Experimental Analysis of Fibre Metal Laminates

Giridharan D¹, Bhupal Rakham²

¹M.Tech, Aerospace Engg., MLR Institute of Technology, Hyderabad.
²Assistant Professor, Dept.of Aero., MLR Institute of Technology, Hyderabad.
email : ¹giridharandhanapal@gmail.com, ²bhupalrakham@gmail.com.

Abstract: Aircraft structures are prone to impact damages and one of the several methods to overcome this, is to use Fibre Metal Laminates in the construction of structures. Fibre Metal Laminates is a new class of advanced aerospace materials. They consist of thin metallic sheets bonded together with fibre reinforced adhesive matrices. In this work, strength characteristics of fibre metal laminates and fibre laminates are studied and compared as follows; Case I - Fibre metal laminate (Top & Bottom layers of 0.3 mm thick aluminium alloys sheets + 5 layers of (0/90/0/90/0) cross ply glass fibre laminates) is compared with 7 layers of (0/90/0/90/0/90/0) cross ply glass fibre laminates and Case II - Fibre metal laminate (Top & bottom layers of 0.3 mm thick aluminium alloy sheets + 7 layers of (0/90/0/90/0/90/0) cross ply glass fibre laminates) with 9 layers of (0/90/0/90/0/90/0/90/0) cross ply glass fibre laminates. The specimens are fabricated such that the seven layers FML and seven layers GFRP has the same thickness. Similar, is the case for nine layered laminates. To prepare the surface as per ASTM D 2651 of the aluminium alloy for adhesive bonding, both mechanical and chemical approaches have been employed. Surface pre-treatment would also be able to increase surface tension or change the surface chemistry to enhance adhesion with the aid of a chemical bond. Experimental facilities used for this experiment are, Impact test machine used for impact strength analysis as per ASTM D 5628 FD. The deformation, energy absorbed and force upon impact are considered to evaluate the characteristics of the laminates. From the results, it is concluded that the fibre metal laminates are stronger when compared to the GFRP laminates. The stiffness is more than 3 times higher compared to a GFRP. The energy during impact is also high for the fibre metal laminate. The Fibre metal laminate is able to withstand more than twice the energy compared to a GFRP laminate. Similarly, the force upon impact is also high for the fibre metal laminate which indicates that the fibre metal laminate is stronger when compared to a GFRP laminate.

Key words: Composite material, Fibre Metal Laminates.

1. Introduction
FML is one of a class of the metallic materials consisting of a laminate with several thin metallic layers are bonded with layers of selected composite material. This allows the material to behave much as a simple metal structure, but with the considerable specific advantages regarding the properties specific such as metal fatigue, impact, corrosion resistance, fire resistance, weight savings, and specialized strength properties.

Being mixtures of monolithic metals and composite materials, FMLs belong to the class of heterogeneous mixtures. Aramid fibers and GLARE are examples of FML.
2. Application of GLARE in Aerospace
Recently, GLARE is used as the main fuselage skin and the leading edges of the horizontal and vertical tail planes of the new, high capacity Airbus A380 as shown in figure. The latter application is a consequence of the excellent impact resistance of the FML concept utilizing the high strength glass fibers with strain rate effect. With the excellent impact characteristics, GLARE is being evaluated for use as cockpit crown, forward bulkheads, the leading edge and the flame-resistant capability of GLARE makes it suitable for high flame sensitive areas such as; fire walls, cargo-liners, etc. in aerospace applications.

3. Scope and Objective
This project has been undertaken to study and compare the strengths of Fibre Metal Laminates (FML) with Glass Fibre Reinforced Polymer (GFRP) Laminates. The type of FML chosen for study is Glass Laminate Aluminium Reinforced Epoxy (GLARE). Composites are being used more and more in many applications. However, their application in areas that require high strength is limited. This can be overcome by the use of FML. This experimental study aims at finding out the mechanical characteristics and impact strength of GLARE and GFRP for the same no. of layers and thickness and to compare them. The effect of no. of layers is also experimentally analyzed. As the same epoxy resin is being used for both the cases, the effect of resin and / or filler materials has not been considered here.

The main objective of this project is to validate the strength of GLARE composites and to prove that they are better compared to the GFRP composites. Knowing, the strength of the laminate with respect to the no. of layers will enable in easy manufacture of different aerospace parts according to their strength requirements. Application of GLARE to aircraft construction will result in a large proportion of weight savings. This will be profitable as the payload can be increased and / or fuel consumption will be lower. If the payload can be increased, then the cost of air transport will come down.

4. Experimental Methodology
The experimental methodology is as depicted in the following flow chart,
5. Surface Treatment
The treatments for modification of metal surfaces can be classified into:
1. Mechanical treatments.
2. Chemical treatments.
3. Electrochemical treatments.
4. Coupling agent treatments.
5. Dry surface treatments.

Solvent degreasing is very important, because it removes the contaminant materials which inhibit the formation of chemical bonds. However, solvent degreasing, while providing a clean surface, does not promote the formation of acceptable surface conditions for longer term bond durability. The degreasing stage usually makes use of the chlorinated solvents such as trichloroethylene, 1-trichloroethane, perchloroethylene or dichloromethane or alternatively non-chlorinated solvents including methyl ethyl ketone, methanol, isobutene, toluene or acetone. All aluminium alloy sheets were initially degreased prior to further surface pre-treatment steps. The first step in the fabrication of baseline test specimens was methyl ethyl ketone (MEK)-wiping of aluminium substrates with lint-free tissues to degrease the surface.

6. Chemical Treatment
The most commonly used chemical treatments are based on a chromic–sulphuric acid etch. This treatment consists of immersion of the substrate in a solution of sulphuric acid and potassium dichromate.

Chemical acid etches are given in Table with the concentration of compounds, used temperature and immersion time.

Table 1: Chemical acid etches and their application process.

| S.No | Chemical etch type | Application process |
|------|-------------------|---------------------|
| 1    | CAE               | Immersion in a water solution with 330 ml/l chromic–sulphuric acid (97% v/v) and 50 g/l potassium dichromate, at 60°C for 15 min, and rinsed in tap water Immersion in a water solution with 185 ml/l chromic–sulphuric acid (97% v/v) and 127 g/l ferric sulphate, at 65°C for 8 min, and rinsed in tap water (percentages by weight: 48% H₂O, 37% H₂SO₄ and 15% FeSO₄) Immersion at 15 min in a 65°C followed by tap and de-ionized water rinsing Involves treatment of the adherend surface with an aqueous acidic solution containing Fe (III). (1) Immersing the adherend in the P2 solution at 65°C for 8 min, (2) rinsing the specimen in DI water for 2–3 min, and (3) drying the aluminium bars in an oven at 60°C for 30 min. The P2 solution was prepared by dissolving 122.5 g Fe₂(SO₄)₃ 4H₂O and 0.185 l of concentrated sulphuric acid in enough water to make a liter of solution Treat with optimized FPL for 30 min at 62°C. After treatment in the acid, the aluminium was washed for 20 min in cold running tap water and finally dried in an oven at 40°C for 30 min |
| 2    | P2                |                     |
| 3    | FPL               |                     |
Typically, chemical treatment, i.e., acid etching, is an intermediate production step between degreasing, alkaline cleaning, and electrochemical treatment. Three classical acid-etching solutions were introduced to modify the metallic surfaces: chromic–sulphuric acid (CAE), Forest Product Laboratory (FPL), and sulfo-ferric acid (P2) etches. The most effective etches incorporate mixed chromic and hydrofluoric acids. However, non-chromate acid etchants have been demonstrated to provide good adhesion results. The surfaces treated with acid-etch were consistently reported to be out-performed by anodized surfaces so that the inconsistent results made them unsuitable for stand-alone treatment in primary bonded structures.

7. Materials
The FML to be fabricated consists of 3 layers of Aluminium alloy 1100 grade sheets of 0.3mm thickness with 2 cross-ply layers of unidirectional S-glass fibers (220gsm) of 0.2mm thickness. To cure the epoxy, Hy951 hardener was added to Ly 556 resin. Raw materials are shown in figure.

8. Fabrication of FML Laminates
Before fabricating the laminate, solvent degreasing is important, because it removes contaminant materials which inhibit the formation of the chemical bonds. However, solvent degreasing, while providing a clean surface, does not promote the formation of acceptable surface conditions for longer term bond durability. All aluminium alloy sheets were initially decreased prior to further surface pretreatment steps. The first step in the cleaning of test specimens is acetone then followed by NaOH cleaning treatments and finally Potassium chromate with H₂SO₄ cleaning.

9. Scratching of Aluminium surface
Bonding strength of aluminium sheet is increased only by increasing the frictional effect of the surface which contact with the resin. So, the surface of the aluminium sheet is scratched with emery paper as shown in figure. After that contaminant of aluminium powder particles are removed under the following process.
10. Acetone Cleaning
The following steps are followed for cleaning the aluminium sheet by the use of acetone. Refer figure.
1. ¼ liter acetone is poured in the washing tray.
2. Aluminium sheet is dipped in the tray and rinsed.
3. Process is continued till the colour of acetone becomes pale black.
4. Then, the sheet is rinsed with hot water to remove the acetone residue.

11. NAOH Etching
In figure, after finishing the acetone cleaning process, the next step is to clean the sheet with the NAOH. It is in the form of white granules.
1. 5 grams of NaOH is dissolved in 1 liter of distilled water.
2. This solution is heated up to 60-65°C and poured onto the aluminium sheet.
3. Rinse the sheet until solution begins to create white bubbles.
4. Then the sheet is rinsed with hot water to remove the NaOH residue.
12. Sulfo-Chromic Acid Etching
Because of the above chemical treatments, white NaOH is precipitated on surfaces of the aluminium sheet. Hence, Potassium Chromate cleaning is necessary to remove the NaOH precipitate. The process is explained as follows and also shown in figure.
1. 10 grams of Potassium Chromate (in powder form) is dissolved in 300ml of distilled water and stirred until all the powder is completely dissolved in water.
2. 100ml of H2SO4 is slowly added into 300ml of distilled water-potassium chromate solution.
3. This mixture is then heated at a temperature of 60 – 65 °C till the color of the solution changes to pale yellow.
4. The sheet is rinsed with this solution and then rinsed with hot water to remove residue and then dried for 1 hour before the next step.
13. Resin Preparation
After sheet pretreatment, the resin is prepared as depicted in figure.
1. Epoxy resin and the hardener are mixed in a cup or a bowl in the ratio of 10:1.
2. Mixture is stirred till it becomes slack.

14. Laminate Preparation
The process is explained as follows and also shown in figure.
1. Glass fibre sheet is bonded to the aluminium sheet using a strong adhesive of Araldite AW106 with hardener 956 taken in 1:1 ratio
2. Cross plies of 0/90 degree orientation are laid onto the former layer with consecutive application of the resin using a brush and roller and then another sheet is bonded.
3. Laminate is placed between metal plates and weight is placed upon it and then left for curing.
4. Two types of laminates are made for the testing purpose. One type is a fiber metal laminate with five layers of GFRP in between two aluminium sheets. It is to be compared with a 7 layer GFRP laminate.
5. Another one is a fiber metal laminate with seven layers of GFRP in between two aluminium sheets. It is to be compared with a 9 layer GFRP laminate.
6. All the laminates are made for the same thickness.
Figure 9: Laminate preparation

15. Curing Process
1. Due to the weights during curing, there will be some internal stress.
2. To reduce or remove the internal stress the laminate is again cured at 100°C in the oven for 4 hours.

16. Specimen Preparation
A water jet cutter, also known as a water jet, is an industrial tool capable of cutting a wide variety of materials using a very high-pressure jet of water, or a mixture of water and an abrasive substance.

Figure 10: Specimen preparation

The cutter is commonly connected to a high-pressure water pump where the water is then ejected from the nozzle, cutting through the material by spraying it with the jet of high-speed water. Additives in the form of suspended grit or other abrasives, such as garnet and aluminium oxide, can assist in this process. The specimens are shown in figures.

An important benefit of the water jet is the ability to cut material without interfering with its inherent structure, as there is no "heat-affected zone" (HAZ). Minimizing the effects of heat allows metals to be cut without harming or changing intrinsic properties.

Water jet cutters are also capable of producing intricate cuts in material. With specialized software and 3-D machining heads, complex shapes can be produced.

Flat test specimens shall be large enough so that they can be clamped firmly if clamping is desirable. The thickness of any specimen in a sample shall not be different by more than 5% from the average specimen thickness of that sample specimen.

The specimen is carefully examined visually to make sure that samples are free of cracks or other obvious imperfections or damages, unless these imperfections constitute variables under the experimental study. Samples known to be defective should not be tested for specification purposes.
Specimens may have flat smooth surfaces on both sides, be textured on one side and smooth on the other side, or be textured on both surfaces. Both surfaces may have the same texture or two different levels and types of texture. When testing, special attention must be paid to how the specimen is positioned on the support.

All the specimens must be tested under the same environmental conditions and hence, the room temperature has to be maintained properly. Further, before testing, the specimens are exposed to the room temperature at least half an hour before the test is carried out.

![Figure 11: Test Specimen – Seven layer GFRP Laminates and Five Layer GFRP with 2 Al Sheets FML](image1)

**Figure 11:** Test Specimen – Seven layer GFRP Laminates and Five Layer GFRP with 2 Al Sheets FML

![Figure 12: Test Specimen – Nine layer GFRP Laminates and Five Layer GFRP with 2 Al Sheets FML](image2)

**Figure 12:** Test Specimen – Nine layer GFRP Laminates and Five Layer GFRP with 2 Al Sheets FML

17. Impact Test ASTM D 5628 FD

A free-falling dart (tup) is allowed to strike the supported specimen directly. Either a dart having fixed mass is dropped from a various heights, or a dart having an adjustable mass is dropped from a fixed height specified. This procedure helps us to determine the energy (mass x height) that will cause 50% of the specimens tested to failure (mean failure energy).

The technique that is used to determine mean failure energy is commonly known the Bruceton Staircase Method or the Up and - Down Method. Testing is concentrated near the mean, reducing the number of specimens that is required to obtain a reasonably precise estimate of the impact resistance.
Each of the test method permits the use of different tup and test specimen geometries to obtain different modes of the failure, permit easier sampling or test limited amounts of material. There is no known means for correlating the results of the tests made by different impact methods or procedures. Figures show the specimen after being subjected to impact test.

Striker Velocity : 6 m/s
Total mass : 1.92kg
Tup Diameter (mm) : Ø 12.7 Hemispherical
Specimen Dimensions: 89 mm x 89 mm

Figure 13: Impact Test Specimen after failure

The test parameters are obtained through the computer interface. The data can information on deformation, force, energy, striker velocity with respect to time. These data are then used for result analysis and comparison.

18. Results and Discussion
Models for Analysis
The cases analyzed in this project are as follows,

- 7 Layer GFRP laminate (7G)
- 5 Layer GFRP laminate with 2 Layer Aluminium sheets fiber metal laminate (5G2Al)
- 9 Layer GFRP laminate (9G)
- 7 Layer GFRP laminate with 2 Layer Aluminium sheets fiber metal laminate (7G2Al)

Three trials were carried out for each case.

Force vs Time Plots
The plot of force against time shows the impact resistance offered by the specimen and also that how fast the specimen is failing.

Figure 14: Force vs Time plot for 5G2Al and 7G
We can see the variation of force with respect to time. For the same time interval, the GLARE is taking up much higher load on comparison with GFRP. The FML was able to withstand a maximum peak force of 3194 N out of all the trials, whereas the GFRP laminate had a peak load of 2835 N.

Figure 15: Force vs Time plot for 7G2A1 and 9G

From the plots we can see clearly that the fiber metal laminates are withstanding more force when compared to the GFRP laminates. The force level is higher in the case of 7G2A1 when compared to 5G2A1 as seen in figure 5.2. The 9 layered FML was able to withstand a maximum peak force of 4283 N out of all the trials, whereas the GFRP laminate had a peak load of 3809 N.

Deformation vs Time Plots

The plot of deformation against time gives information about the stiffness of the laminates.

Figure 16: Deformation vs Time plot for 5G2A1 and 7G

We can see that GLARE experiences lesser deformation compared to the GFRP laminate. This is due to the reinforcement provided by the aluminium sheets. As seen in the figure, the deformation is not much different initially but as time increases, there is a significant difference in the deformation between the two cases. The seven layered FML experiences a maximum deformation of 16.37 mm out of all the trials whereas, the GFRP has a maximum deformation of 13.22 mm.
From the plots it is clear that the fiber metal laminates are deforming very less compared to the GFRP laminates. Their stiffness and strength have increased due to the inclusion of aluminium sheets. 7G2A1 has much higher resistance to deformation when compared to 5G2A1 as can be seen in figure 5.4. The nine layered FML experiences a maximum deformation of 13.11 mm out of all the trials whereas, the GFRP has a maximum deformation of 14.99 mm.

Energy vs Time Plots
These plots give details of the energy absorbed by the specimen during impact. It is an indirect measure of the impact strength.

The energy taken up by the specimen with time is shown. It can be seen that the GLARE is able to take up much higher energy on comparison with the GFRP laminate. The seven layered FML absorbs a maximum energy of 22 J out of all the trials whereas; the GFRP has a maximum energy of 16.8 J.
Figure 19: Energy vs Time plot for 7G2Al and 9G

It is clear that the energy absorbed by the fiber metal laminate is much higher than the GFRP laminate. It is also clear that the energy absorbed increases as the no. of layers are increased as shown in figure. The nine layered FML absorbs a maximum energy of 29.7 J out of all the trials whereas; the GFRP has a maximum energy of 24.4 J.

Force vs Deformation Plots

Through the force – deformation plots, we will get information about the stiffness of the material fabricated.

Figure 20: Force vs Deformation plot for 5G2Al and 7G

Indicates the deformation of the specimen with respect to the force applied. The peak force is also indicated in the plot. It is noticed that the peak force is higher for GLARE laminate than GFRP laminate. The seven layered FML has a maximum stiffness 532.33kN/m whereas; the stiffness of the GFRP laminate is 567kN/m.
It is clear that force taken upon impact by the fiber metal laminate is much higher than the GFRP laminate. It is also clear that the peak force increases as the no. of layers are increased as shown in figure 5.8. The seven layered FML has a maximum stiffness of 713.83kN/m whereas; the stiffness of the GFRP laminate is 761.8kN/m.

19. Summary and Conclusions

Summary

Aluminium alloy sheets of grade 1100 and thickness 0.3 mm were subjected to surface treatment by chemical etching using Acetone, Sodium Hydroxide and Sulfo – Chromic acid etching. 6 S – glass fibre – epoxy cross plies of 0/90 degree orientation were placed in between the aluminium sheets and bonded together using a strong adhesive.

After, the curing of the fibre metal laminate, specimens were cut out of it using the water jet cutter with dimensions according to the ASTM standards.

Two types of laminates are made for the testing purpose. One type is a fiber metal laminate with five layers of GFRP in between two aluminium sheets. It is compared with a 7 layer GFRP laminate.

Another one is a fiber metal laminate with seven layers of GFRP in between two aluminium sheets. It is compared with a 9 layer GFRP laminate.

Impact Test was experimented according to the standards ofASTM D 5628 FD.

Conclusions

From the test results, we can see that the mechanical properties of the aluminium metal sheet and glass fiber composite is better compared to the glass fiber reinforced polymer laminate. GLARE laminates suffer less deformation and are able to absorb more energy compared to GFRP laminates. Also, they have higher impact strength and stiffness when compared to GFRP laminates. This is a good result as the mechanical properties are better on the use of composite because it has comparatively lesser weight.

The bonding of the aluminium sheet and glass fibers is very challenging. However, in this test, the bonding between them was good. From the impact analysis, we can see the magnitude of damage taken up by the specimen and it is comparatively less compared to GFRP laminates.

In future work, further work will be carried on where there will be a detailed analysis of this type of composite. Different ply orientations and the effect of fillers will be studied.

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