Impact response and damage resistance behavior of GFRP/aluminium fiber metal laminates during low velocity impact test

V Asha Melba & A Senthil Kumar*
Department of Mechanical Engineering, Sethu Institute of Technology, Kariapatti 626 115, India

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Fiber metal laminates (FMLs) are widely used for aerospace applications. Impact response and damage resistance are the two important parameters to be considered for the effective use of FMLs. Glass fiber/epoxy-aluminium metal laminate (GEAML) is a class of FML prepared as a laminate with glass fiber mats and aluminium metal sheets staked in alternate layers with epoxy adhesive bonding. In this experimental work, woven fiber mats and chopped strand mats (CSM) of glass fiber were used along with aluminium sheets to prepare Woven based GEAML and CSM based GEAML respectively. Low velocity impact test was conducted as per ASTM standards using an instrumented falling weight impact testing machine on woven based GEAML and CSM based GEAML. For comparison, aluminium sheets of the same thickness were also subjected to low velocity impact test. The woven based GEAML withstood higher impact load and its absorbed energy is 3.4% higher than that of CSM based GEAML. The damage area and the depth of penetration of Woven based GEAML are much lower than that of CSM based GEAML and aluminium sheets. The woven based GEAML exhibited better impact response and damage resistance than CSM based GEAML and aluminium sheets.

Keywords: Low velocity impact, Fiber metal laminate, GEAML, Energy absorption, Drop weight Impact test, Damage resistance and Impact behaviors

Fiber metal laminates were used in aircraft structures for its high strength to weight ratio and improved damage tolerance characteristics. The glass fiber/epoxy-Al metal laminate (GEAML) provides weight reduction for aircraft structures due to its lower weight than monolithic aluminium sheets resulting in better aircraft efficiency and lower operating costs. Fiber metal laminates (FML) consist of successive layers of metal sheets and fiber mats with polymer adhesive binding. The fiber reinforced polymer (FRP) layer is responsible for carrying the majority of load and also performing the important task of resistance to spread off contact forces, whereas the metal layer helps to absorb impact energy. Fiber metal laminates (FMLs) have high tensile strength, fatigue resistance, low thermal expansion and good corrosion resistance. Asundi and Alta reported that FMLs are promising candidates for the fuselage and lower wing materials. GEAML materials have the benefits of both aluminium and fiber glass composites, especially in fatigue and impact. GEAML is used for fuselage skin structures of aircraft for its enhanced the mechanical properties.

Many researches have been carried out on FML to evaluate the mechanical properties like tensile strength, flexural strength, impact strength etc. Hayes et al. studied about the influence of different sized glass fibers on the mechanical properties of GEAML. Mouritz et al. stated that damage tolerance could be enhanced by using bidirectional woven fabrics. Straznicky et al. carried out numerous low velocity impact tests that demonstrate the impact response of FMLs and they were better than the traditional materials. It is also reported that weight savings and durability in airframe structures can be achieved by using FMLs. Banakar and Shivananda reported that the mechanical properties were mainly dependent on the fiber orientation. The FMLs used in aircraft structure are subjected to low velocity impact during maintenance and high velocity impact during flight. The deformation during low velocity impact may be considered as quasi-static. Ardakani et al. investigated the damage characteristics of FMLs under low velocity impact and concluded that the sequence of stacking and adhesive bonding between the layers contribute to the impact behavior of the laminates. Moreover, the impact behavior of GEAML laminates is dependent on their thickness. The laminates with poor interfacial adhesive bonding exhibited larger damage area than that with good bonding. Chandra et al. carried out the simulation...
studies using finite element method for the FMLs and the aluminum sheets. The material properties were acquired through characterization tests and found that FMLs had failure modes similar to that of aluminum. Abdullah et al. reported that the primary energy absorbing mechanisms in FML laminates were plastic deformation in the aluminum and ductile tear in the FRP. Researchers extensively studied internal impact damage in FML and demonstrated that it was confined to a relatively small area immediately surrounding the point of impact. Mathivanan and Jerald investigated the impact behavior of woven glass epoxy laminates and found that the response of these laminates depended on the elastic properties of the fiber material. Vlot and Gunnink stated that the laminates fail by perforation as the impact velocity increases. Tiberkak et al. reported that the fiber-reinforced composite plates failed by matrix cracking, delamination and fiber breakage on impact testing. Aymerich et al. reported that composite materials normally dissipate energy by the failure of matrix/fiber and delaminations whereas the metals dissipate by plastic deformation. Jaroslav et al. found that the low velocity impact resistance of carbon fiber/Al laminates depended up on ply configuration. The FMLs with (0°/90°) and (+/- 45°) fiber orientations exhibited the best behavior followed by the (0°/0°) configuration. Mathivanan and Mouli used ANN to study the low-velocity impact characteristics of woven glass epoxy laminates of EP3 grade. Rajkumar et al. studied the low velocity impact behavior of the laminates GEAML, CEAML (carbon fiber epoxy-aluminium metal laminate) and aluminium and concluded that GEAML exhibited an excellent impact damage resistance and its energy absorption was higher than CEAML. Thiagarajan et al. evaluated the influence of nanoclay and E-glass fiber reinforcement and found that the energy absorption increased for CSM fiber composites, when 3% nanoclay was added. Palaniradja et al. also evaluated the influence of nanoclay in epoxy-based fiber-glass composite laminates and showed that the addition of 1% and 3% nanoclay increased the load bearing capacity and energy absorption. Due to the increasing focus on the impact response of fiber metal laminates, further studies are necessary for their effective use in structural application. Even though a lot of studies were carried out on fiber metal laminates, the impact response and damage resistance behavior of various types of glass fiber/epoxy aluminium metal laminates (GEAML) have to be studied carefully, since these laminates are widely used for aircraft application. The main objective of this work is to analyze the impact response and damage resistance behavior of the laminates subjected to low-velocity impact testing.

Materials and Methods

Materials and specimen fabrication

Two different types of laminates were fabricated: (i) Woven glass fiber epoxy-aluminium metal laminates (woven based GEAML) and (ii) CSM glass fiber epoxy-aluminium metal laminates (CSM based GEAML). For fabrication of the both FMLs, 0.3 mm thick Al 6061 alloy sheets supplied by Noble Tech Industries, Chennai, India were used. The laminates were fabricated using a hand lay-up technique. Hand lay-up technique was chosen as it was suited to manufacture low volume with minimum cost. The FRP layers used in this study were 600 gsm plain woven glass fiber with 0/90° fiber orientation and 300 gsm CSM glass fiber, LY556 epoxy resin with K7 hardener. Woven based GEAML has a stacking sequence of Al-WG-Al-WG-Al and CSM based GEAML has a stacking sequence of Al-CG-Al-CG-Al (where WG denotes woven glass fiber mat and CG denotes CSM fiber mat). The nominal weight fraction of fibers in GFRP was kept constant at 60%. The surfaces of the laminates were covered with 25 micron Mila film to prevent the layup form external disturbances. The plates were then post-cured in an oven at 100°C for 4 h after they had been cured under 15 kPa pressure for one day at room temperature. These laminates were then cut to suit ASTM dimension by a water jet cutting machine and the edges were ground. These laminates were then cut to dimensions of 100 × 150 mm size. For comparison, the aluminium sheets of the same thickness as that of the FML specimens were used for impact studies.

Low-velocity impact testing

The falling weight impact test was used to investigate the low-velocity impact behavior of the specimens. The tests were performed using an instrumented falling weight testing machine (Instron, Dynutup-8200) with no energy storage device. The maximum impact energy is limited by the adjustable falling height (up to a maximum of about 1500 mm) and the fixed mass, 10 kg, of the impactor. This peak energy from the falling weight is about 150 J with an impact velocity of 6.25 m/s, completely supplied by the gravitational force. The impactor mass together
with the height of drop determines the energy of impact. The dart material used was steel. The energy absorbed by the test specimen is the impact energy required to just fracture or break the specimen. In accordance with ASTM D 7136 standard\textsuperscript{28}, the specimens with dimension 100 × 150 × 2 mm were clamped on a fixture. The impactor has a mass of 2.5 kg with smooth hemispherical striker tip having a diameter of 12.5 mm. The onset of specimen impactor contact was noted by the detection of a non-zero contact force. The piezoelectric load cell is placed at the other extremity of the calibrated cylindrical rod that constitutes the dart, at which the pushing mass is connected. A fixed impactor with the dart is released from varying heights. As the impactor struck the specimen, the specimen deformed and a local depression was formed as the contact force increased. The velocity detector measured the velocity of the tip before it struck the specimen. The data was recorded by the computer. Woven based GEAML, CSM based GEAML and aluminium materials were subjected to low velocity impact at impact velocity 2.426 m/s. In order to check the repeatability, five tests were conducted. For each impact, the position and acceleration of the impactor were continuously monitored. Images of damaged areas were also captured. The Low velocity impact testing parameters are given in Table 1. The damage area of the specimens was measured using a toolmakers microscope (Metzer-model METZ 1395) with 30X magnification factor and a micro-stylus dial gauge with a least count of 1 micron was used to measure the depth of penetration.

**SEM observation**

**Sectioning of samples**

Machining or sectioning of the specimen was performed in water jet cutting machine DARDI Make, China (Model No: DWJ1525 – FB). The specimens were marked with a dimension of 10 mm × 15 mm and placed in the water jet cutting machine. Garnet was used as abrasive material with 80 mesh size. In order to avoid delamination, fine cutting parameters of low transverse speed, high jet pressure and minimum standoff distance were used. The machining parameters used are presented in Table 2. The machining was carefully performed to avoid any damage to the specimen due to machining.

**Scanning electron microscopy**

Scanning electron microscopy (Hitachi make SEM with Model No: S-3400N) was used to observe the surface of the impacted composite laminates. The samples were prepared for SEM analysis by cutting 10 mm × 15 mm of the impacted surface of the samples. The sectioned specimens were placed in scanning electron machine for observation. The SEM micrographs were analyzed to identify the failure mechanism responsible for the damage of the specimens.

**Results and Discussion**

The fiber metal laminates woven based GEAML, CSM based GEAML and the aluminium sheet were analyzed for the impact response and their damage resistance behavior during low velocity impact test. The impact load is the response force of the specimen against the impactor. The impact energy is the initial potential energy from the impactor before the test and the absorbed energy is the energy absorbed by the material. Damage resistance in fiber metal laminates during low velocity impact test is a measure of the relationship between the amount the impact load, energy associated with impact and the resulting damage size and type. In this work, impact response and the damage resistance of the materials are analyzed.

**Impact response**

Composite materials normally dissipate a significant amount of energy by fracture mechanism such as matrix crack delamination, fiber fracture, fiber matrix re-bonding and fiber pull out. The energy absorbed by the composite materials up to the peak load is through elastic deformation and all the energy absorbed beyond the peak load is assumed to be absorbed through the creation of damages. Impact load versus deflection provides clear picture about the maximum load and the corresponding deflection and progress of deflection up to peak load.

<table>
<thead>
<tr>
<th>Material</th>
<th>Height of fall (mm)</th>
<th>Impact Velocity (m/s)</th>
<th>Impact energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woven based GEAML</td>
<td>300</td>
<td>2.426</td>
<td>7.36</td>
</tr>
<tr>
<td>CSM based GEAML</td>
<td>300</td>
<td>2.426</td>
<td>7.36</td>
</tr>
<tr>
<td>Aluminium</td>
<td>300</td>
<td>2.426</td>
<td>7.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Machining parameters</th>
<th>Machining values used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet pressure</td>
<td>300 MPa</td>
</tr>
<tr>
<td>Traverse speed</td>
<td>1 mm/s</td>
</tr>
<tr>
<td>Standoff distance</td>
<td>2.5 mm</td>
</tr>
</tbody>
</table>
Impact load

A typical impact load-deflection curve of woven based GEAML, CSM based GEAML laminates, aluminium is shown in Fig. 1. In woven based GEAML, the curve increases steeply and the impact load increases until it reaches the maximum (1210 N). The woven based GEAML withstood a maximum load of 1210 N. The woven based GEAML underwent minimum deformation leading to its impact resistance. In CSM based GEAML, the impact load increased gradually and reached the peak value of 860 N with proportionate increase in the deflection. However, the impact load caused tear in the exterior aluminium layers, suggesting possible failures like crack initiation and crack propagation of the aluminium sheets. The deformation of fiber mat was mostly elastic in nature until failure, and significant spring back occurred reducing the permanent strain in both of the laminates. In aluminium, the slope of the curve is very low and the maximum impact load it withstood is 460 N. As metals underwent permanent deformation after its yield strength, aluminium with low yield strength, underwent deformation with lower impact load. In woven based GEAML laminate the damage was less when compared to aluminium and CSM based GEAML laminate. The elastic behaviour of woven based GEAML caused less permanent deformation. The major failure mechanisms of fiber metal laminates are debonding, micro-cracking of the resin, failure of the fibers and rupture of an aluminium layer by tear, whereas the main failure mechanism of aluminium is plastic deformation. The failure occurred in aluminium at lower impact load as the load withstanding capacity was lower and the fibers in the GEAML laminates withstood higher impact load. The load bearing capacity of the woven based GEAML laminate was higher than that of CSM based GEAML laminates and aluminium.

Absorbed energy

Figure 2 compares the absorbed energy vs. time curve of the woven based GEAML laminate, CSM based GEAML laminate and aluminium. Owing to the ductility nature of metal, it can absorb large amount of impact energy in the elastic region up to yield and deform in the plastic region by absorbing additional energy before failure. In contrast, the laminates can absorb impact energy in the elastic region before undergoing different modes of failure. The composites have the advantage of metal and the fiber, hence they are subjected to elastic and plastic deformation. Generally, the energy up to the peak load is absorbed through the elastic deformation and all the energy that is absorbed beyond that is assumed to be absorbed through the creation of damages. From the figure, it can be observed that all specimens show a gradual increase in absorbed energy with respect to time. Based on the test results, it was found that woven based GEAML laminate showed higher energy absorption when compared with the CSM based GEAML laminate and aluminium. The energy is absorbed by the specimens through elastic and plastic deformation. The energy absorbed depends upon the impact strength of the material and the ductility of the material ability to undergo strain. Aluminium due to its ductile nature and its ability to undergo plastic deformation absorbs impact energy. The laminates have the advantage of the fiber with higher yield strength, undergo elastic deformation up to the peak load and absorb impact energy. Woven based GEAML laminate absorbed higher impact energy.
than the CSM based GEAML laminate and the aluminium. In CSM based GEAML laminate, discontinuous fibers are reinforced in the fiber mat. Since the chopped strand mat (CSM) composite has discontinuous fibers, they have less strength and modulus than continuous fiber composites like woven mat composites. In the CSM, the fibers are random in alignment and the aspect ratio of the discontinuous fiber is less compared to continuous fibers, which reduce their strength and modulus. Hence, the absorbed energy of CSM based GEAML was less than that of woven based GEAML. However, the density of the CSM based GEAML was less when compared to the woven based GEAML. Woven based GEAML can be used where the strength is the main criterion whereas CSM based GEAML can be used where weight/density is the major criterion. The maximum impact load withstood by the laminates and the aluminum sheet and the corresponding impact energy absorbed at the maximum load are given for comparison in Figs 3 and 4. The specimens undergo deformation both elastic and plastic until the maximum impact load beyond which, they fail due to rupture. The energy absorbed by the laminates and the aluminum sheets at the maximum load corresponds to the energy absorbed by the specimens. It can be noted that both the maximum impact load and the energy absorbed for the woven based GEAML laminate was higher than that of CSM based GEAML laminate and aluminium. The impact response of the Woven based GEAML laminate is better than the CSM based GEAML laminate and Aluminium.

**Damage resistance**

During impact, the material undergoes elastic deformation initially and subsequently plastic deformation. During these deformations, energy is absorbed by the material and after these deformations failure of the material occurs, causing damage to the material. The ability to undergo minimum damage may be called the damage resistance. The damage resistance of the laminates and the aluminium was analyzed, while subjected to impact load. The area of damage, the depth of penetration, the mode of failure and the damage mechanism are the important criteria to be considered.

**Impact damage analysis**

Apart from the impact response, damage analysis is also important because a small damage in the aircraft fuselage may cause catastrophe in the aircraft. In this study, the damaged surfaces of the woven based GEAML laminate, CSM based GEAML laminate and aluminium specimens after the impact were analyzed. The photographs of the front and rear surfaces of the specimens after impact are shown in Fig. 5(a-f). In woven based GEAML laminate the impactor made dent at the front surface and a small bulge was observed in rear surface. There was no appearance of perforation or tear at either faces. However, the circumference of the damage area was subjected to severe strain, leading to the initiation of the damage. In CSM based GEAML laminate, the front and the rear layers were subjected to ductile tear due to the impact loading. The fiber was stretched inside the laminate due to its elastic behavior, whereas the aluminium sheet in the CSM based GEAML laminate was not able to match the elongation of the fibers. The aluminium layers in the CSM based GEAML laminate at the exterior ends were subjected to ductile tear, due to the mismatch of elongation between aluminium layers and FRP layers. In aluminium sheet, the deformation was mainly due to its plasticity. The deformation was not limited to a local area but also the surrounding area of

![Fig. 3 — Comparison of the maximum Impact load of the laminates and the aluminium sheet](image)

![Fig. 4 — Comparison of the absorbed energy of the laminates and the aluminium sheet](image)
the impact location. The damage formed at the front surface and thin localized crack appeared surrounding the circumference of the dent. The damage area and the depth of penetration of the laminates and the aluminium sheet are given in Table 3.

From Table 2, it can be observed that the area of damage in woven based GEAML less than that of CSM based GEAML and aluminium. The depth of penetration in woven based GEAML was also lower when compared to the other specimens. The impact load was transferred from the aluminium layer to the woven glass fiber mat. As the woven glass fiber mat was bi-directional, it was able to transfer the load through the glass fibers in both directions. Even though the density of the woven based GEAML was slightly higher than the CSM based GEAML, the area of damage and the depth of penetration were lower.

**Mode of failure and damage mechanism**

Generally, the modes of failure in the laminates are debonding/delamination, fiber pullout, tear of aluminium sheet, cracking of the matrix etc. The damage or failure mechanism is a complex phenomena, because the laminates consist of metal sheet, fibers and polymer resin. Metal sheets undergo elastic and plastic deformation before failure by tear and debonding from the subsequent FRP layer. The failures of FRP in the fiber metal laminates are generally of two types (i) delamination at the interface of the FRP composite and the metal sheet and (ii) the failure related to individual constituents of FRP such as matrix and fiber. The fibers have high elastic strength and they deform elastically until failure as they undergo negligible plastic deformation. The fibers in FRP fail by breaking, when the stress exceeds the limit, causing debonding and fiber pullout from the matrix. Stress concentrations are developed in the matrix due to the impact. Matrix cracking occurs due to stress concentrations and increase of stress in the matrix beyond the limit. SEM micrograph of the woven based GEAML is given in Fig. 6.

![Fig. 5 — The photograph front and the rear surfaces of the specimens subjected to low velocity impact (a & b) woven based GEAML, (c & d) CSM based GEAML and (e &f) aluminium](image-url)
lateral cut section of the damaged face is shown in the micrograph. The profile of the damage is clearly visible from the micrograph. Figure 6 shows the damage lateral profile of the woven based GEAML laminate and it can be observed that the laminate is subjected to debonding. Since the woven based GEAML laminate has continuous fiber, the failure of fiber is very rare. However, debonding/delamination is the main failure or damage mechanism and it can be clearly noted from the SEM micrograph. Due to the mismatch in the elongation of the glass fiber and aluminium and poor bonding between the aluminium sheet and the fiber mat, debonding occurs around the damage area. However, the area of damage is less in woven based GEAML than that of the other specimens. Figure 7 shows the damage lateral profile of the CSM based laminate and it can be observed that in addition to debonding, tear occurred in the front and rear layers of the laminate. The CSM fiber mat is comparatively weaker than the woven fiber mat because CSM fiber contains discontinuous fibers and the strength of the discontinuous fiber is less than that of the continuous fiber\(^2\). In CSM based GEAML, the load bearing capacity of the chopped fibers was reduced and the fibers transferred partial load to the matrix and the subsequent aluminium sheet. As the epoxy matrix and aluminium sheet bore considerable amount of load, the CSM based laminate underwent debonding and also subjected to tear of aluminium sheet. The discontinuous fibers were not able to bear the impact load fully due to its low aspect ratio, the discontinuous fibers were subjected to fiber pullout. Figure 8 shows the fiber pullout in the CSM based GEAML laminate. The impact damage in CSM based laminates is severe when compared to that in woven based laminates. The damage profile of CSM based laminate is larger than that of the woven based GEAML laminate. Aluminium sheets were subjected to plastic deformation, thinning, localized necking, perforation etc during impact loading. Figure 9 shows the damage lateral profile of the aluminium and it can be observed that aluminium is subjected to plastic deformation.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm(^3))</th>
<th>Area of damage (mm(^2))</th>
<th>Depth of penetration (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woven based GEAML</td>
<td>1.81</td>
<td>8.55</td>
<td>1.02</td>
</tr>
<tr>
<td>CSM based GEAML</td>
<td>1.65</td>
<td>35.24</td>
<td>2.2</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2.7</td>
<td>23.75</td>
<td>2.3</td>
</tr>
</tbody>
</table>

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Fig. 6 — SEM micrograph showing the lateral cut section of the damage profile of woven based GEAML specimen subjected to low velocity impact

Fig. 7 — SEM micrograph showing the lateral cut section of the damage profile of CSM based GEAML specimen subjected to low velocity impact

Fig. 8 — SEM Micrograph showing the fiber pullout in the CSM based GEAML laminate
deformation and thinning. The combined effect of plastic deformation and thinning caused failure to the aluminium sheet. While considering the damage profiles of the laminates and aluminium, the area of damage and the depth of penetration of woven based GEAML were less than that of the CSM based GEAML and aluminium. Hence, woven based GEAML has higher damage resistance than the other two materials.

Conclusions
The impact response and the damage resistance of the woven based GEAML laminate, CSM based GEAML laminate are considered and they are compared with aluminium sheet. The load bearing capacity is superior in woven based GEAML laminate when compared with both CSM based GEAML laminate and Aluminium sheets. The energy absorbed by the woven based GEAML laminate is slightly higher than the aluminium sheet and the CSM based GEAML laminate. The damage area and the depth of penetration are much lower in case of woven based GEAML laminate than the CSM based GEAML laminate and aluminum sheets. The major failure mechanisms exhibited by the laminates are depending, tear and fiber pullout. The performance of CSM based GEAML laminate was affected by the lower strength of the discontinuous fibers. In conclusion, woven based GEAML laminate exhibited better impact response and damage resistance than the CSM based GEAML laminate and aluminium sheet.

References