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Bearing Strength and Failure Modes Analysis of Carbon Reinforced Aluminium Laminate

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Abstract*: Objective of this paper is study the bearing strength and failure modes of the Fiber Metal Laminates prepared by hand layup technique in two different stacking sequences. Parameters like ratio of hole distance to hole diameter (e/D), ratio to the width of composite to hole diameter (W/D) are varied during the experiment. Hole diameter is kept constant as 6mm and e value is taken as 6mm, 12mm, 18mm, 24mm, 30mm and 36mm. Similarly the width of the FML specimen is maintained as 24mm and 36mm respectively. Results show that laminate with [Ca0°/Ca90°/Al/Ca90°/Ca0°]s orientation is having a bearing strength 3.94% higher than that of [Al/Ca0°/Ca90°/Al/Ca0°]s orientation. In terms of failure modes the specimens with distance-diameter ratio greater than 3 and the two width- diameter ratio 4 and 6 exhibited bearing failure. For smaller ratios, the failure is due to shear out which involves combination of bearing and net tension failure.

Index Terms*: Bearing strength, failure modes, CARALL, e/D ratio, W/D ratio

I. INTRODUCTION

The composite materials that contain a metal as the matrix and a ceramic fiber as the reinforcement are called as Fiber Metal Laminates (FMLs). They are also classified as hybrid composites made up of interlacing thin metals sheets bonded together with fiber reinforced adhesives. There are many commercially available FMLs which is named after the constituent materials such as ARALL (Aramid Reinforced Aluminium Laminate), GLARE (Glass Reinforced Aluminium Laminate) and CARALL (Carbon Rein- forced Aluminium Laminate).FMLs has enhanced mechanical properties compared to aluminium alloys and fiber reinforced composites. It has the advantages of good fatigue, better toughness and weight saving properties compared with metallic structures [1, 2].Applications of FML in aerospace, marine and automotive industries generally need the composite to be joined with other composites or metals. The joining of the different composites can be done using bonded joint, riveted joint, pinned joint and bolted joints. These joints plays an important role in influencing the load carrying capacity and structural integrity of the structures since it is the weakest point in the structure [3].

The usage of pin joints in complex structures because of its simplicity, ease to dismantle and repair with an advantage of low cost. It is essential to determine the failure strength and modes of failures of these pin jointed connections. The main parameters influencing the pin joint design are W/D as well as e/D ratios, which shows the interactions of the pin diameter, D, width, W and distance between the center of the hole to the edge of the FML [4].There are several researches conducted on the composites made up of bolted or pinned joint[5–9]. Zhinan Zhang et al. [10] determined the influence of the effect of pin load on the crack growth behaviour in the FML through experimental approach. They concluded that the load applied through the pin was the sole cause for the crack propagation within the vicinity of the pin hole. Kulwinder Singh et al [11] studied that the addition of metals in the composite materials increases the ultimate load carrying capacity along the joint. Further it redistribute the load per unit area around the circumference of the hole by reducing the stress concentration that are developed around the hole. Luigi Calabrese et al. [12] studied the bearing strength of the pin –loaded glass laminate by varying the geometrical configurations like e/D and W/D ratios. The experimental test results indicates that the maximum laminate strength is achieved for e/D and W/D ratios higher than 1.6 and 2.1 respectively. The effect of stacking sequences on the mechanical properties of the bolted joint was studied by various researchers [13–15]. U.A. Khashaba et al. [15] conducted a study to find the influence of sequences in which the components of the FML are stacked. Their study compared the bearing strength of the glass fiber reinforcement of the FML with four different configuration that include [0/90]2s,[15/-75]2s,[30/-60]2s,[45/-45]2swere chosen. The maximum failure displacement and ultimate failure stress is observed in the specimen with configuration [0/90]2s.Though different types of research works are going on in the field of the bearing strength of the FML. An attempt is being made to study the bearing strength and failure modes of CARALL experimentally by varying the stacking sequences and having two different widths of the specimens.

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II. MATERIALS AND METHOD

A. Materials

Unidirectional Carbon Fiber with a gsm of 240 was chosen as the reinforcement, 0.2 mm thick aluminium alloy AA2024 T3 was selected as the matrix material and epoxy resin prepared using Araldite LY556 and hardener HY951 was used as the binding element. Carbon fiber along with epoxy resin and hardener are purchased from M/s Go Green Products, Chennai, India. Aluminium sheet is brought from M/s J.N steels, Chennai, India. The mechanical properties of the composition material used to make the FML in this research are shown in the Table 1.

Table 1. Mechanical physical properties of fibers, metal and resin used in this research [16, 17].

Properties	Carbon Fibers	Al 2024-T3	Epoxy
Density (g/m3)	1.82	2.78	1.20
Tensile strength (MPa)	4900	469	110
Tensile modulus (GPa)	240	73.1	3.05

B. Stacking sequence

The laminate lay – up would affect the mechanical properties of the produced FML. The carbon fiber are oriented along 0° and 90° w.r.t the rolling direction.

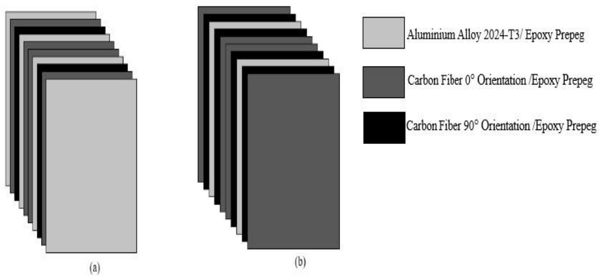

Fig.1. Different stacking sequences of CARALL laminates. (a)Stacking Order I (SOI), (b) Stacking Order II (SOII).

Fig.1 shows the two different stacking orders taken for CARALL preparation. Stacking Order I (SOI) as [Al/Ca0°/Ca90°/Al/Ca0°]s with aluminium as top layer and Stacking Order II (SOII) [Ca0°/Ca90°/Al/Ca90°/Ca0°]s with carbon as top layer .Each stacking sequence is of 10 layers.

III. MANUFACTURING METHOD

The CARALL specimens were produced using the hand layup method. A mould of dimension 300mm x 300mm is made. The epoxy resin and hardener mixture in the weight ratio of 10:1 is prepared. Then, stacking order 1 (SOI) is chosen for fabrication. To remove the smoothness of the surface aluminium sheets were scratched with emery paper before laminating. This was done to ensure good bond between the matrix material and the reinforcement [18]. Initially releasing agent is applied on the surface of the mould then resin mixture is applied on the mould. The first layer of aluminium sheet is placed on the mould and then resin mixture is applied on the aluminium surface using a brush later second layer of Carbon fiber with 0o orientation is placed on the aluminium surface and rolling operation is done to remove the air bubbles and voids. Similar procedure is followed for the remaining layers of carbon fibers with 90 degree orientation and Aluminium sheets to complete the fabrication process.

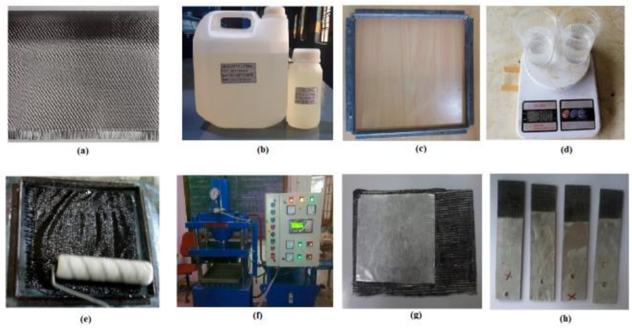

Fig.2. Fabrication process of CARALL laminates. (a) Carbon Fiber, (b) Epoxy Resin and Hardener, (c) Mould, (d) Weighing of resin mixture, (e) Rolling operation, (f) Compression Moulding, (g) Fabricated laminate, (h) Specimen as per ASTM

The fabricated laminates are cured in the open atmospheric for a duration of 4h. Later the laminates are placed in the moulding machine used for compressing the FML for about 10 min at 70°C temperature and 70kg/cm^2 pressure were applied to the laminates in order to remove the entrapped air bubbles and voids. After completing the fabrication process, the CARALL specimens are cut into required dimensions as per ASTM standard D5961. Fig.2 shows the fabrication process of CARALL laminates.

IV. FIXTURE FOR TESTING

For testing of the laminates a fixture is prepared as per ASTM D5961 M-10 standards with a total length of 200mm, width of 36mm, grip thickness of 5mm, grip length of 50mm, hole diameter of 6mm, pin diameter of 6mm and pin length of 42mm. Fig.3 shows the schematic diagrams of the specimen and the fixture.

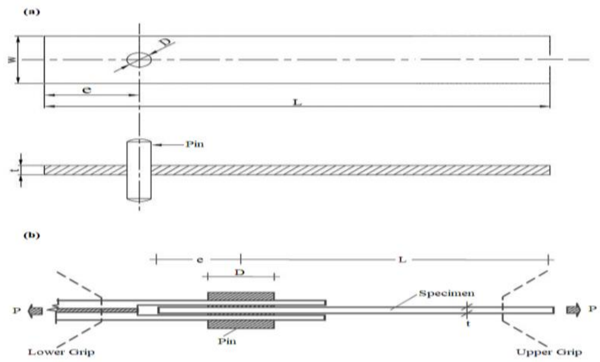

Fig.3. (a) Schematic diagram of the specimen, (b) Schematic diagram of the fixture

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V. E/D RATIO AND W/D RATIO

The influence of parameters like e/D, W/D and stacking order are few parameters that influence the strength to withstand external load against damages in the CARALL, while the diameter of the hole is kept constant, D=6mm. The parameter e/D ratio is varied from 1 to 6. The distance of the hole from the edge of specimen are taken as 6mm, 12mm, 18mm, 24mm, 30mm and 36mm. The parameter W/D ratio is taken as 4 and 6.Since diameter of the hole is kept constant, the width of the specimen is varied in order to get two different W/D ratios. The widths of specimen taken are 24mm and 36mm. Geometric Variation of e/D and W/D ratio varied in this work is shown in the Table 2.

Table 2.Geometric variation of e/D and W/D

S.No	D (mm)	e (mm)	e/D	W (mm)	W/D
1	6	6	1	24	4
2	6	12	2	24	4
3	6	18	3	24	4
4	6	24	4	24	4
5	6	32	5	24	4
6	6	36	6	24	4
7	6	6	1	36	4
8	6	12	2	36	4
9	6	18	3	36	4
10	6	24	4	36	4
11	6	32	5	36	4
12	6	36	6	36	4

VI. MATERIAL TESTING

There are three procedure prescribed by ASTM D5961 namely Procedure A, B and C to test the bearing strength of composite materials. In this experiment, Procedure A is adapted. It involves double shear and tensile force is applied. A flat specimen having a constant rectangular cross section with a center line hole located near the smaller edge of the specimen is loaded at the hole in bearing. The load applied to the test specimen is typically applied with a close tolerance, tightly torqued fastener or pin that sustains double shear via a fixture.

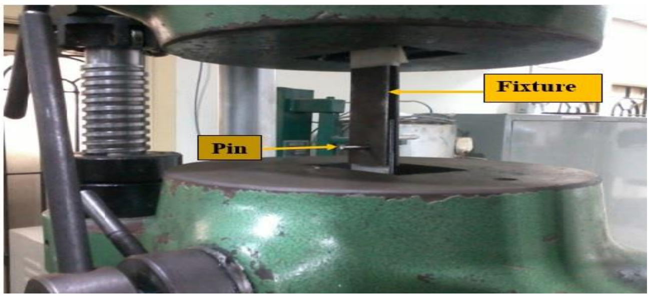

Fig.4. Bearing test on pin loaded CARALL specimens.

Tests to measure the bearing of the FML are performed on a 400 kN. Servo-Hydraulic Instron UTM test frame according to ASTM D5961. The specimens were fitted in the fixture as shown in Fig.4.

The fixture was held in the upper jaw of UTM and the other end of specimen was held in lower jaw. The lower jaw is fixed and the specimen was give axial tensile load by moving the upper jaw of UTM at a constant cross head speed of 1 mm/min. The Load Vs Displacement graphs are plotted automatically. In order to observe the mode of failure in the FML, the test was assumed to end as soon as the applied load observed to reduce to 90% of the maximum load. However, in case the experiment did not stop after the reaching of maximum load, the linear movement of the bolt would lead to severe deformation of the specimen. This will give rise to a secondary failure, which can make it harder to distinguish the initial failure mode. The bearing force is created by applying the load along the longitudinal axis of the FML in the testing machine. Both the applied force as well as the accompanying deformation of the hole are observed. The specimen is loaded until a maximum force is attained, Load Vs. displacement and bearing stress versus bearing strain for the entire loading regime is plotted, and failure mode noted.

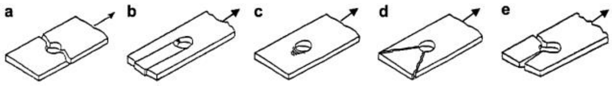

Fig.5. Bearing test failure modes for ASTM D 5961/D 5961M-05: (a) lateral (net-tension), (b) shear-out, (c) bearing, (d) tear out, and (e) cleavage [19]

The mode of failure of the specimen is found to be tear out, shear out and bearing failure. Different types of failure modes of the FML are shown in Fig.5.

VII. RESULT AND DISCUSSION

The advancement of the failure on the FML was observed visually. Maximum load that the CARALL specimen can withstand, the bearing stress and the type of failure observed in the specimens are tabulated in Table 3.

Table 3. Bearing stress and failure mode for SOI &SOII

W/D Ratio	e/D Ratio	Maximum load Pmax (kN)	Bearing Stress (MPa)	Observed failure
4	1	2.8	155.56	Shear Out
4	2	4.5	250	Shear Out
4	3	5.1	283.33	Shear Out
4	4	5.15	286.11	Bearing
4	5	5.4	300	Bearing
4	6	5.65	313.89	Bearing
6	1	1.69	93.89	Shear Out
6	2	3.64	202.22	Tear Out
6	3	4.49	249.45	Shear Out
6	4	5.33	296.11	Bearing
6	5	5.64	313.33	Bearing
6	6	5.84	324.45	Bearing
4	1	2.73	151.67	Tear Out
4	2	4.46	247.78	Shear Out
4	3	5.26	292.23	Shear Out
4	4	5.47	303.88	Bearing
4	5	5.58	310	Bearing
4	6	5.65	313.88	Bearing

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6	1	3.72	206.67	Shear Out
6	2	4.93	273.88	Shear Out
6	3	5.59	310.55	Shear Out
6	4	5.84	324.44	Bearing
6	5	5.96	331.11	Bearing
6	6	6.08	337.78	Bearing

The table reveals that in the laminate material with SOI outperformed the laminates with SOII. This was because the initial stacking order had incorporated four layers of aluminium sheets which acted as its skin as well as one of the reinforcements. The aluminium sheets shared its properties with the carbon fibers and epoxy. However, the latter had only two layers of aluminium sheets that was hidden within the layers of the laminate material. Irrespective of the stacking orders as well as W/D, the laminate materials exhibited the bearing mode failure when the e/D was greater than 3. This indicates that e/D is influential parameter which affects the load transferred within the layers of the laminate as well as its ability to undergo deflection. This is justified by the fact that the tear out failure occurred when e/D < 3. In case of SOI, the specimen succumbed to tear out when w/D=6 and e/D=2. The presence of aluminium as its skin as well as reinforcement increased its ability to stretch and deform which enabled it to withstand greater load before rupture at the hole. Thus it exhibited shear mode of failure when the w/D was in lower and also when the e/D=1. Because of the presence of only two layers of aluminium sheet in SOII, the laminate was not able to deform as much as that exhibited by its counterpart. Hence it succumbed to tear out when w/D=4 and e/D=1.

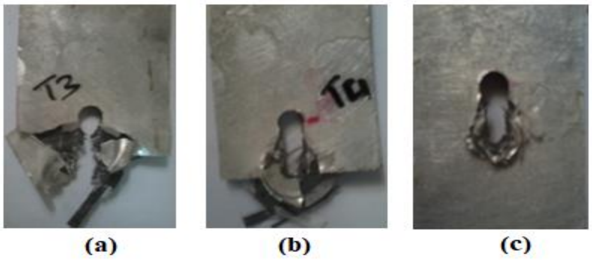

Fig.6. Failure modes in CARALL specimens (a)Tear out (b) Shear out (c) Bearing

Fig.6 shows the three modes of failure that had occurred in the produced laminate i.e., CARALL. The figure reveals that e/D had influence on the mode of failure, since tear out occurred when the hole was much closer to its smaller edge. It changed to shear out failure when the distance increased and again to bearing failure when the distance was shifted further away. Bearing failure is desirable because the laminate does not yield but instead continue to bear the load even under extensive damage to the hole.

The Fig.7, 8, 9 and 10 shows the plot of load versus pin displacement curves. The curves are linear at the start and then the load decreases suddenly and remains constant after that for both the stacking orders.It is observed that for all cases, irrespective of the stacking order and W/D, the CARALL specimen having e/D=1 showed the lowest ultimate load. The reason of the sudden decrease in load is the fiber breakage in the region between the pin and the holes. Successively, the ultimate load increased proportionally with the e/D. However, every laminate used in the study exhibited characteristics of ductile material. After attaining the peak

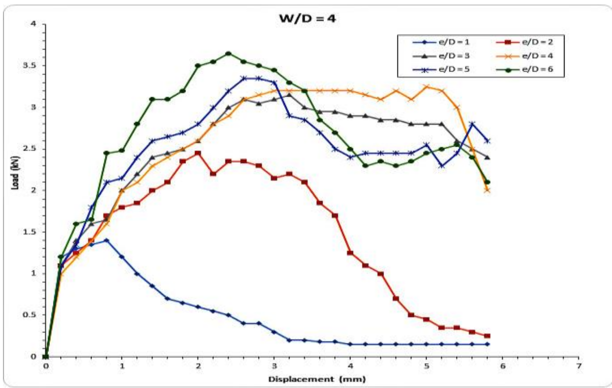

Fig. 7. Load Vs displacement for SOI with W/D=4

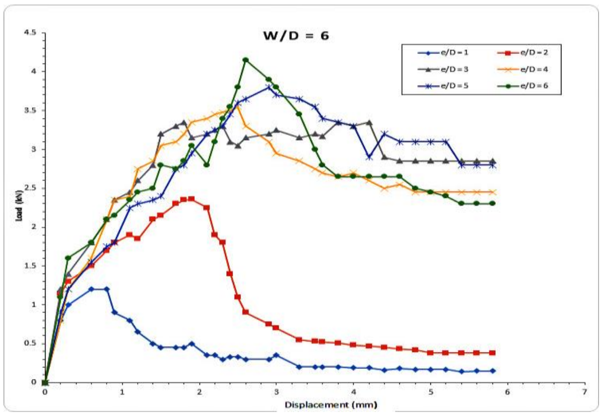

Fig.8. Load Vs displacement for SOI with W/D=6

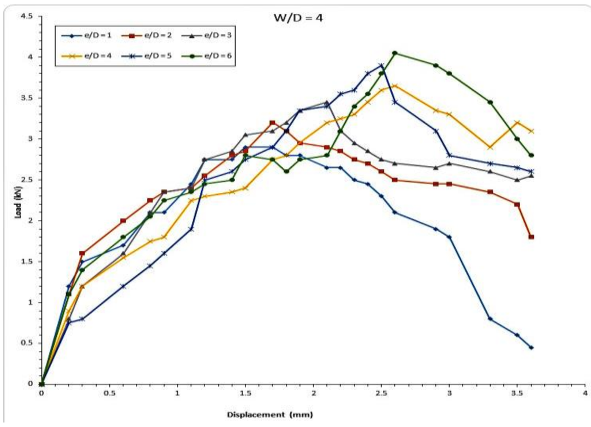

Fig.9. Load Vs displacement for SOII with W/D=4

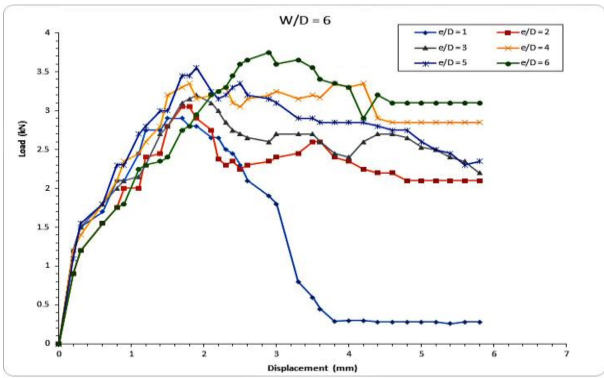

Fig.10. Load Vs displacement for SOII with W/D=6

value, the load decline steadily while the material continued to show displacement. Though this characteristics was

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sustained in all the laminates in this study, the load Vs displacement curve was different in the laminate having SOII. After reaching the peak load, the materials irrespective of the e/D dissipated the load quickly. This characteristics was because in this case, W/D=4, there number of aluminium layers was less. So much of the load was absorbed by the carbon fibers which are brittle in nature. Hence, it showed comparatively greater peak load, the brittle materials snapped but after that it underwent displacement which was absorbed by aluminium layer.

VIII. CONCLUSION

An experimental study has been carried out to investigate the bearing strength, failure load and failure mode of pin loaded CARALL specimens. In order to obtain the optimum geometry, the ratio of the edge distance to pin diameter (e/D) and the ratio of the specimen width to the pin diameter (W/D) were systematically varied during experiments. Also the two different stacking orders are considered for CARALL. From the above results and discussions, the conclusions could be summarized as following.

- In case of CARALL with stacking Order I (SOI), bearing strength of specimens with W/D = 6 found to be 3.25 % higher than the specimens with W/D = 4.
- That with stacking Order II (SOII), bearing strength of specimens with W/D = 6 was found to be 7.07% higher than the specimens with W/D = 4.
- For W/D=4, the SOI found to have same bearing strength as stacking order II.
- For W/D = 6, the SOII found to have bearing strength 3.94% higher than stacking order I.

The geometrical parameters end distance from the hole center (e), width of the plate (W) remarkably affects the load bearing performances of the FMLs. The specimens with e/D>3 and W/D = 4, 6 exhibited bearing failure mode. Ultimate load capacity of all different configurations increases with increase in the geometric dimensions. For smaller e/D ratios, the failure is due to shear out or tear out or mixed mode which involves combination of bearing and net tension failure mode.

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