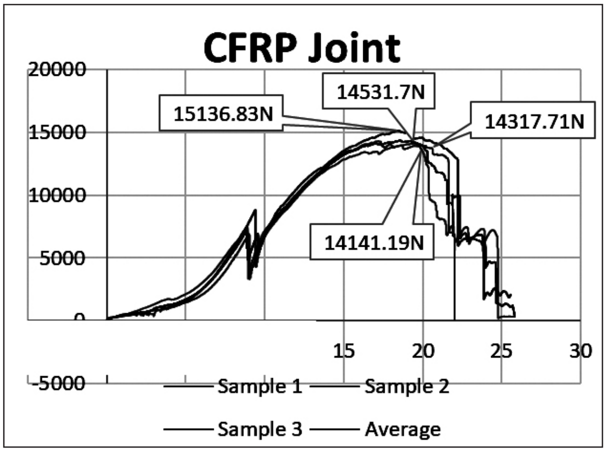


Fig. 14. Load vs displacement of CFRP joint.

3.1. Comparison of the joints

The strength and efficiencies of different joints are compared. It is clear from the Table 3, joint strength of the CFRP hybrid joint is the highest (602Mpa) followed by the of CFRP+GFRP hybrid joint (484.88Mpa) and GFRP- GFRP hybrid joint (135.06Mpa) respectively. In contrast to the joint strength, CFRP+GFRP has the highest joint efficiency with 73.28% followed by GFRP (62.92%) and CFRP hybrid joint(58.4%).

Table 3
Strengths and efficiencies of hybrid lap joints.

Sample	Tearing strength of laminate Mpa	Shearing strength of bolt Mpa	Shearing strength of Laminate Mpa	Crushing strength of Laminate Mpa	Efficiency %	Breaking load from tensile test (KN)
			GFRP			
1	135.06	339.73	122.68	368.04	66.37	8.53859
2	119.95	309.03	108.96	326.88	58.95	7.76687
3	129.1	320.32	117.29	351.87	63.45	8.0507
Average	**128.03**	**323.02**	**116.31**	**348.93**	**62.92**	**8.11872**
			CFRP+GFRP			
1	177.93	416.72	161.62	484.88	74.26	10.4735
2	179.2	430.78	160.53	481.6	73.8	10.8265
3	174.4	419.3	156.26	468.79	71.8	10.5384
Average	**177.17**	**422.26**	**159.47**	**478.42**	**73.28**	**10.6128**
			CFRP			
1	199.16	562.93	180.74	542.22	56.83	14.14119
2	201.64	569.94	182.99	548.97	57.54	14.31771
3	213.18	602.54	193.45	580.37	60.83	15.13614
Average	**204.66**	**578.47**	**185.72**	**557.18**	**58.4**	**14.53168**

Table 4
Comparison of the hybrid lap joints.

Type of joint	**Average Joint Strength (Mpa)**	**Average Joint Efficiency (%)**	**Observed mode of failure of the joint**
GFRP joint	135.06	62.92	Tearing of the laminate
CFRP+ GFRP joint	484.88	73.28	Crushing of the laminate
CFRP joint	602	58.4	Shearing of the bolt

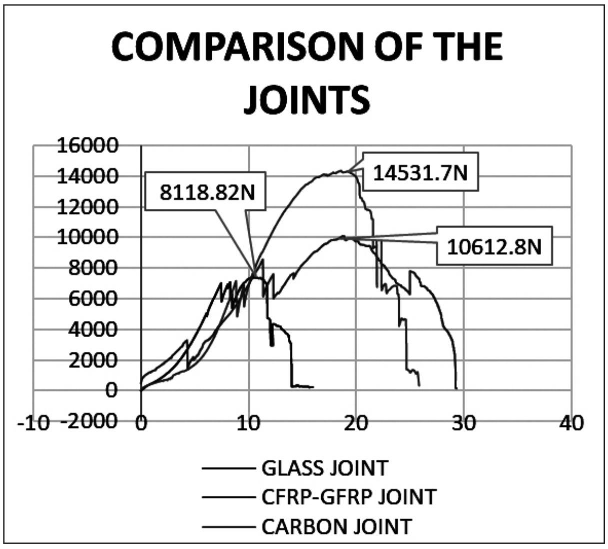


Fig. 15. Comparison of the joints.

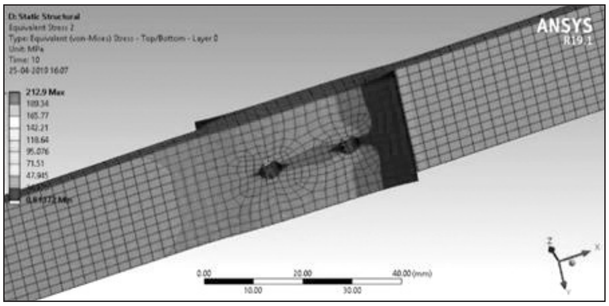


Fig. 16. Von-mises stress on GFRP joint.

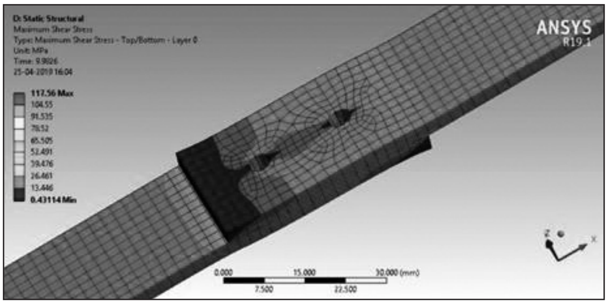


Fig. 17. Shear stress on GFRP joint.

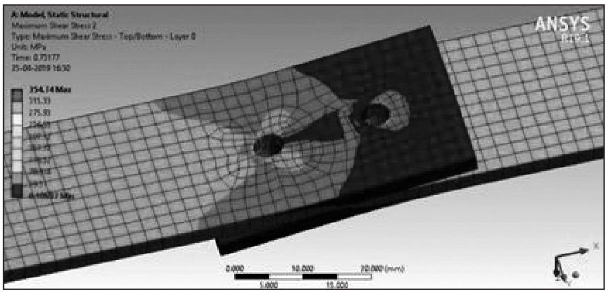


Fig. 18. Shear stress on CFRP+GFRP joint.

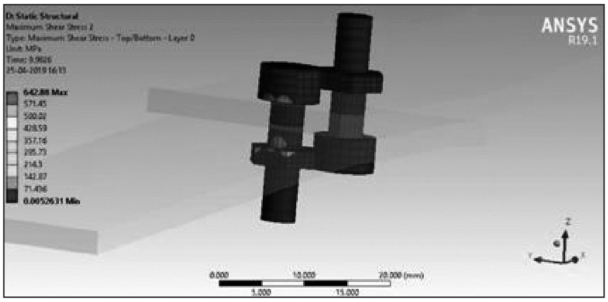


Fig. 19. Shear stress on CFRP joint bolts.

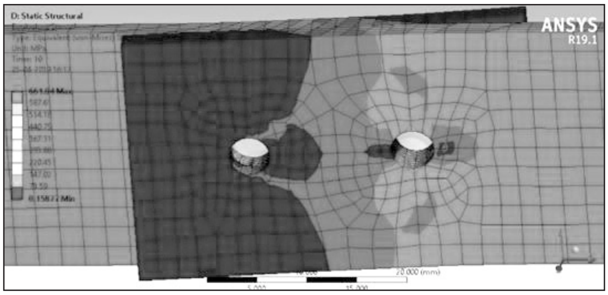


Fig. 20. Von-mises stress on CFRP joint.

The joints strengths are compared by drawing load vs displacement graphs for GFRP, CFRP+GFRP, CFRP joints respectively. (Ref. Fig. 15)

3.2. Results from Ansys

A numerical study is conducted on hybrid composite lap joints of glass-fiber reinforced plastic (GFRP), carbon-fiber reinforced plastic (CFRP) and CFRP+GFRP laminates. The figures belowshows the distribution of various stresses for hybrid lap joints. From FEA results, it is observed that the maximum value of stresses occurred at holes of the laminates.

The figure 16 shows Von-mises stress and shear stress distribution on GFRP hybrid lap joint when it is subjected to tensile loading. From the results it is observed that the maximum value of the von-misesstress (212.9Mpa) on the laminate exceeds the permissible stress value which is 203Mpa. Therefore, the failure of the laminate will occur across the hole. And the same type of failure is observed in experimental data.

The figure 18 shows Von-mises stress and shear stress distribution on CFRP+GFRP hybrid lap joint when it is subjected to tensile loading. The experimentally observed mode of failure in CFRP+GFRP hybrid lap joint is crushing between the bolts and laminate. Since, it is not possible to determine crushing stress in Ansys, an identical stress, shear stress is used. From the figureit is known that the maximum value of the stress is 354.74Mpa and because of this the hole deformation occurs at the bolt and laminate interface.

In CFRP hybrid lap joint, the maximum stress is observed in the bolts. The figure 19shows the shear stress variation on bolts with a maximum value of the stress 642.88Mpa which exceeds the permissible shear stress value of the bolt (600Mpa). (Ref, Fig. 16-20)

Conclusion

From the experimental tensile test results some relevant observations were made about hybrid lap joint failure and determine the strengths and efficiencies of different hybrid joints. Following such considerations, hybrid lap joints with different composite materials were fabricated and tested. The simulation results from Ansys coincided with the experimental results.

It is clear from the graphs that initially, the joint load is distributed between the adhesive and bolt, after debonding of the adhesive occurs the load is solely bared by bolt till failure occurs. The graph also shows that for almost all the joints, irrespective of the laminate material used, the strength of the adhesive remains to be the same. The efficiency of CFRP hybrid joint is 58.4% and the failure is due to shear failure of the bolts, the efficiency can be further increased by using stronger bolts. The tearing failure and shear failure of the composite joints is not acceptable because they are catastrophic. It is clear from the results that GFRP joints are failed due to the tearing failure of laminate. Therefore, in order to prevent such failures design parameters like pitch, margin should be increased.

As mentioned earlier that tearing failure and shear failure are not recommended the laminate geometry is chosen to assure a progressive crushing/bearing failure mode. This type of failure is occurred in CFRP+GFRP joint which has a joint efficiency of 73.28%.

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