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An Experimental and Numerical Investigation on Bolted Joints of Woven Glass Fabric/Epoxy Composites

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ABSTRCT

In the present work, an attempt is made to study the mechanical response of woven glass fabric/epoxy composite laminates using numerical modelling and experimentation. For this two different configurations namely double lap joined with single and double bolts are chosen. These laminates are subjected to numerical modelling using finite element analysis to study the joint strength and stress analysis. The joint strength of woven glass fabric composites is studied experimentally by conducting tensile test. Along with this the effect of varying edge distance to diameter ratios are studied both numerically and experimentally to arrive at safe design. Both numerical analysis and experimentally obtained bearing strength of composite laminated bolted joints are correlated. This is done in order to predict the the failure load and failure mechanisms in the composite laminate bolted joints. The variation in the numerically and experimentally obtained bearing strength values were well within 5% diference for both cases of single and double bolted joints.

Keywords-- Woven Fabric, Polymer Matrix Composites, Joints, Finite Element Analysis, Bearing Strength, Failure Analysis.

INTRODUCTION & LITERATURE REVIEW

Materials are used to build structures, components or instruments which have to support loads, to reflect or transmit light, to conduct heat or to insulate against heat or electricity, to survive in extremely hostile environmental conditions. The development of new materials are driven by ever increasing demand for highly efficient materials with good performance, low cost, multifunctional properties and they should not damage or effect the environment. The transportation industries like automotive and aerospace are very much in need of materials with multifunctional properties. The first choice would be a material which not only has low density but a good mechanical property so that weight will be reduced leading and fuel consumption is also low. For these reason we go for composites materials because of their high specific stiffness, specific strength, fatigue strength and low density. Out of available composite materials, polymer composites are quite popular when compared to that of metal or ceramic matrix composites. Polymer matrix composites in earlier days were restricted to be used in making small household needs like chairs and tables but now they have matured enough to be used as structural materials in many applications in the field of automobile and aerospace. The main advantages for opting polymer composites when compared to metal and ceramic composites is that they are much easy to fabricate due to low processing temperatures involved, they are light weight and have good mechanical properties [1 - 3].

In the recent years fabrics made up of fibres which are oriented along two perpendicular directions and woven together have becomes quite famous for reinforcing the polymer matrices. This was mainly because the fibre reinforced composite laminates have poor mechanical properties in the direction of fibre thickness and also prone to interlaminar delamination. So by having woven fabric in the composites it was found that it can provide tridirectional properties [4-5]. Aitharaju and Averill [6] developed a simple numerical model for the estimation of the stiffness of the woven fabric composites. The analysis was carried out on the unit cell of the composite which is divided into three regions depending on the tow waviness and assembling them. The stiffness results obtained from this model were found to be accurate when compared to that of complex finite element method. Icten et al [7] produced the composite plates made up of woven Kevlar fabric and epoxy matrix material. The woven Kevlar-epoxy prepregs were subjected to curing at 150°C for about 5 hours under a pressure of 10 MPa. Here the volume fraction of woven Kevlar fibre was about 54% of the total volume fraction of the composite plate.

It is well known that composites with their specific manufacturing capabilities can help in developing highly integral design concepts in order to produce a component or structure with minimal

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need for joining or welding. With the reduced structural joining one can have reduced structural weight, production time, costs, less time consumption in assembly and inspection. Despite of these advantages one cannot simply avoid joining which is mainly due to technological limitation in obtaining complex shape and size of components. Although the composites have many advantages in transportation industry but the main issue is joining of these with other component and with the composite themselves. The mechanically fastened joints are the most preferred for joining of composite laminates and with the other parts as well. These joints are inexpensive to fabricate and can be disassembled easily. Despite of having many disadvantages like drilling of holes in composites as major one, the mechanical fastening still continues to dominate as main joining technique for large composite components or parts. For having an efficient structure and good performance we need to have thorough understanding of bolted joints and its behaviour under various loading and working conditions [8,9]. In their work, Aktas et al [10] used 42CrMo4 hardened steel as a pin material for preparing glass/epoxy composite pin joints. The holes drilled in the composite plates were inserted with polished hardened steels without any clearance. In another work, Egan et al [11] used aerospace grade titanium bolts (Ti-6Al-4V) for fastening the joints of carbon/epoxy prepreg. The bolts had 130° countersunk heads and steel nuts of grade ASNA2536. It is very important to note that these pin and bolted joints need to have holes in the composite laminates and requires special attention in the design process.

In order to use a composite material for a specific application needs a complete knowledge about its mechanical and dynamic behaviour. It becomes more important when the composite laminates are joined together by fastener or bonding. Under these conditions the strength of the joint needs to be analysed and how it vary according to geometry and more importantly how it fails. When a composite joint is subjected to tensional displacement by fixing one end of the plate and applying displacement to another, the resulting load-displacement curves define the behaviour of the composite. Typically a composite can fail in number of modes but the three main or what we say the principal failure modes of bolted joints for polymer based composite materials. The joints can fail in any one of the three failure modes shown below which are net-tension, shear-out and bearing and in addition to this the failure of composite joints can be combination of any of the above three failure modes. Literature published so far tells that there has been lot of experimental and numerical investigations on pinned and bolted joints [12-14]. Most of the studies were concentrated on glass fibre/epoxy composite laminates because of cost of the material and good mechanical properties. For instance Karakuzu et al [15] studied the failure analysis of woven laminated glass/vinylester composites with pin loaded hole by both numerically and experimentally. The effect of edge distance to diameter and width to diameter ratio on failure load and failure modes was studied. The numerical results obtained using Hashin criteria to predict failure modes were in well agreement with that of experimental results. It was found that by increasing the geometric parameters the bearing strength of the composite plates was found to be increasing. At the low values of edge distance to diameter ratio the failure modes were net-tension or shear-out. Ozen and Sayman [16] carried out the numerical and experimental studies to investigate the failure load of bolted joints of woven glass fibre/epoxy laminated composites. The finite element method was used to conduct the numerical analysis and ANSYS 11.0 FE was used to develop the model. The failure mode obtained using Tsai-Wu criteria were similar to that of experiments while the error between the failure loads was less 10%. The higher values of K/D, W/D and E/D contributed in increase in failure load.

The present work is focussed upon on the development of woven glass fabric and epoxy composite laminates using hand lay-up technique. The composite laminates with double lap, single and multiple bolted joints were fabricated and there corresponding mechanical properties were studied. The studies related to strength and failure mode of composite joints for different edge to diameter ratio has also been conducted. Further the numerical analysis on composite laminates was carried using finite element method using ANSYS software and compared with those obtained from experimental ones.

NUMERICAL AND EXPERIMENTATION
NUMERICAL MODELLING

In this study, we have following joints namely; double lap single bolt and double lap double bolt joints. Here the composite laminate has a hole of 6 mm diameter (D) which is located along the centerline of the laminate. Further the hole center is located at a distance of E mm from the one edge of composite laminate. This is for composites having single bolt joints whereas for the composites having two bolted joints, two parallel holes are made such that they are located at distance W/2 from one end while from the edge they are located at a distance of E mm. Here the distance between two parallel holes is taken as 50 mm so that the failure mode obtained in these cases gives bearing modes. The overall dimension of the plate is length 100 mm, width 50 mm and the thickness is about 10 mm. The bearing strength and failure mode of composite joints are

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dependent on many geometrical parameters such as width and length of the specimen, edge distance and loading conditions. Here the plate dimension and E/D ratio are chosen based on the vast literature survey such that the mode of failure should be bearing mode. Based on this the effect of edge distance to hole diameter ratio (E/D) on bearing strength and failure mode of the composite laminate joints, we have varied the ratio from 2 to 5 in the steps of 1 is being studied. The E/D ratio is varied for all the cases of double lap single and double bolted joint composites so that optimum ratio can be obtained through the numerical analyses. Here most of the geometrical parameters are chosen such that they should fail in bearing mode which is characterized as local and progressive failure.

The first step in this work is to develop a finite element model for all cases of composite laminates. A 3D finite element model is developed for all the cases of double lap single and double composite bolted joints using ANSYS FE code using eight-noded SOLID46 3D ANSYS layered element. Once the models are created the next step is to mesh the components of the models and the meshing process along with the geometry is so detailed that they replicate the key features of composite laminates and bolt. Once the meshing is done, the next step is apply the boundary conditions like fixing on edge of composite laminate joint while load is applied to the other end. But before doing that here the important point is to define the properties of individual constituent of composite material or it can be modeled with linear elastic law and consider it as orthotropic material. The latter one is chose for present study and in order to have good representation of stress-strain field one element is used for each ply through the thickness. The element input data includes for plane stress conditions and properties of each composite layer corresponds to element coordinate directions. Further the contact surface between the joined composite laminates is chosen as the sliding interface with a known coefficient of friction. The sliding surface here is between the fasteners and plates and also between the upper and lower plates. In this study the coefficient of friction for the interface between the composite laminates is set to 0.2 and for laminate (upper or lower) to fastener interface the value is set to 0.07.

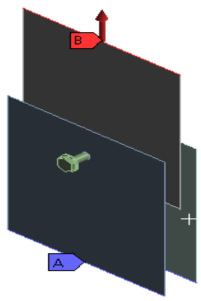

Figure 1: *Boundary Conditions Applied On Double Lap Single Bolted Composite Laminate.*

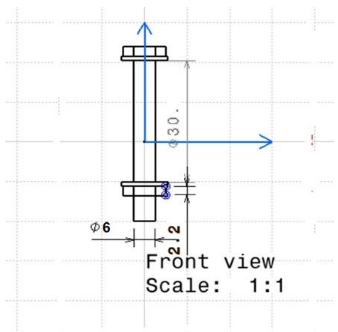

Figure 2: *Bolt and Nut Used For Joining the Composite Laminate.*

When it comes to application of boundary conditions, one end is clamped perfectly such that all the degrees of freedom are suppressed while the other end is allowed to move freely but only along

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the longitudinal direction. The one end which can move or can have displacement in only x-direction and is no rotation of this end is allowed. The model created for double lap with single bolt joint is shown in Fig. 1, which represents the exact condition where a tensile specimen is placed between the two pairs of jaws in the experimental tension test. A schematic of bolt and nut with dimensions is shown in Fig. 2. The thread part which is not in contact with the nut is modeled as axial revolution of thread in order to avoid the mesh complexity during stress analysis.

When a uniform tensile load is applied to one end of the composite laminated bolted joint, the load is resisted by the rigid bolt. The load applied is parallel to the composite laminate and is symmetric with the centerline such that the load cannot create a bending moment about X, Y and Z axes. The load-displacement values are obtained from the numerical analysis and the corresponding bearing strength is calculated from the following expression.

$$\sigma_b = \frac{P}{D \times t}$$

Where P is the peak tensile load, D is the bolt whole diameter and t is the thickness of the composite laminate respectively. Further the corresponding stress distribution curves along with deformation snapshots are obtained from the numerical analysis to study the failure modes in these composite laminate joints.

Table 1: *Linear Densities of Raw Materials.*

Material	**Density (g/cm^3)**
Epoxy resin (LY 556)	1.15 – 1.20
Woven E-glass fibre	2.54 – 2.60

EXPERIMENTATION

In order to study the joint strength of composite laminates composite laminates were made of woven glass fabric/epoxy are fabricated. A commercially available woven glass fabric with plain weave morphology is used as reinforcement material while epoxy resin (LY 556) is used as matrix material. The linear densities of both the composite constituent materials are shown in Table 1. The composite laminates with a thickness of 10 mm are fabricated using dry hand lay-up technique. The fabrication of composite laminate begins with the stacking the woven glass fabric one above the other with the polymer resin mix evenly spread between these woven glass fabrics with the help of brush and flat plate. The matrix material is combination of epoxy resin and hardener mixed in a ratio of 100:80 by weight. The epoxy resin and hardener mix is applied in between the woven glass fabric layers and the process is repeated until a laminate thickness of 10 mm is obtained. once the stacking is done, next step is to compact the layers with the help of a roller which not help in eliminating the entrapped air that could later lead to voids or layer separations but also in obtaining dense composite laminate. Once this is done they are subjected to curing process is which they cured using proper temperature and pressure for specific periods of time. The laminates are cured in an oven held at a temperature of 120°c and held them for about 6 h. the high temperature is necessary to dry the epoxy resin while the pressure is applied to get the bonding between the woven glass fabric and epoxy. With the help of hydraulic press, a pressure of 15 MPa is applied on these laminates and later cooled slowly to room temperature in order to avoid or minimize thermal residual stress.

Once the fabrication is completed, the next step is to machine the composite laminates for required dimensions used diamond cutter. Here the diamond cutter is used for cutting the composite laminated because to avoid the possibility of delamination at the ends and other geometrical discontinuity. A Twinspin machine based on a new orbital drilling was used to drill the holes in the composite laminates with appropriate distance E mm from the edge of the composite laminate. This machine is used for its advantages like its cutting tool revolves at high speed on its axis while lower speed eccentrically around a principal axis which helps in obtaining hole diameter of accurate diameter. The possibility of the eccentricity of the cutting tool is avoided in this machine and delamination free holes are obtained in the woven glass fabric composite laminates which is shown in Fig. 3. So from Fig. 3 we can see that the hole drilled in laminates are free from the delamination and are having accurate diameter without any eccentricity.

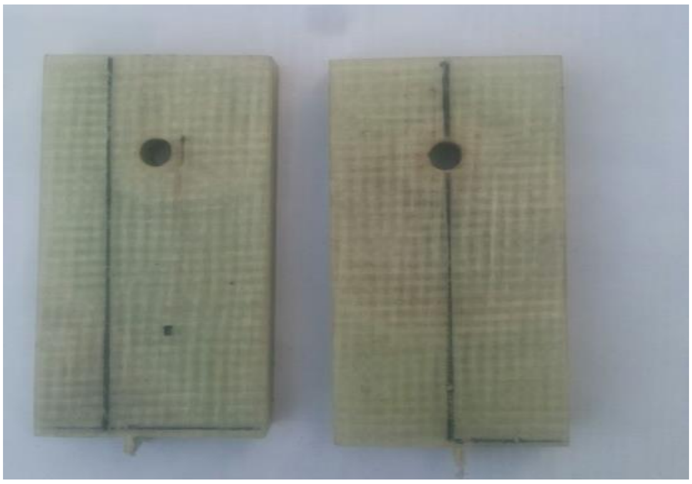

Figure 3: *Machined Woven Glass Fabric Composite With Holes Drilled In Them.*

The tensile tests were conducted on composite laminate bolted joints according to the ASTM D3039-76 standard in which the test specimens were cut with a circular diamond blade saw into the rectangle blank where each composite laminate is having a dimension of 100×50×10, mm^3. As mentioned earlier the composite laminate edges were carefully finished using emery papers to avoid the catastrophic influence of surface flaws. The tensile specimen as shown in Fig. 4 is placed in a universal testing machine and alignment is taken care with respect to longitudinal axis of the composite laminate specimen. The details of tensile test carried and the equipment details are given in Table 2. The tensile tests on all configurations of composite laminate bolted joints were conducted at room temperature of 20°C with cross-head speed adopted was 1.2 mm/min. Three tests were conducted for each type of configurations of composite laminate bolted joints and average bearing strength values were calculated. Further after failure of each bolted joints, photographs were taken to study the failure modes. These failed bolted joints were subjected to analysis and correlated with that of numerical ones.

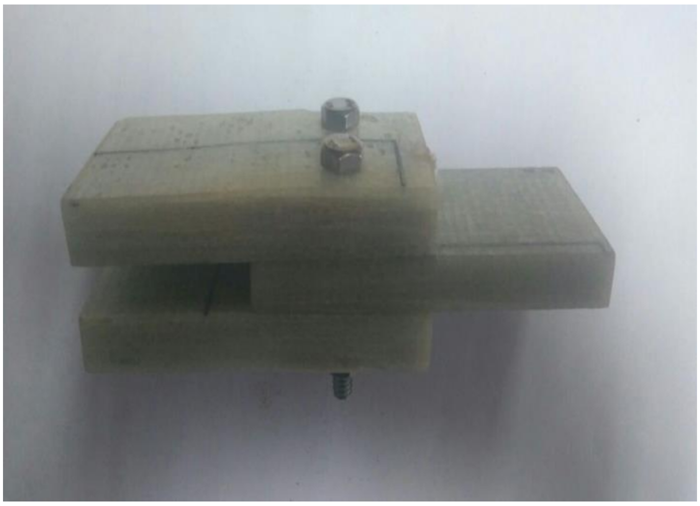

Figure 4: *Composite Joint Prepared By Joining the Laminates with the Bolt and Nut.*

Table 2: *Tensile Test Details.*

Instrument used	Universal Testing Machine
Load Capacity	0-60N
Strain rate	1.2mm/min
Temperature	Room Temperature
Make	FIE, India
Model	UTE-60
Make	FIE
Capacity	0-60 Tons

RESULTS AND DISCUSSION

In the present work we are focused on determining the failure loads and failure modes of double lap joints with single and double bolts. For numerical analysis of the composite laminates, the properties of its constituent materials like, woven glass fabric and epoxy are taken in to account and used for modelling and simulation work. Though there are many variables involved in the joints, but complete characterization of joints is highly dependent on the geometry of the hole and edge distance.

Numerical Results

The load/displacement behaviour for different E/D ratio composite laminates was analysed. It is usually observed that the first failure and ultimate bearing strength values are highly dependent on the E/D ratio.

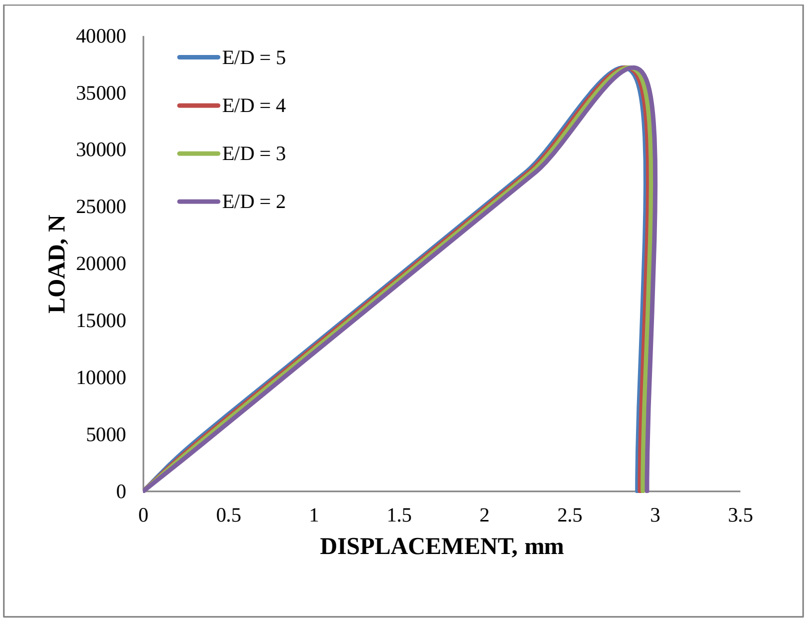

Figure 5: *Load-Displacement Curves For Double Lap Single Bolted Joints with Different E/D Ratio's.*

Fig. 5 shows the load-displacement curves plotted for the different E/D ratios obtained numerically for double lap single bolt joint. It is observed from the Fig. 5 that in all the cases with the increase in load the displacement is found to increase. All load-displacement curves are nearly linear until final load or ultimate load is reached thereafter it decreases suddenly indicating failure of the joint. The peak load at which the bolt joint has failed is about 35.5, 36.5, 38.75 and 36.75 kN for E/D ratio 2, 3, 4 and 5 respectively. It can be noted that the peak load for failure is observed for E/D ratio 4 is the highest when compared to that of other E/D ratios. Here the FEA results indicate a mixed

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mode failure for some bolt joints especially the one with E/D = 4 ratio.

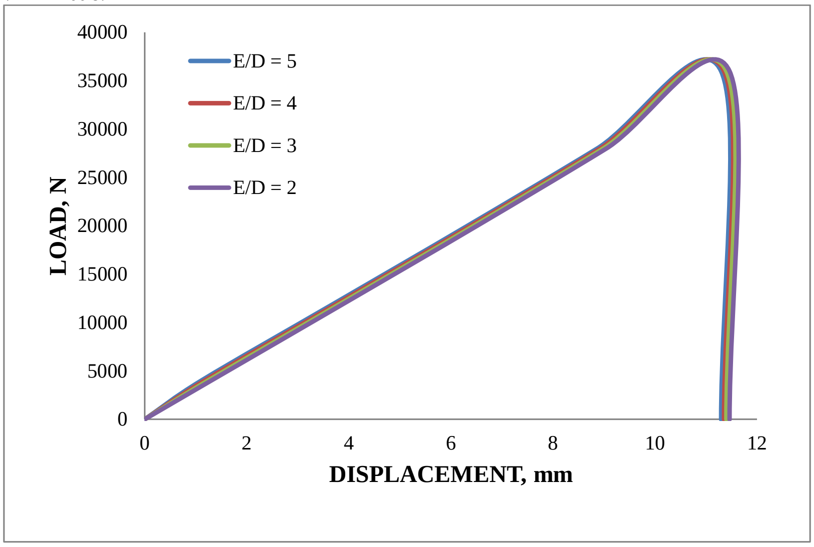

Figure 6: *Load-Displacement Curves For Double Lap Single Bolted Joints with Different E/D Ratio's.*

Fig. 6 shows the load-displacement curves plotted for the different E/D ratios obtained numerically for double lap double bolt joint. It is observed from the Fig. 6 that all load-displacement curves are nearly linear until final load or ultimate load is reached thereafter it decreases suddenly indicating failure of the joint. The peak load at which the bolt joint has failed is about 36.75, 38.50, 40.75 and 37.50 kN for E/D ratio 2, 3, 4 and 5 respectively. It can be noted that the peak load for failure is observed for E/D ratio 4 is the highest when compared to that of other E/D ratios. Here the FEA results indicate a mixed mode failure for some bolt joints especially the one with E/D = 4 ratio.

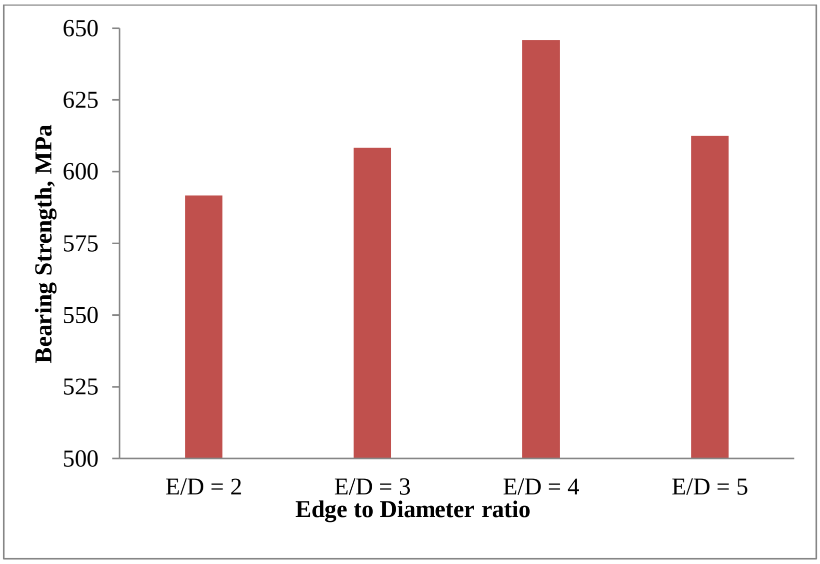

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***Figure 7:** Bearing strength for double lap single bolted joints with different E/D ratio's*.

Fig. 7 is the bearing strength values evaluated from the load-displacement curves obtained for the all the E/D ratios of double lap single bolt joint. It is observed that the with the increase in the E/D ratio from 2 to 4, the bearing strength was found to increase in this but later for E/D ratio of 5 the bearing strength was found to decrease. The highest bearing strength was obtained for E/D ratio 4 which had value of 645.83 MPa while lowest bearing strength value was recorded for E/D ratio 2 which has value of 591.67 MPa. So when compared to E/D ratio 2, the increase in the strength for E/D ratio 4 is about 9.15%.

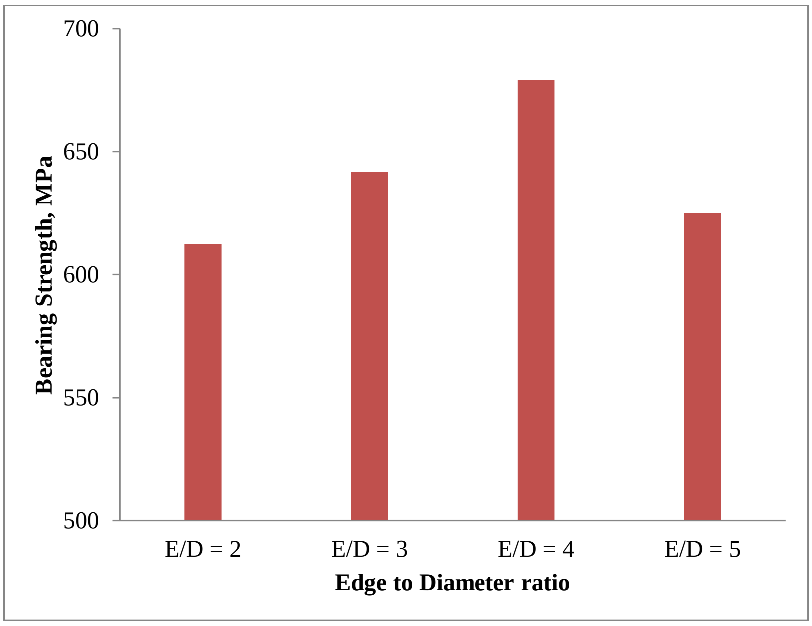

***Figure 8:** Load-Displacement Curves For Double Lap Double Bolted Joints with Different E/D Ratio's.*

Fig. 8 is the bearing strength values evaluated from the load-displacement curves obtained for the all the E/D ratios of double lap double bolt joint. It is observed that the with the increase in the E/D ratio from 2 to 4, the bearing strength was found to increase in this but later for E/D ratio of 5 the bearing strength was found to decrease. The highest bearing strength was obtained for E/D ratio 4 which had value of 663.48 MPa while lowest bearing strength value was recorded for E/D ratio 2 which has value of 612.50 MPa. So when compared to E/D ratio 2, the increase in the strength for E/D ratio 4 is about 8.32%. Further it can be observed that the bearing strength values for double bolt joint are higher than that of single bolt joints. For instance when we compare the bearing strength for E/D ratio 4 we can see that double bolt has a value of 663.48 MPa while that for single bolt joint is 645.83 MPa which is almost 2.7% increment in bearing strength. Though the increment is not so significant but it clearly indicates that the increase in number of bolts can increase the strength of composite laminate joints.

Fig. 9 & 10 shows the stress distribution around the hole of for double lap single bolt and double bolt joint for E/D ratio equal to 2. Here the FEA analysis shows the maximum stress concentration around the joint region and exhibits mixed failure modes for all the cases of E/D ratio. Both the cases exhibit the same macroscopic failure mechanism and damage progression. Here as compared to that of single bolt joint, the stress are comparatively less in double bolt joint and also has less displacement. This indicates that the load carrying capacity of double bolt joints is quite higher than that of single bolt joints. From the results it is observed that both single and double bolted joints display mixed failure modes with bearing mode as predominant failure modes. This indicates that the effects are damage accumulation in the laminated composite is in the region of joint area and we can

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expect the ultimate failure of the composite due to mixed mode.

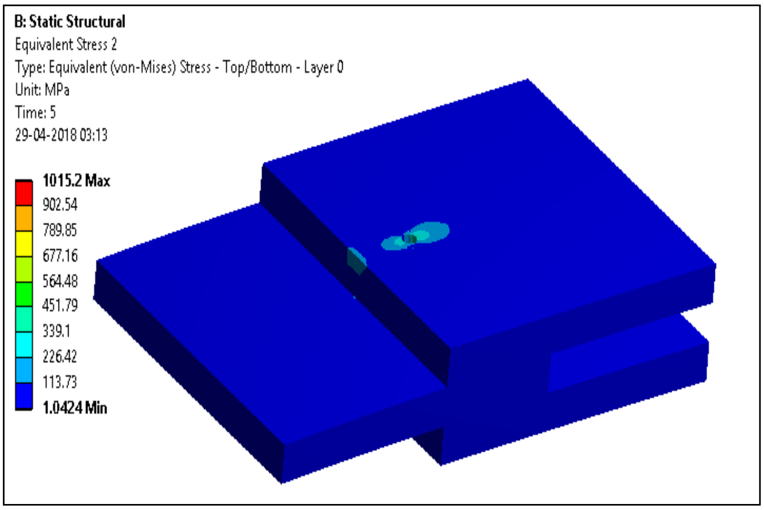

Figure 9: *Stress Distribution for E/D = 2 for Double Lap Single Bolted Joint.*

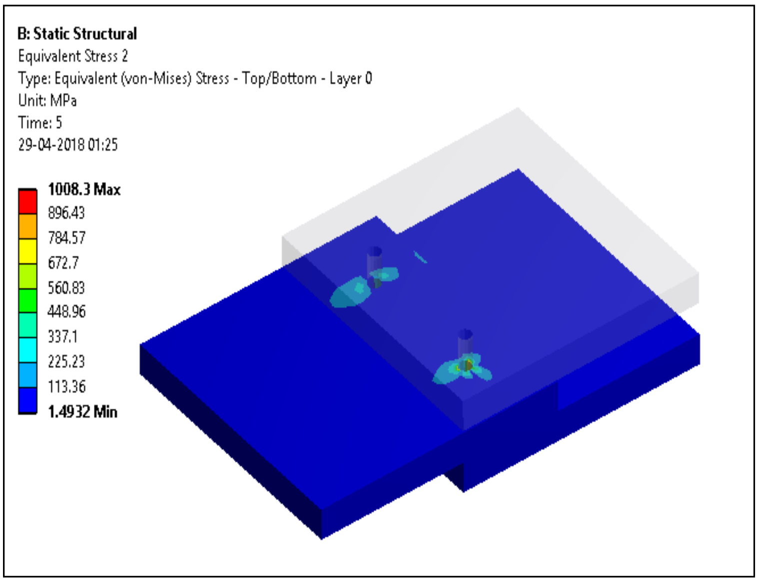

Figure 10: *Stress Distribution for E/D = 2 for Double Lap Double Bolted Joint.*

Experimental Results

Fig. 11 shows the bearing strength values obtained from tensile test and are evaluated from the load-displacement curves of the all the E/D ratios of double lap single bolt joint. It is observed that the with the increase in the E/D ratio from 2 to 4, the bearing strength was found to increase in this but later for E/D ratio of 5 the bearing strength was found to decrease. The highest bearing strength was obtained for E/D ratio 4 which had value of 672.31 MPa while lowest bearing strength value was recorded for E/D ratio 2 which has value of 618.29 MPa. so when compared to E/D ratio 2, the increase in the strength for E/D ratio 4 is about 8.73%.

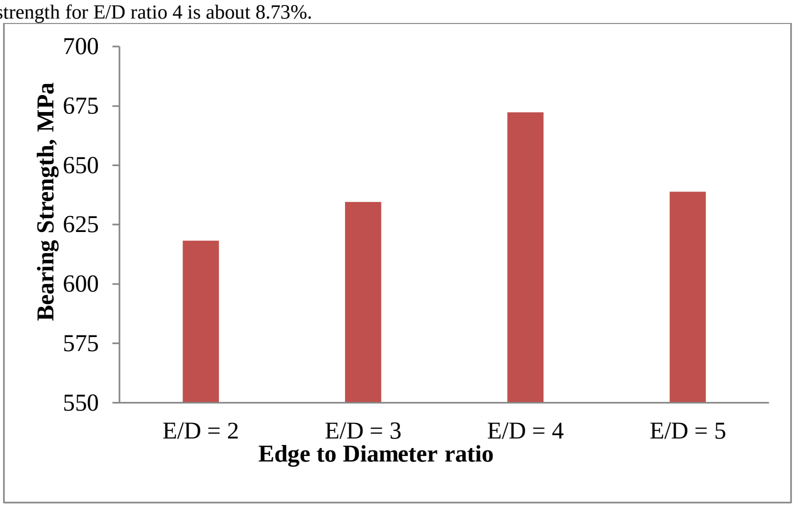

Figure 11: *Experimental Bearing Strength for Different E/D Ratio's For Double Lap Single Bolted Joint.*

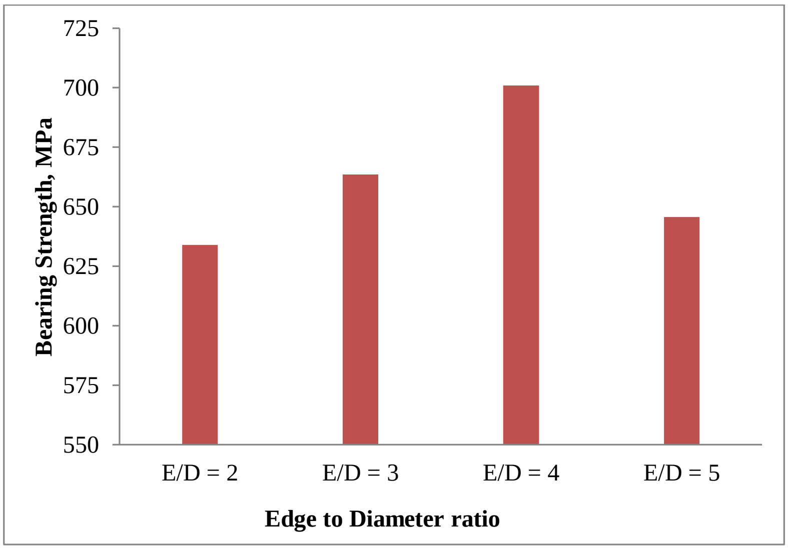

Figure 12: *Experimental Bearing Strength for Different E/D Ratio's For Double Lap Double Bolted Joint.*

Fig. 12 shows the bearing strength values obtained for all the E/D ratios of double lap double bolt joint. It is observed that the with the increase in the E/D ratio from 2 to 4, the bearing strength was found to increase in this but later for E/D ratio of 5 the bearing strength was found to decrease. The highest bearing strength was obtained for E/D ratio 4 which had value of 700.90 MPa while lowest bearing strength value was recorded for E/D ratio 2 which has value of 633.94 MPa. So when compared to E/D ratio 2, the increase in the strength for E/D ratio 4 is about 10.56%. Further it can be observed that the bearing strength values for double bolt joint are higher than that of single bolt joints. For instance when we compare the bearing strength for E/D ratio 4 we can see that double bolt has a value of 700.90

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MPa while that for single bolt joint is 672.31 MPa which is almost 4.2% increment in bearing strength. Though the increment is not so significant but it clearly indicates that the increase in number of bolts can increase the strength of composite laminate joints.

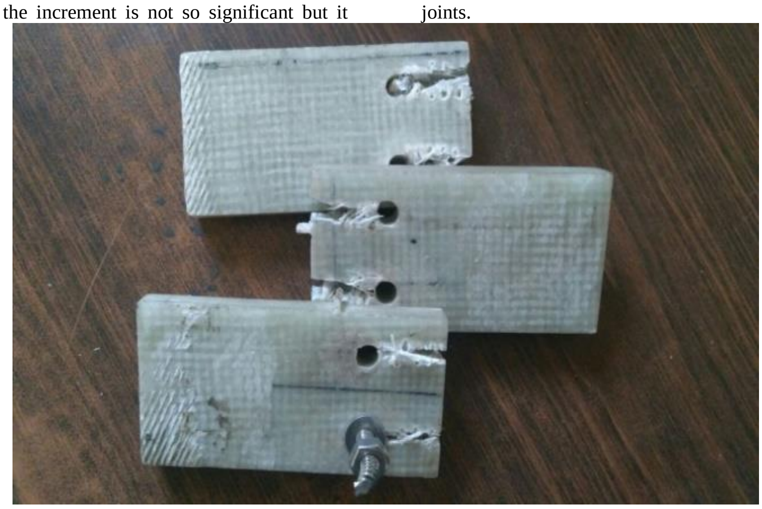

Figure 13: *Photograph of failed ratios for double lap double bolted joint*.

Mixed failure with shear-out failure mode as predominant failure mechanism is observed in case of double lap double bolted joint with E/D ratio equal to 2. As shown in Fig. 13 the failure mode is combination of bearing with shear-out occurring in bolted joints with lower E/D ratio. The accumulation of local damage at the bolt region particularly in the vicinity of the hole boundary is the indication of bearing failure mode. Here when we say it is local damage mechanism it consists of various mechanisms like failure of fibres, cracking of matrix and matrix/fibre deboning. Further with the increase in number of bolts in these joints shows the transition of failure mode from mixed bearing-shear out to ultimately shear-out failure. The increase in number of bolts increases the stiffness of joints which is one of the main reason for shifting of failure mode from bearing failure to shear out mode or combination of both [17,18]. When we compare experimental and numerical results of double lap single bolt joint, the variation in the strength value different E/D ratios is in the range of 4.1 – 4.5%. On the other hand for double lap double bolt joint the strength values is in the range of 3.2 – 3.5%. In both cases of bolted joints the error is just within 5% indicating the effectiveness of study.

CONCLUSIONS

The following considerations are made from the current work,

1. The fabrication of woven glass fabric/epoxy composite by using low cost manufacturing technique like hand lay-up until a thickness of 10 mm thickness was achieved.
2. Numerical study showed that for double lap single bolt joint, the highest bearing strength was obtained for E/D ratio 4 which had value of 645.83 MPa while double bolt joint, the highest bearing strength was obtained for E/D ratio 4 which had value of 663.48 MPa.
3. The stress distribution around the hole of both double lap single and double bolt joints results showed maximum stress concentration is in bolted joint region indicating the damage accumulation in the region of joint area and the ultimate failure of the composite due to shear-out or mixed mode.
4. Experimental study showed that for double lap with single bolt joint, the highest bearing strength was obtained for E/D ratio 4 which had value of 672.31 MPa while for double bolt joint, the highest bearing strength was obtained for E/D ratio 4 which had value of 700.90 MPa.
5. Experimental failure analysis for all cases of composites bolted joints were in line with the numerically obtained stress analysis results. Both the results reveal the mixed mode failure composed of bearing and shear out failure modes for all type of composite bolt joints for all E/D ratios.
6. The comparison for double lap single bolt joint shows that the variation between the numerical and experimentally obtained strength values is in the range of 4.1 – 4.5% while for double lap double bolt joint it is in the range of 3.2 – 3.5%.

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7. It is concluded in present case that the variation in the numerical and experimentally obtained bearing strength values are well within 5% for all cases of bolted joints.

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