Experimental and Finite Element Analysis of GFRP Composite Laminates with Combined Bolted and Bonded Joints

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Abstract

The scope this research work is to develop and study the finite element analysis of GFRP composite laminates with combined bolted and bonded joint. Polymer matrix composite materials are widely used due to the reason of high strength to weight ratio. Design techniques for fastened joints have received valuable attention due to the different nature of the stress field in the proximity of the joint, the different of failure modes that can occur. A foremost goal of bolted joint research is to limit the effect of several bolting parameters on the bearing strength of the joints. These parameters such as: (a) joint geometry (b) joint configuration (c) loading condition (d) fastening parameters and (e) material parameters. The scope of the project is to examine the influence of certain factors on the strength of bolted joints in [0/90]4s GFRP composites. These features include the tightening torque (T= 15, 20, 25 & 30 Nm). The mechanical properties (Tensile & Compressive) of GFRP laminates have been examined experimentally and theoretically. From the investigational study, it is found that bolted joint and bolted - bonded joint with 6 mm diameter, 25 Nm tightening torque has the extreme strength. Most of the test specimens failed in (a) Bearing failure (b) Net tension failure (c) Shear out failure (d) Cleavage tension failure.

Keyword: Epoxy Resin, Failure Modes, Glass Fibre, Tightening Torque, Washer Size

1. Introduction

Increasing use of composite materials in many fields of engineering has been observed in the past few decades. The advanced composite materials such as graphite, carbon, Kevlar and glass with suitable resins are widely used because of their high specific strength and high specific modulus. The automotive industry is exploiting composite material technology for structural components construction in order to obtain the reduction of the weight without decrease in vehicle quality and reliability. The tensile failure of scarf joint was studied14 using 2-D model. Various methods had been proposed for study of adhesively bonded joints15-17. The initiation and propagation of damage was studied17 at meso-scale level. Stress analysis of pinned joint is performed by most models using FE models18 and numerical code is established for evaluating the failure load, failure mode and the propagation of failure of composite laminate with fiber orientation, material properties and geometries. Different approaches had been adapted to find the failure load of bolted joints such as finite element method, statistical approach19, boundary element method20 etc. However in case of bolt-loaded laminates, the maximum stress state in the locality of the bolt is three dimensional and be subject to on several critical parameters like friction between the composite laminate, fastening torque, laminate stacking sequence which cannot be considered in 2D models21. In case of 3D a progressive damage model has been intended22,23 which may consider the three important levels like stress analysis, failure analysis and material degradation. A grouping of failure conditions and material property directions

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that leads to correct strength prediction is projected in\textsuperscript{14}. In order to analyse multi-bolted joints\textsuperscript{15}, their failure progression, ultimate strength and load circulation is associated with single fastened joint.

Combination of bolted-bonded joints has limited application, because bonded joints provide stiffer path. Lateral compression due tightening torque improves damage tolerance. Performance of hybrid joints has more fatigue strength than adhesive joints. The objective of this research is to evaluate the efficiency of bolted, bonded and combined bolted-bonded joints laminated composites with single-lap shear configuration.

1.1 Necessity to Study Fiber Reinforced Plastic (FRP) Joints

Modern aerospace structures require extensive use of advanced materials such as composite in order to reduce the weight and to improve performance. Over the recent years fiber reinforced composites joints found numerous applications as load-carrying components predominantly in aerospace applications. Generally load bearing members are jointed either by bolted or adhesive joints in aerospace structures.

Adhesive joints are used extensively for secondary aircraft parts and automotive parts. Occasionally there also used in primary parts of aircraft. The success of adhesive bonding depends strongly on the surface treatment of the adherents and adhesive layer parameters, which needs to be optimized to ensure that structural integrity is maintained under service conditions for the required life of the component.

2. Experimental Work

2.1 Composite Plate Manufacturing

An inflexible platform was selected and the aluminium foil sheet was kept on the glass plate platform and a thin film of polyvinyl alcohol was applied as a releasing agent. Lamina was cut from the roll of woven roving. The first layer was placed over the glass plate. The resin was placed on the mould by using brush, whose main purpose was to offer a smooth exterior surface and to shield the fibres from direct exposure to the atmosphere. By using the steel rollers, air gap was removed. Then the next layer of the specimen was placed before the resin got dried and the subsequent layers were filled. Then a heavyweight flat metal unbending platform was kept top of the plate for compressing purpose, with a force of around 225 – 300 N, for over a minimum of 48 hours to get the exact samples. The entire processing of the manufacture was done at the controlled atmosphere, at an average humidity of 65%.

2.2 Specimen Preparation

The GFRP composite laminates with 1.8 ± 0.2 mm thickness were made-up using hand lay-up process. The fundamental materials of the composite laminates are illustrated in Table 1 and the mechanical properties of composite laminate are indicated in Table 2. Composite Plate volume fraction (V\textsubscript{f}) was 60%.

2.3 Experimental Setup

Experiments are conducted on a fully computerised universal testing machine with loading capacity up to 200kN shown in Figure 1. The universal testing machine consists of two jaws. The upper jaw is fixed while the lower is given a displacement and the load applied on the lower jaw is calibrated and recorded on the computer. The displacement is given gradually the load displacement curve is plotted on the computer screen simultaneously. The joints were made from Glass Fiber Reinforced Polymer matrix (GFRP) composite plate and araldite 2012 was used as

| Material                     | Type                        |
|------------------------------|-----------------------------|
| Reinforcement                | E- glass fiber (Woven roving) 200 GSM |
| Matrix                       | Epoxy: Araldite LY556      |
| Hardener                     | HY951                       |

Table 1. Composition of GFRP composite laminates

| Property                  | Values  |
|---------------------------|---------|
| Modulus of Elasticity (GPa)| $E_1 = 30.13$ |
|                           | $E_2 = 30.13$ |
|                           | $E_3 = 7.95$  |
| Poisson’s ratio            | $\nu_{12} = 0.34$ |
|                           | $\nu_{23} = 0.28$ |
|                           | $\nu_{13} = 0.28$ |
| Shear Modulus (GPa)        | $G_{12} = 4.22$ |
|                           | $G_{23} = 3.06$ |
|                           | $G_{13} = 3.06$  |

Table 2. Mechanical Properties of composite laminate
adhesive to join the adherents in case of bonded joints. A steel bolt with nut was used to join the composite plates in case of bolted joints. The ends of the test specimen are glued with aluminium grippers for enabling proper gripping in the jaws. For each varying parameter three sets of specimens were prepared and tested for failure.

2.4 Tensile Test

Tensile properties of the laminate on the angle-ply \([0/90]_4\) GFRP composites using computerised tensile testing machine. The cross-head speed of the loading member in tension is 2 mm/min and operated at a temperature range of 25°C with the relative humidity of 65°C. Tensile results of the composites were determined experimentally giving to ASTM D3039. The yield strength, ultimate tensile strength and other mechanical property was calculated from the load-displacement curve. Figure 2, Figure 3, Figure 4 and Figure 5 shows the Dimensions of tensile test specimen, Test Specimen for tensile test, Experimental setup for tensile test and stress-strain curve for tensile test specimen. Experimental values are indicated in Table 3.

2.5 Compression Test

The compression properties of the composite laminates were determined experimentally in Table 4, using ASTM...
Table 3. Experimental values of tensile test specimen

| S. No | Yield Strength (kN) | Ultimate Strength (kN) | Young's Modulus (GPa) | Poisson's ratio | Experimental Stress (N/mm²) | FEA Result (N/mm²) | % of error |
|-------|---------------------|------------------------|-----------------------|----------------|----------------------------|--------------------|------------|
| 1     | 3.04                | 3.2                    | 37.5                  | 0.25           | 32                         | 35.427             | 9.6        |
| 2     | 3.12                | 3.28                   | 40.12                 | 0.18           | 32.8                       | 35.427             | 7.4        |
| 3     | 3.08                | 3.14                   | 32.14                 | 0.23           | 31.4                       | 35.427             | 11.3       |
| 4     | 3.04                | 3.2                    | 38.19                 | 0.19           | 32                         | 35.427             | 9.6        |

Table 4. Experimental values of compression test specimen

| S. No | Ultimate Strength (kN) | Experimental Stress (N/mm²) | FEA Result (N/mm²) | % of error |
|-------|------------------------|-----------------------------|--------------------|------------|
| 1     | 2.8                    | 46.66                       | 48.57              | 3.9        |
| 2     | 2.6                    | 43.33                       | 48.57              | 10.7       |
| 3     | 2.5                    | 41.66                       | 48.57              | 14.2       |
| 4     | 2.6                    | 43.33                       | 48.57              | 10.7       |

D3518/M compression test fixture. The dimension and test specimen of compression test are shown in Figure 6 and Figure 7.

2.6 Bolted Joints

Bolted joints are tested for different configurations of varying geometry. Three identical test specimens for each configuration are prepared for testing of bolted joints. GFRP laminate plates and steel bolt (6 mm) was used for the bolted connection. The dimensions of the fastened joint specimen and test samples is shown in Figure 8(a), Figure 8(b) and Figure 8(c).

2.7 Effect of Tightening Torque

The bolt holes were machined using two step procedure. First step used 4 mm with 1200 rpm. Then a 6-mm drill to enlarge the hole at a speed of 1100 rpm. Washers were used on both sides of the specimens. The Washer ID and OD are 8 mm and 25 mm respectively. Four dissimilar torque levels were applied using Dayton torque wrench. The first torque range was recommended 15 Nm. The second & third torque range was the full, recommended torque of 20 Nm and 25 Nm. The fourth torque range was the maximum torque of 30 Nm.

2.8 Bonded Joints

Three identical test specimens of bonded joint (L = 250 mm are prepared, each configuration (Figure 9) are tested. The specimens are loaded with a min feed rate of 1mm/min. To calculate the failure load and failure mode a sequence of experimentations were achieved. The effect of the lap length was studied in case of bonded joints. The failure of joint is obtained as the load at which the load displacement curve showed abrupt change in its
slope. The failure loads for all the above configurations are noted and the type of failure in each joint is observed (Figure 10).

2.9 Combined Bolted and Bonded Joints

Connection of composite materials has conventionally been accomplished by bolted joints or bonded joints. Joining these methods has been measured a new type of investigation in aerospace industry. The objective of this research is to evaluate the efficiency of bolted-bonded joints laminated composites with single lap shear configuration. Four different configurations of combined bolted and bonded joints were tested (Table 5) with experimentally and finite element analysis. In all the joint configurations, adhesive failure was observed first, subsequently bolt failure was noticed. Bond failure loads were found to be relatively higher than those of bolt failure loads.

2.10 Finite Element Analysis

It consists of two plates made of fiber reinforced Glass/epoxy composite laminates and a protruding head bolt. The orientation was selected to be $[0/90]_{ss}$. For analysing of the composite laminate the eight-noded SOLID46 element was used. The bolt contact on hole has been studied. Longitudinal loading is given in terms of displacement, the mimic quasi static displacement. Mesh is refined at the bolt hole. The bolt was layered 3D SOLID46 element in ANSYS 10.0. One element is used for each layer; eight elements were described in through thickness direction. Contact 174 and Target 170 elements are used for 3D contact surface. A 2D PLAN182 and 3D SOLID45 elements fully integrated finite element have been carried out with plain strain condition. Six element meshes is done along through thickness of adhesive. The large dimensional variation, properties variation between adhesive and adherent has been consider seriously while finite element modelling to avoid ill-condition, different mapping and element aspect ratio were analysed to
Table 5. Experimental values of combined bolted - bonded joint specimen

| S. No | Tightening Torque (Nm) | Experimental failure load (kN) | Experimental Stress (N/mm²) | FEA Results (N/mm²) | % of error | Failure mode       |
|-------|------------------------|-------------------------------|-----------------------------|--------------------|------------|-------------------|
| 1     | 15                     | 14.48                         | 144.8                       | 140.54             | 2.9        | Fiber Failure     |
|       | 15                     | 13.82                         | 138.2                       |                    | 1.6        | Fiber Delamination|
|       | 15                     | 13.24                         | 132.4                       |                    | 5.7        | Shear out         |
| 2     | 20                     | 15.16                         | 151.6                       | 147.14             | 2.9        | Matrix Failure    |
|       | 20                     | 14.84                         | 148.4                       |                    | 1.4        | Shear out         |
|       | 20                     | 13.56                         | 135.6                       |                    | 7.8        | Fiber Failure     |
| 3     | 25                     | 17.48                         | 174.8                       | 169.66             | 2.9        | Fiber Delamination|
|       | 25                     | 17.08                         | 170.8                       |                    | 1.2        | Matrix Failure    |
|       | 25                     | 16.56                         | 165.6                       |                    | 2.3        | Shear out         |
| 4     | 30                     | 14.32                         | 143.2                       | 138.99             | 2.9        | Matrix Failure    |
|       | 30                     | 15.48                         | 154.8                       |                    | 10.2       | Shear out         |
|       | 30                     | 14.80                         | 140.8                       |                    | 1.28       | Shear out         |

Figure 11.  (a) Loading and boundary condition of bolted joint (b) FEA of single lap bolted joint with 15 Nm torque.

Figure 12. Failure modes of combined bolted and bonded joints.

avoid numerical errors. To achieve high accuracy in the calculations of the inter-laminar stresses for the composite laminate eight layered elements stacked together were used in the thickness direction (Figure 11(a) and Figure 11(b)). Three dissimilar grouping of contact surfaces are defined between the different surfaces in contact of the joint (i) Between the bolt head and top plate (ii) Between the shank of the bolt and the hole surface of the plates. (iii) Between the nut and the lower plate.

2.11 Failure Modes of Combined Bolted and Bonded Joints

Failure Modes of combined bolted and bonded joints (Figure 12)

3. Conclusion

The mechanical characteristics of GFRP composite laminates such as tensile and compressive properties were examined experimentally and theoretically. For the adhesive joint of 25 mm lap length have the average maximum strength of 6.65 kN, the shear stress for this joint found to be almost equal for both experimental and FEA results. Bolted joint and Combined bolted and bonded joint samples with 6 mm diameter and 25 Nm tightening torque has better bearing strength. Maximum samples were failed in the subsequent orders: (a) Net tension failure (b) Shear-out failure (c) Cleavage tension failure and (d) Bearing failure.

4. References

1. Kumara SB, Sridhar I, Sivashankar S, Osiyemi SO, Bag A. Tensile failure of adhesively bonded CFRP composite scarf
joints. Materials Science and Engineering. 2006 Jul 25; 132(1–2):113–20. Crossref
2. Sheppard A, Kelly D, Tong L. A damage zone model for the failure analysis of adhesively bonded joints. International Journal of Adhesion and Adhesives. 1998 Dec; 18(6):385–400. Crossref
3. Kairouz KC, Matthews FL. Strength and failure modes of bonded single lap joints between cross-ply adherends. Composite. 1993 Sep; 24(6):475–84.
4. Radice J, Vinson J. On the use of quasi-dynamic modeling for composite material structures: analysis of adhesively bonded joints with midplane asymmetry and transverse shear deformation. Composite Science and Technology. 2006 Nov; 66(14):2528–47. Crossref
5. Delale F, Erdogan F, Aydinoglu MN. Stresses in adhesively bonded joints: a closed-form solution. Journal of Composite Materials. 1981 May 1; 15:249–59. Crossref
6. Apalak ZG, Apalak MK, Genc MS. Progressive damage modeling of an adhesively bonded unidirectional composite single lap joint in tension at the Meso scale level. Journal of Thermoplastic Composite Materials. 2006 Nov 1; 19:671–80. Crossref.
7. Karakuzu R, Gulem T, Icten BM. Failure analysis of woven laminated glass-vinylester composite with pin-loaded hole. Composite Structures. 2006 Jan; 72(1):27–32. Crossref
8. Icten BM, Karakuzu R. Progressive failure analysis of pin-loaded carbon-epoxy woven composite plates. Composite Science and Technology. 2002 Jul; 62(9):1259–71. Crossref
9. Schulz KC, Hietalab HJ, Packmanb PF. A statistical approach to the analysis of ultimate strength of bolted joints in laminated composites. Composites Science and Technology. 1996; 56(5):505–17. Crossref
10. Lin C–C, Lin C–H. Stress and strength analysis of composite joints using direct boundary element method. Composite Structures. 1993; 25(1–4):209–215. Crossref
11. Kradinov V, Madenci E, Ambur DR. Combined in-plane and through the thickness Analysis for failure prediction of bolted Composite Joints. Composite Structures. 2007 Jan; 77(2):127–47.
12. Mc Carthy MA, Mc Carthy CT, Lawlor VP, Stanley WF. Three-dimensional finite element analysis of single-bolt, single-lap composite bolted joint: part I-model development and validation. Composite Structures. 2005 Nov; 71(2):140–58. Crossref
13. Camanho PP, Matthews FL. A progressive damage model for mechanically fastened joint in composite laminates. Journal of Composite Materials. 1999 Dec; 33(24):2248–80.
14. Xiao Y, Ishikawa A. Bearing strength and failure behaviour of bolted composite joints. Composite Science and Technology. 2005 Jun; 65(7–8):1032–43. Crossref
15. Tserpesa KI, Labeasb G, Papanikosb P, Kermanidisa Th. Strength prediction of bolted joint in graphite/epoxy composite laminates. Composites Part B: Engineering. 2002 Oct; 33(7):521–9. Crossref