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Effect of Natural Fibre-epoxy Plies on the Mechanical and Shock Wave Impact Response of Fibre Metal Laminates

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Abstract

Fiber metal laminates (FMLs) are novel materials employing stack-up configurations for alternate fiber-polymer plies and monolithic metallic sheets. These materials combine the superior mechanical properties of metals/alloys with lightweight and low thermal expansion of fiber-polymer composite layers. Synthetic fiber fabrics like aramid fiber, basalt fiber, carbon fiber, and glass fiber are commonly used in fiber metal laminates. The effect of natural fibers as sandwiched plies in fiber metal laminates has been freshly explored in the current work. Banana fiber-epoxy layers have been combined with high-strength, synthetic fabrics of aramid and ultra-high molecular weight polyethylene. Stacking sequences were developed with the varied location of banana fiber-epoxy ply with AA6061 sheets as skins. The laminates were subjected to mechanical characterization comprising static tensile and flexural tests, followed by shock impact within a shock tube. There was a ~4-5% reduction in the tensile strength, ~37%-52% reduction in tensile modulus, ~5-23% reduction in the flexural strength, ~ 28-53% reduction in flexural modulus for the FMLs containing banana fiber-epoxy plies as compared to that without this ply. But, the FMLs with banana fiber-epoxy plies showed enhanced shock impulse response as compared to the sequence without banana fiber-epoxy ply, with lower overall relative deformation (~14-21% lesser deformation).

Keywords: Natural fiber; Fibre Metal Laminates; Tensile properties; Flexural properties; Shock impact resistance.
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1. Introduction

The most important engineering parameters for material selection in industrial and structural applications are weight, cost, and specific strength. fiber metal laminates belong to the class of novel materials employing stack-up configuration for alternate fiber-polymer plies and monolithic metallic sheets. Currently, metals such as aluminum, titanium, and magnesium are used as laminates, and reinforced fiber layers such as aramid fiber, glass fiber, and carbon fiber, are used as fiber-reinforced composites. fiber metal laminates combine the high stiffness and strength, exceptional fatigue characteristics, and corrosion resistance, of fiber-reinforced polymer along with high bearing strength and impact resistance of metals, thus overcoming most of the drawbacks of single monolithic material sheets. FMLs when compared with conventional composite lamina show excellent mechanical properties like outstanding strength-to-weight ratio and high corrosion resistance.[1,2] Presently, industries such as aircraft, marine, and automotive sectors are showing an increasing amount of interest in fiber Metal Laminates, due to their impact and fire resistance and better resistance towards fatigue. To date, there are different varieties of FMLs are being used for example ALOR (aluminum and organic fibers), ARALL (aramid fibers and aluminum), CARALL (Carbon fibers and aluminum), GLARE (glass fiber and aluminum), TIGR (titanium and graphite fibers).[3–5]

Fiber metal laminates (FMLs) are made up of fiber-polymer plies sandwiched between monolithic metal sheets. To ensure adequate adhesion, metal sheets are treated to an extraordinary surface treatment, whilst pre-impregnated with polymer, high-strength fibers are utilized to create the layers of the composites in a one-directional, cross-ply, or fiber arrangement. Hot pressing is often used to create FMLs, which comprises molding the metal plies to the appropriate shape and curing the composite layers. FMLs offer the following advantages over monolithic metals, partly combining the advantages of metals and composite materials- Increased tensile strength (~60% higher) due to the incorporation of high-strength fibers, lower mass density (by around 15-20%), elastoplastic behavior due to high degree of linear elasticity in composite plies, enhanced fatigue strength (fiber layers offer

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through-thickness resistance to the propagation of cracks, improved damping characteristics, impact resistance.[6] Alternately, FMLs suffer from various disadvantages- FML stiffness was lower than that of the monolithic metals because the shear modulus and Young's modulus of bidirectional/cross-ply fiber fabrics are lesser than the equivalent properties of the metal. Similar behavior can also be observed for FMLs containing titanium as metal and carbon-epoxy as the intermediate layers.[6,7] When the strain in the layers of metal reaches the threshold limit, yielding begins, and FMLs have a lower modulus, leading to lower yield stress. Residual inter-laminar tensions are created when FMLs are hot-pressed. The use of FMLs in crushed sections of the construction is hampered by delamination produced by an impact. FMLs have a cost that is typically much higher than metals.[3]

Natural fibers are bio-degradable, non-abrasive, renewable, have a high calorific value, have great mechanical characteristics, and may be burned for energy recovery. They also have a low density and are cheap. Because of their environmental friendliness, the materials are highly popular in technical areas such as the construction and automobile industries.[8] Many research groups have recently focused their attention on lignocellulose fibers such as banana, sisal, coconut fibers, and oil palm fibers as polymer reinforcement. These fibers offer several benefits over synthetic fibers, including biodegradability, cheap cost, low density, and recyclability. These fibers comprise lignin, hemicellulose, cellulose, soluble material, waxes, and pectin, the first three of which are important for the fiber's physical and mechanical characteristics. The availability of natural fibers and the simplicity with which they may be processed is an appealing quality that makes them a suitable replacement for synthetic fibers in the composite sector.[9–12] Natural/synthetic fiber composites have good fatigue characteristics, are corrosion-resistant, and have a high stiffness-to-weight ratio and strength. Another benefit of mixing natural and synthetic fibers is that it reduces respiratory and skin irritation issues produced by synthetic fibers such as carbon and glass fibers.[13] Natural fibers include sisal, jute, hemp, flax, coir (coconut), and abaca fiber (banana). Each of the above-listed fibers is grown as crops in different areas of the globe. Natural fibers are made up of micro-fibrils of cellulose distributed in hemicellulose and amorphous lignin matrix. The concentration of cellulose ranges from 60% to 80% by weight depending on the type of plant fibers, while the composition of lignin ranges from 5% to 20% by weight. Furthermore, natural fibers can have a moisture level of ~20% by weight. Natural fibers have the following advantages- They are environmentally sustainable because they are recyclable, require minimal energy to create, and have a density of 1.25 - 1.5 g/cm^3, whereas E-glass fibers have a density of 2.54 g/cm^3 and carbon fibers have a density of 1.8 - 2.1 g/cm^3, higher modulus to weight ratio over synthetic. Acoustic damping characteristics offered by natural fiber-reinforced composites are more prominent making them feasible for attenuating noise, which can be extended to shock mitigation applications. Natural fibers, on the other hand, have numerous disadvantages. Natural fibers have a relatively low tensile strength. Other constraints include low moisture absorption and melting point. Natural fibers begin to deteriorate at temperatures over 200 °C, initially by hemicellulose degradation and subsequently through lignin degradation.[14] Degradation causes mechanical property deterioration, volatile emission, discoloration, and odor.[15] Banana fiber production is dominated by India and Brazil. fibers of bananas are manually removed from the plant stems that have been frequently dumped after harvesting bananas from the field. In the paper industry, these harvested fibers of bananas can be utilized because of their low lignin and high cellulose content. Several studies have attempted to improve the adhesion of matrix fiber by chemically treated fibers. When compared with untreated fibers, the treated banana fiber had greater interfacial-shear stress and tensile strength.[9] From the literature review, it is concluded that studies on sandwiching Natural fibers in FMLs are considered a novelty, and Shock resistant materials employing lightweight natural fiber-epoxy lamina are not explored. The present paper describes the fabrication of Hybrid fiber Metal Laminates (FMLs) using Aluminium 6061 sheets, Aramid fiber, Ultra-high-molecular-weight polyethylene (UHMWPE), banana fiber and epoxy incorporated as a random strand mat as sandwich plies. Three sequences of fiber metal laminates were fabricated, by varying the location of the banana fiber/epoxy lamina. This study aimed to investigate the mechanical characteristics- tensile and flexural properties of the different sequences of fabricated FMLs and evaluate the shock shielding capability of the different sequences by shock impact inside a shock tube. Table 1 compares the mechanical properties of natural fibers with synthetic fibers. Mohammed *et al.*[13] studied the flexural, tensile, and compression strengths of the combination of synthetic/natural fibers as reinforcements with metal laminates as skins. The materials included aluminum alloy 2024, carbon fibers, kenaf fibers, flax fibers, and epoxy as the binder. Two stacks of hybrid fiber metal laminate were developed. The configurations were Carbon and flax fiber-reinforced aluminum alloy (CAFRALL) and kenaf and Carbon-fibre-reinforced aluminum alloy (CAKRALL). CAFRALL showed higher mechanical characteristics, with a maximum modulus of elasticity of 4.4 GPa. CAFRALL's tensile and compressive strengths were 14.8% and 20.4% higher than CAKRALL's, respectively. The flexural strength of the kenaf composite was 33.7% greater than the flax composite. Kali *et al.*[10] utilized bamboo fiber in FMLs, manufactured by the hand-layup method. Three FML sequences were subjected to vibration studies. The incorporation of bamboo strips in the central ply led to a significant reduction in peak acceleration. This is because of the high stiffness and fewer weight properties of bamboo fiber. Malingam *et al*[16] in their research fabricated FMLs based on glass and kenaf fibers with different orientations and stacking sequences. The impact and tensile characteristics were

Table 1. Mechanical properties of natural fibers as compared to conventional reinforcing fibers.[14,17,18]

Fibers	Young's Modulus (GPA)	Tensile Strength (MPa)	Elongation (%)	Density (g/cm^3)
Jute	10-30	393-800	1.5-1.8	1.3-1.46
Cotton	5.5-12.6	287-597	3.0-10.0	1.5-1.6
Flax	27.6-80	345-1500	1.2-3.2	1.4-1.5
Banana	20	550-700	4.5-6.5	1-1.5
Softwood kraft	40.0	1000	–	1.5
Ramie	44-128	220-938	2.0-3.8	1.5
Hemp	70	550-900	1.6	1.48
Coir	4.0-6.0	175-220	15.0-30.0	1.2
Sisal	9.0-38.0	400-700	2.0-14	1.33-1.5
S–glass	86.0	4570	2.8	2.5
E–glass	70.0	2000-3500	2.5-3.0	2.5
Carbon (High Modulus)	230.0-240.0	4000	1.4-1.8	1.4
Aramid	63.0-67.0	3000-3150	3.3-3.7	1.4

investigated. Hybrid stackups containing glass fiber and kenaf plies showed lesser tensile strength as compared to stackups with glass fiber layers. When hybrid FMLs were compared to kenaf fiber-reinforced FMLs, both impact and tensile strength were improved. When compared to fiber having an orientation of 0°/90°, 45° orientation fiber showed an improvement in impact strength but a loss in tensile characteristics. Finally, hybrid FMLs containing kenaf fiber plies sandwiched between glass fiber plies demonstrated better impact and tensile characteristics. Zareei *et al.*[19] explored the potential of basalt and jute hybrid fibers in an epoxy matrix with aluminum 2024-T6 as metallic skins. The FMLs were made using the hand lay-up technique followed by curing at ambient temperature at a pressure of 4 MPa for 24 hours. Mechanical testing comprising tensile characteristics and interlaminar shear strength was performed. The interlaminar shear strength, tensile strength, and elastic modulus of the FMLs in which jute fiber ply was sandwiched by basalt fiber plies were the highest. The microstructural analysis indicated that fibers of jute bonded poorly to the aluminum sheets, but fibers of basalt bonded well. According to micro and macro studies of the structures of FMLs, delamination and pull-out were exhibited by fibers of basalt from the sheets of aluminum, while the fibers of jute exhibited delamination, pull-out, and fiber fracture from the sheet of aluminum. El-Baky *et al.*[20] studied the FMLs comprising glass/jute fiber plies with aluminum alloy facing layers. The effects of the weight content of fiber plies and the position of the fiber layers on flexural and tensile behaviors were investigated. Flexural and tensile testing, as well as other mechanical tests, were performed. According to the findings, Jute reinforcement containing FMLs shows improvement in flexural and tensile properties, which is because of the hybridization of reinforcement. A decrease in flexural resistance and an increase in tensile characteristics were observed when fibers having high strength were fused at the core of the composite.

The employment of natural fibers in FMLs and the response of such FMLs to shock waves were not explored. Hence, in the current work, FMLs comprising banana fiber-epoxy lamina with different stacking sequences were fabricated and subjected to mechanical and shock response characterization. The present paper describes the fabrication of Hybrid fiber Metal Laminates (FMLs) using Aluminium 6061 sheets, Aramid fiber, Ultra-high-molecular-weight polyethylene (UHMWPE), banana fiber and epoxy incorporated as a random strand mat as sandwich plies. Three sequences of fiber metal laminates were fabricated, by varying the location of the banana fiber/epoxy lamina. This study aimed to investigate the mechanical characteristics- tensile and flexural properties of the different sequences of fabricated FMLs and evaluate the shock shielding capability of the different sequences by shock impact inside a shock tube.

2. Materials and methods

2.1 Material preparation

The constituents of the FMLs were AA6061-T6 face sheets (0.7 mm thick), Core plies composed of Aramid BD fabric (480 GSM), UHMWPE UD fabric (130 GSM), and Banana fiber-epoxy ply. The binder CT/E – 556 epoxy resin and CT/AH – 951 polyamine hardener were procured from Composites Tomorrow, Gujarat. Raw banana fiber required alkaline treatment before fabrication since the elasticity modulus, tensile strength, flexural modulus, and flexural strength of the composite of banana fiber treated with NaOH solution having 5% concentration was found to be excellent.[21] For the treatment, 150 g of NaOH pellets were mixed with 3000 ml of water to form a 5% concentration NaOH solution. The fibers were immersed in the alkaline solution for 1 hour, followed by washing and neutralization with dilute hydrochloric acid. The banana fibers were sundried for a week and then cut to size (1.5-2 cm length). Before commencing the fabrication, aramid fabrics, AA6061 sheets, UHMWPE fabric, and the banana fiber were kept in hot air over for three hours at a temperature of 80 ºC, to remove the moisture. To enhance interfacial adhesion, the surface of contact of AA6061 sheets was mechanically sanded with grit levels of P80 and P600 emery papers.

Table 2 shows the number of layers for the different layered configurations. The schematic of the layups is shown in Fig. 1. To accommodate the banana fiber-epoxy random strand ply, one of the aramid-epoxy plies (in AFL-1) was removed, to maintain a near uniform thickness of the FMLs. Three alternatively stacked FML sequences were prepared by manually laying up the layers according to the sequence and later compressing them in the compression molding machine at room temperature. In AFL-2 and AFL-3, banana fiber-epoxy plies were utilized with varied stacking sequences as shown in Fig. 1. Table 3 shows the weight fractions of the different constituents in each of the stackups.

2.2 Mechanical characterization

The tensile testing of the FMLs was conducted on a universal testing machine with a capacity of 50 kN as per ASTM D3039 standard. Five specimens of 250 mm length and 25 mm width were subjected to the tensile test with a strain rate of 2 mm/min. The Tensile modulus, tensile strength, and strain to failure for the different sequences were computed. Flexural testing of the FMLs was conducted as per ASTM D790 standard. Five specimens of 127 mm length and 12.7 mm width, with a crosshead speed of 1 mm/min. The flexural strength, flexural chord modulus, and strain to flexural failure were calculated for the three sequences. To determine the dynamic performance of the FMLs, the circular specimens (100 mm diameter) of the different sequences were subjected to primary shock impact inside a shock tube. The schematic of the shock tube is shown in Fig. 2(a), with nitrogen as the driver gas. The shock tube consisted of a driver section and a driven section partitioned by a flange holding an aluminum diaphragm (4 mm thick). On switching on the gas supply inside the driver section, the pressure builds up till the point of rupture of the diaphragm, whence shock waves generated travel through the driven section loading the specimen placed at the end with a primary compression wave impact (Fig. 2(b)). Two side-on pressure sensors (100 mm apart) placed near the end cap, connected to the signal conditioner and the oscilloscope record the live pressure data which were used to compute the shock velocity

Table 2. Details of the different stacking sequences.

Stacking Sequence	Details of Layers	No. of Layers	Thickness (mm)
AFL-1	AA6061/ Aramid-epoxy/ Aramid-epoxy/ UHMWPE-epoxy/ UHMWPE-epoxy/ AA6061	6	3.65
AFL-2	AA6061/ Aramid-epoxy/ UHMWPE-epoxy/ UHMWPE-epoxy/ Banana-epoxy/ AA6061	6	3.5
AFL-3	AA6061/ Aramid-epoxy/ Banana-epoxy/ UHMWPE-epoxy/ UHMWPE-epoxy/AA6061	6	3.5

Table 3. Weight fractions of different constituents for the sequences.

Stacking Sequence	Weight fractions (%)				
	AA6061-T6	Aramid	UHMWPE	Banana fiber	Epoxy Resin+ Hardener
AFL-1	59.93	17.90	4.68	-	21.66
AFL-2	60.53	8.72	4.04	4.37	22.34
AFL-3	60.18	8.54	4.03	4.61	22.54

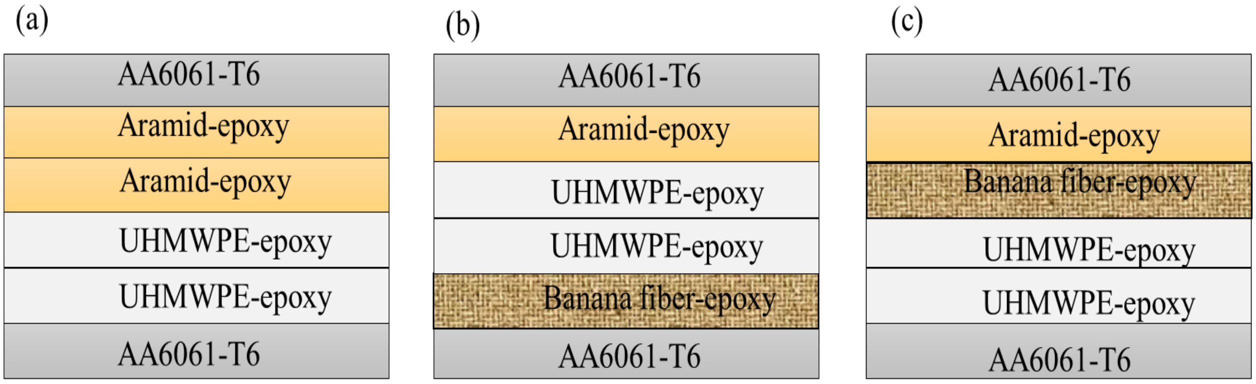

Fig. 1 Different sequences of hybrid FMLs (a) AFL-1, (b) AFL-2, and (c) AFL-3.

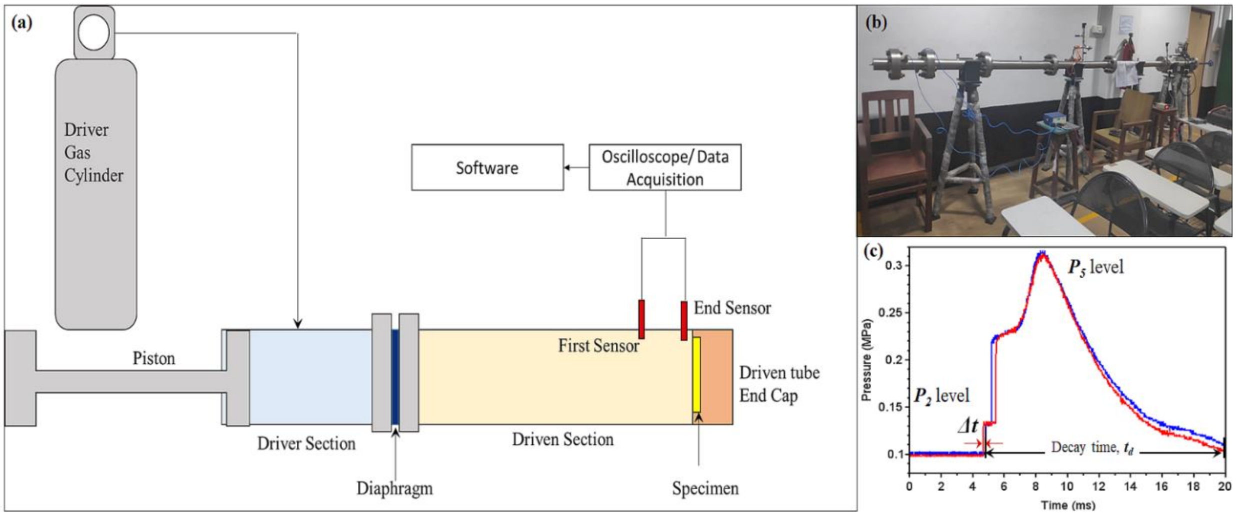

Fig. 2 (a) Schematic of the Shock Tube Apparatus, (b) Shock tube apparatus, and (c) Sample Pressure-time plot.

and the pressure rise. The extent of shock mitigation by the different sequences was measured by the deformation profiles on the facing and the rear side of the FMLs. Fig. 2(c) shows the typical pressure-time pulse for the sequence AFL-1.

3. Results and discussion

From the tensile behavior, it was observed that the FMLs showed a smooth transition from the elastic to the plastic region without a noticeable kink. Initially, curves exhibited linear response up to 0.5% to 1% strain, after which a gradual increase in the stress value with increasing strain till the peak was observed. The stress-strain curves are shown for AFL-1 (Fig. 3(a)), AFL-2 (Fig. 3(b)) and AFL-3 (Fig. 3(c)), respectively. Table 4 shows the tensile properties of all three sequences of hybrid FMLs AFL-1, AFL-2, and AFL-3. Variations in tensile strength and tensile modulus of hybrid

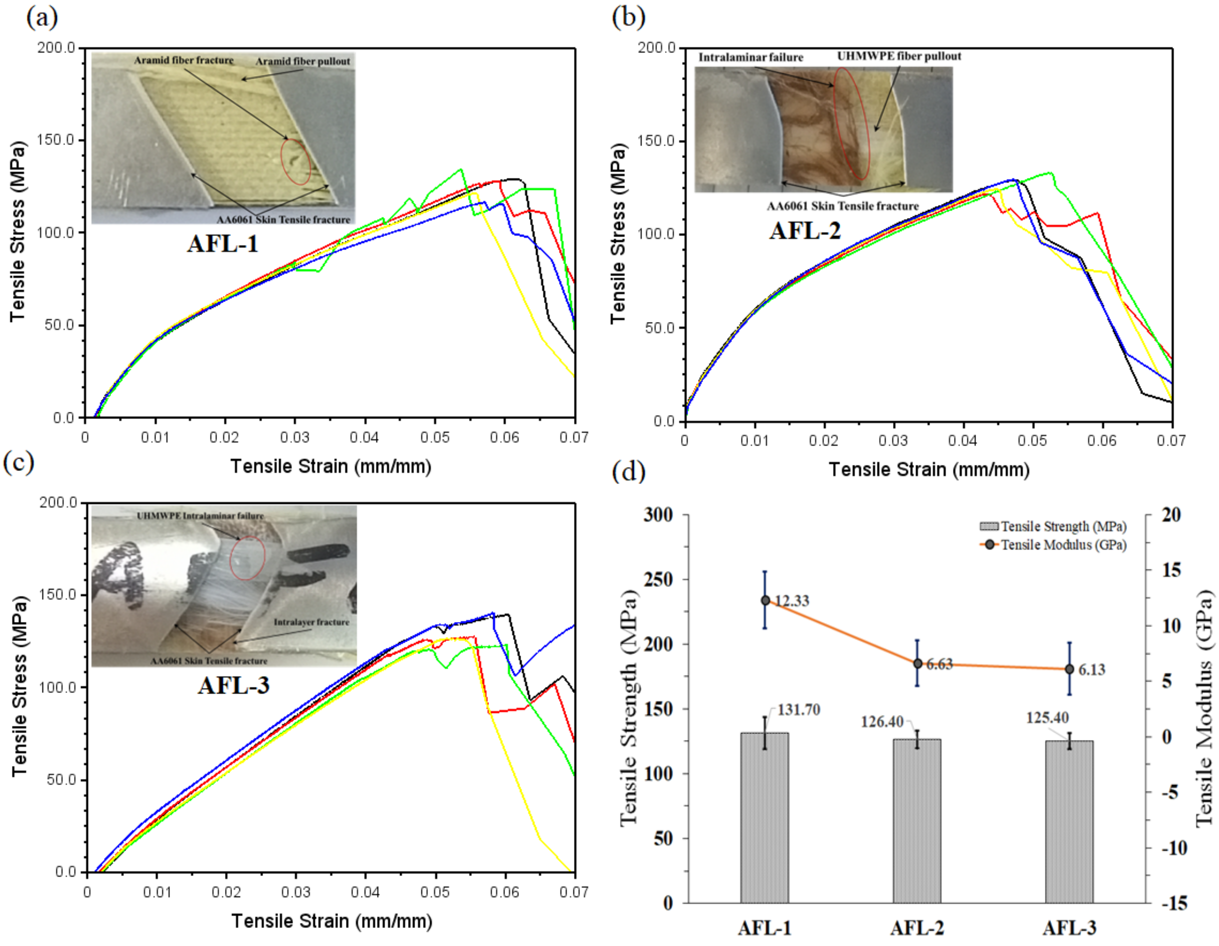

Fig. 3 Tensile Stress-Strain Plots for (a) AFL-1, (b) AFL-2, (c) AFL-3, and (d) Tensile strength and Modulus comparison for the sequences.

FMLs are shown in Fig. 3(d).

It was observed that AFL-1 with a tensile strength of 131.68 MPa, was higher than AFL-2 and AFL-3 by 4.16% and 5.02%, respectively. AFL-1 also showed the highest tensile modulus of 12.33 GPa amongst all the sequences. This implies the addition of natural fiber plies as intermediate layers lowers the tensile properties of the FMLs, although the positioning of the ply does show a minor variation in the tensile response. This can be attributed to the inferior mechanical properties of the natural fibers as compared to the high strength of synthetic fibers like aramid and UHMWPE. However, there was a marginal improvement in the tensile strain to failure in AFL-2 and AFL-3, which could be due to the drop in the tensile modulus for the sequences.[22] In all three stackups, the AA6061 skins underwent failure first through the tensile fracture. In some of the test coupons, delamination of the AA6061 faceplate with the aramid ply was observed. In AFL-2 and ALF-3, the intralaminar fracture was observed in the banana fiber-epoxy ply and UHMWPE plies. Whereas, in AFL-1, the fracture of the aramid fiber and fiber pullout was noticed. During the live tests, aramid ply was observed to fail at the last. The different peaks noticed in the stress-strain plots ascertain the varied failure of the plies at different failure strains.

Table 5 shows the comparison of the flexural properties obtained for the three sequences. AFL-1 showed the highest flexural strength of 59.52 MPa, (5.93% greater than AFL-2 and 37.27% greater than AFL-3 respectively). AFL-1 also displayed the maximum flexural modulus of 18 GPa (40.63 % greater than AFL-2 and 122.22% greater than AFL-3 respectively). The variation of the flexural strength and modulus for the three sequences is shown in Fig. 4. Like the results of the tensile tests, the addition of banana fiber was found to decrease the flexural properties of the FMLs. The FMLs showed buckling and delamination as the primary failure modes during the flexural tests shown within the flexural stress-strain plots. The extent of buckling was found to be pronounced in the case of AFL-2 and AFL-3 respectively, which again show the effect of the presence of banana fiber-epoxy as the sandwiched layers in these two sequences. The delamination was observed on the contact side of the aluminum face sheet with the indenter, in all the sequences as shown in Fig. 4.

The shock parameters obtained during the shock impact trials for the three sequences are displayed in Table 6. Decay time, defined as the time required for the pressure to rise from P_1 level (initial pressure), to P_5 (peak pressure) and then reduce to P_1 level, was found to be highest for AFL-1 (15.1 ms) and lowest for the AFL-2. Impulse loading experiments on circular plates have been carried out using shock tubes by Isaac *et al*,[23] with shadowgrams used to illustrate the deformation of the centerline of the specimens with radial distance from the center.

Referring to Fig. 2(b), the time instant 'Δt' was used to compute the shock velocity (V_s) which when divided by the sound velocity (a), gives the Mach number (Eq (1)). The Mach number for the sequences varied from 1.99-2.06, which was dependent on the value of 'P_4' pressure (characteristic of the diaphragm rupture pressure). Figs. 5(a) and (b) display the faceplate deformation (δ_f) and backplate deformation (δ_b) of the sequences AFL-1, AFL-2, and AFL-3, respectively after the shock impact. Among the sequences, AFL-1 displayed the least faceplate deformation, but the highest back plate deformation. AFL-3 showed the highest faceplate deformation and moderate back plate deformation. As seen from Fig. 5(c), AFL-2, followed by AFL-3 showed the least values of relative deformation despite higher driver-side pressures, while AFL-1 showed the highest relative deformation. Due to the severely large backplate deformation of AFL-1, the sequences AFL-2 and AFL-3 seem to justify the addition of banana fiber-epoxy ply as a sandwich layer between the synthetic high-strength fiber fabrics. The improved shock mitigation can be attributed to the better acoustic damping properties of natural fibers like a banana.[14,24,25]

$$M = \frac{V_s}{a} \tag{1}$$

Table 4. Tensile properties of hybrid FMLs.

Sequence	Tensile Strength (MPa)	Specific Tensile strength (km)	Max. Strain (%)	Tensile Modulus (GPa)	Specific Tensile modulus (km)
AFL-1	131.7	6.79	5.58	12.33	635.47
AFL-2	126.4	8.56	6.5	6.63	448.74
AFL-3	125.4	8.49	5.61	6.13	414.91

Table 5. Flexural properties of hybrid FMLs.

Sequence	Flexural Strength (MPa)	Specific Flexural strength (km)	Max. Strain (%)	Flexural Modulus (GPa)	Specific Flexural Modulus (km)
AFL-1	59.52	3.07	3.14	18	927.69
AFL-2	56.19	3.80	3.64	12.8	866.36
AFL-3	43.36	2.93	1.72	8	541.48

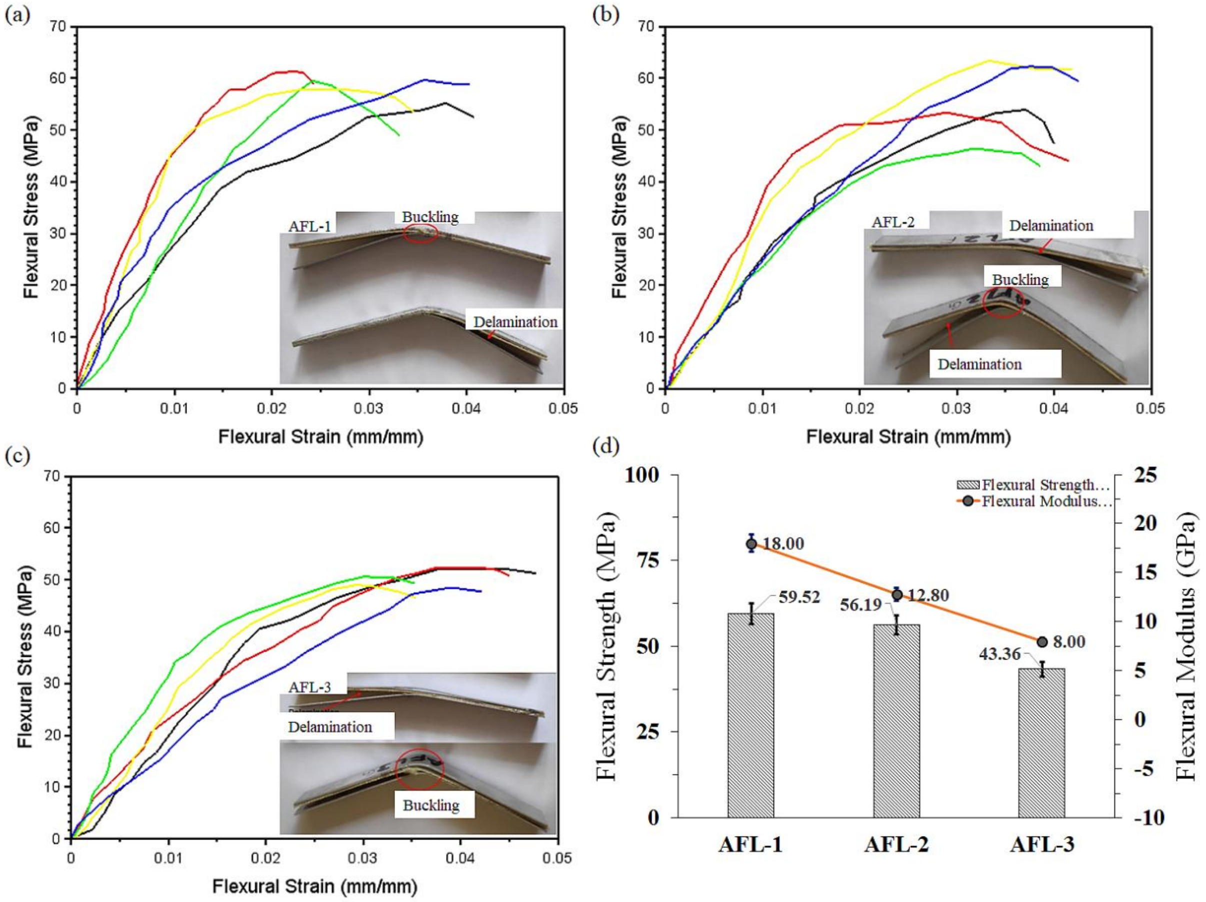

Fig. 4 Flexural Stress-Strain Plots for (a) AFL-1 (b) AFL-2 (c) AFL-3 (d) Flexural strength and Flexural Modulus for the sequences.

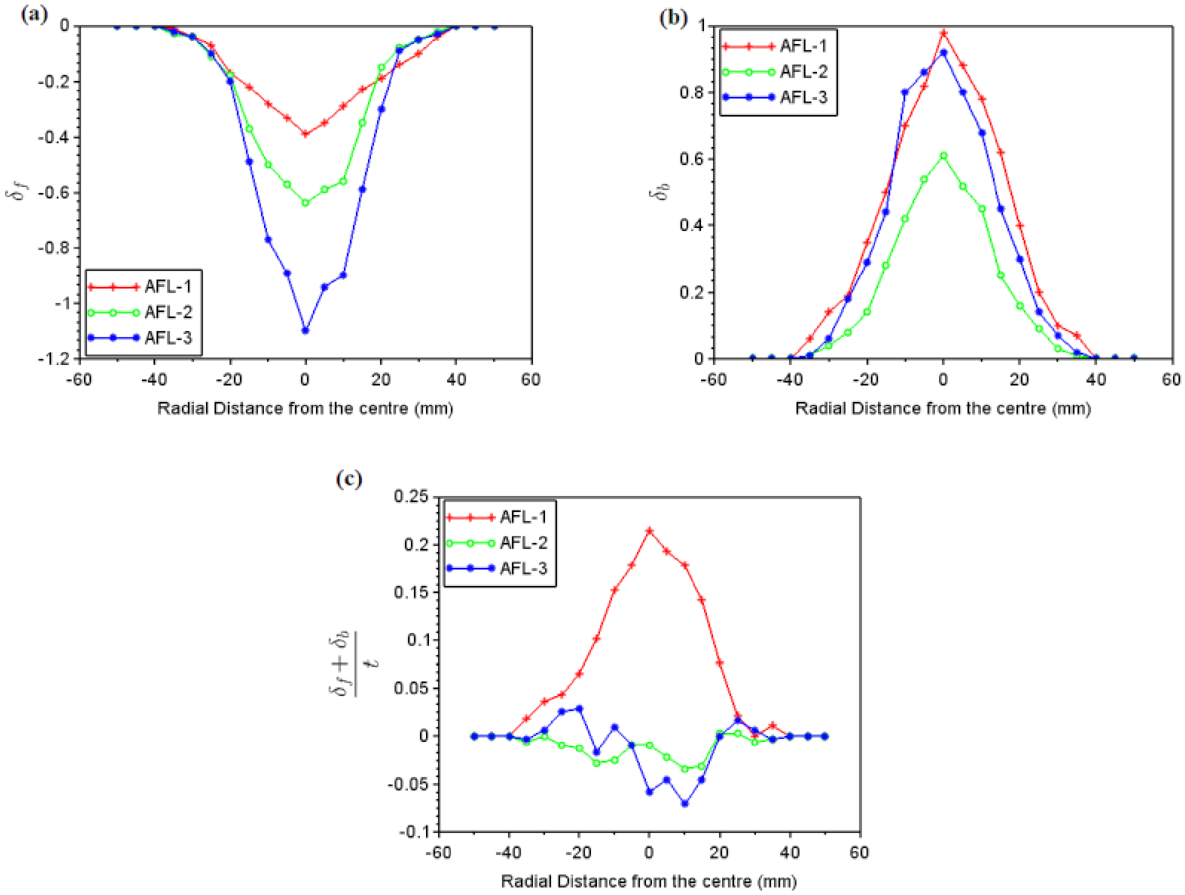

Fig. 5 Deformation profiles for the FMLs (a) Faceplate deformation (b) Backplate deformation (c) Relative Deformation.

Table 6. Shock Parameters for the different sequences.

Sequence	Gas	P_4/P_1 (MPa/MPa)	P_5 (MPa)	t_d (ms)	Mach number
AFL-I	Nitrogen/ Air	4.18/0.07	0.30	15.1	1.99
AFL-2	Nitrogen/ Air	4.24/0.07	0.32	14.4	2.02
AFL-3	Nitrogen/ Air	4.31/0.07	0.34	14.8	2.06

4. Conclusions

The mechanical and shock response of hybrid FMLs comprising AA6061 sheets, and Aramid UHMWPE fabrics sandwiching banana fiber-epoxy ply was investigated. The tensile, and flexural properties were obtained for three configurations of the FMLs. The shock mitigation capability of the three sequences of FMLs was studied by primary shock wave impact inside a shock tube experimental setup. The following conclusion was drawn:

- Including natural fiber plies in FMLs would enable the laminates to be lightweight since AFL-2 and AFL-3 displayed lower density (~15-18%) than AFL-1.
- Addition of natural fibers in form of a chopped strand mat between layers of high-strength, ballistic-grade synthetic fabrics made of aramid and UHMWPE reduces the tensile strength, tensile modulus, flexural strength, and flexural modulus. But there was marginal improvement in the tensile strain to failure in the sequences AFL-2 and AFL-3 containing the banana fiber ply.
- AFL-2 showed the best shock shielding capability among the three sequences followed by AFL-3. This shows that incorporating natural fiber-polymer plies as sandwiched panels in FMLs between synthetic fiber plies is beneficial to mitigate the shock waves.

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Conflict of Interest

The authors declare no conflict of interest.

Supporting information

Not applicable.

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