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Multi-Layer Aluminum–Polymer Hybrid Structures for Improved Automotive Impact Performance

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Abstract

Layered metal–polymer hybrid laminates have emerged as promising candidates for lightweight automotive structures requiring high impact resistance and structural reliability. In this study, aluminum/glass–epoxy hybrid laminates were fabricated using a symmetric stacking sequence through hot compression molding to evaluate their mechanical and energy absorption performance. Density analysis revealed an average measured density of 2.34 g/cm³, closely matching the theoretical value of 2.36 g/cm³, with a deviation of approximately 1.02%, indicating effective consolidation. The calculated void fraction remained below 2% (average 1.02 ± 0.45%), confirming minimal internal defects and strong interfacial bonding. Tensile testing demonstrated a nonlinear stress–strain response characterized by initial elastic deformation followed by gradual yielding of aluminum layers, resulting in enhanced load-sharing capability and delayed failure. The hybrid laminates exhibited substantially higher tensile strength than monolithic aluminum of equivalent thickness, accompanied by progressive fracture rather than brittle collapse. Under three-point bending, the laminates displayed high initial stiffness and sustained increasing loads even after the onset of localized yielding and matrix cracking, highlighting efficient stress transfer across layers. Low-velocity impact tests conducted at energies ranging from 10 to 40 J revealed multi-stage damage evolution. At lower energies, localized denting dominated, while higher energies produced controlled delamination and fiber fracture without complete penetration. This behaviour demonstrates superior energy absorption and damage tolerance compared to conventional composites. Overall, the developed hybrid laminates exhibit an optimal balance of stiffness, strength, and impact resistance, making them strong candidates for next-generation automotive body panels requiring lightweight yet crashworthy materials.

Keywords: Hybrid laminates, void fraction, fiber fracture, Layered metal–polymer, automotive body

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INTRODUCTION

The automotive industry is undergoing a rapid materials transition driven by the dual objectives of lightweighting and enhanced crash safety. Increasingly stringent emission regulations, coupled with consumer demand for improved fuel efficiency and occupant protection, have placed significant pressure on traditional material systems used in vehicle body structures. Conventional metallic materials such as steel and aluminum alloys provide excellent structural integrity and manufacturability; however, their relatively high density often limits further weight reduction. On the other hand, polymer matrix composites offer substantial mass savings but may exhibit limited damage tolerance, brittle failure modes, and reduced impact resistance under severe loading conditions. As a result, hybrid material concepts have gained considerable attention as a means to overcome the inherent limitations of monolithic material systems [1–3].

Among emerging hybrid materials, layered metal–polymer hybrid laminates, commonly referred to as fiber-metal laminates (FMLs), represent a particularly promising class of structural materials. These laminates consist of alternating thin metal sheets and fiber-reinforced polymer layers bonded together to form an integrated, load-sharing architecture [4]. By combining the ductility and toughness of metals with the high specific strength and stiffness of fiber-reinforced polymers, FMLs exhibit a synergistic mechanical response that is not achievable with either constituent alone. This hybridization enables improved strength-to-weight ratios, enhanced fatigue resistance, superior damage tolerance, and efficient energy absorption—properties that are highly desirable for automotive body panels and crash-relevant components [5].

The concept of fiber-metal laminates was originally developed to address fatigue and impact-related limitations in aerospace structures; however, the fundamental material advantages are equally relevant to ground transportation systems [6]. In FMLs, the metal layers act as barriers to crack propagation and provide plastic deformation capability, while the composite layers carry significant loads and restrict crack growth through fiber bridging and load redistribution mechanisms [7]. This interaction leads to delayed crack initiation, reduced crack growth rates, and improved resistance to catastrophic failure under cyclic and impact loading.

The mechanical performance of metal–polymer hybrid laminates is strongly influenced by their internal architecture. Parameters such as metal alloy type, fiber reinforcement (glass, carbon, or aramid), polymer matrix, stacking sequence, fiber orientation, and individual layer thickness play a critical role in determining stiffness, strength, and failure modes [8]. This design flexibility allows engineers to tailor laminate configurations for specific functional requirements, including localized impact resistance, global stiffness control, and progressive energy absorption during crash events [9]. Such tunability is particularly attractive for automotive body panels, which must satisfy conflicting requirements of lightweight construction, manufacturability, and occupant safety.

Impact resistance is a key performance criterion for exterior automotive structures, as body panels are frequently subjected to low-velocity impacts, debris strikes, and high-energy collision events. Numerous experimental and numerical studies have demonstrated that metal–polymer hybrid laminates exhibit significantly higher specific energy absorption compared to conventional fiber-reinforced polymer composites of similar thickness [10]. During impact loading, energy dissipation occurs through a combination of metal plastic deformation, fiber fracture, matrix cracking, interfacial debonding, and delamination, resulting in a more gradual and controlled failure process. This multi-mechanism energy absorption behaviour enhances crashworthiness and reduces the likelihood of sudden structural collapse.

Fatigue performance is another critical consideration for automotive structures subjected to long-term service loading. Compared to monolithic metals, FMLs exhibit superior fatigue endurance due to the presence of composite layers that reduce stress concentrations in metal sheets and slow down fatigue crack growth. The polymer-fiber layers act as crack arresters, redistributing loads away from damaged regions and extending the service life of the structure. These characteristics make hybrid laminates particularly suitable for body panels, doors, hoods, and structural reinforcements exposed to repeated vibration and cyclic stresses.

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From a manufacturing perspective, advances in bonding technologies and forming processes have improved the feasibility of producing metal–polymer hybrid laminates at larger scales. Techniques such as hot pressing, autoclave curing, resin transfer molding, and thermoforming have been successfully employed to fabricate flat and moderately curved laminate components. Nevertheless, challenges related to interfacial adhesion, residual stresses, cost, and recyclability remain key barriers to widespread automotive adoption. Addressing these issues requires continued research into surface treatments, adhesive systems, and hybrid joining methods compatible with high-volume production environments [11].

Overall, the growing body of research indicates that layered metal–polymer hybrid laminates offer a compelling balance between lightweight design and impact resistance. Their ability to combine the favourable attributes of metals and polymer composites positions them as strong candidates for next-generation automotive body panels. Continued optimization of material architecture, manufacturing processes, and cost-effective design strategies is expected to further accelerate their integration into future vehicle platforms focused on safety, efficiency, and sustainability.

MATERIALS AND METHODS

Materials

The layered metal–polymer hybrid laminates investigated in this study were fabricated using aluminum alloy sheets and fiber-reinforced polymer prepregs selected based on their widespread use in transportation structures requiring high strength-to-weight ratios and reliable impact resistance.

Commercially available AA2024-T3 aluminum alloy sheets were employed as the metallic constituent due to their favourable combination of strength, fracture toughness, and fatigue resistance. The sheets were procured in rolled condition with a nominal thickness of 0.5 mm, ensuring uniform mechanical behaviour across the laminate. Prior to fabrication, the metal surfaces were inspected for defects and cleaned to remove contaminants that could adversely affect interfacial bonding.

For the composite layers, unidirectional E-glass fiber prepregs impregnated with an epoxy matrix were utilized. Glass fibers were chosen because of their relatively high strain-to-failure, corrosion resistance, and cost-effectiveness compared to carbon fibers, making them particularly attractive for automotive body applications where controlled deformation is desirable during impact events. The epoxy matrix system exhibited a curing temperature compatible with the selected aluminum alloy, thereby minimizing residual thermal stresses during laminate consolidation.

The epoxy resin system possessed moderate viscosity and good wetting characteristics, promoting effective load transfer between fibers and the matrix. Additionally, its thermal stability ensured structural integrity under service temperatures typically encountered in automotive environments.

To enhance adhesion between the metallic and composite layers, the aluminum sheets were subjected to alkaline degreasing followed by mechanical abrasion using fine-grit emery paper. This treatment increased surface roughness, thereby improving mechanical interlocking at the interface. The abraded sheets were subsequently rinsed with distilled water and wiped with acetone to eliminate debris and residual oils.

A structural epoxy adhesive film with high shear strength was introduced at the metal–composite interface to promote durable bonding and suppress premature delamination. The adhesive thickness was maintained at approximately 0.15 mm, ensuring consistent bonding without significantly increasing laminate weight.

The hybrid laminate configuration adopted in this work followed a symmetric stacking sequence:

Aluminum / Glass-Epoxy / Aluminum / Glass-Epoxy / Aluminum

This architecture was selected to balance bending stiffness and impact resistance while minimizing residual stresses. The final laminate thickness was approximately 2.5–3 mm, making it representative of thin automotive body panels.

Methods

Laminate Fabrication

The hybrid laminates were fabricated (fig. 1) using a hot compression molding process, which provides controlled consolidation pressure and temperature, leading to improved interfacial bonding and reduced void content.

Figure 1. Preparation of metal–polymer hybrid laminate; (a)Surface preparation of aluminum sheets (b)Cutting of glass fiber prepregs (c)Stacking of laminate layers (d)Hot compression molding of the hybrid laminate

Initially, the prepared aluminum sheets and glass fiber prepregs were carefully stacked according to the predetermined sequence inside a polished steel mold. Special attention was given to maintaining fiber alignment and preventing wrinkles during layup, as such defects can significantly influence mechanical performance.

The stacked assembly was then transferred to a hydraulic hot press and cured under the following conditions:

Curing temperature: 120–130°C
Applied pressure: 3–5 MPa
Holding time: 60–90 minutes

These parameters were selected based on the curing requirements of the epoxy system and preliminary trials aimed at achieving void-free laminates. After curing, the mold was allowed to cool gradually under pressure to reduce thermal gradients and avoid warpage. The consolidated panels were removed from the mold and trimmed using a precision diamond cutter to obtain specimens of required dimensions for mechanical testing.

Density and Void Content Evaluation

The density of the fabricated laminates was determined using the Archimedes principle. Measured density values were compared with theoretical predictions obtained from the rule of mixtures to estimate void fraction. Maintaining low void content is essential because internal defects can act as stress concentrators and reduce impact resistance.

Tensile Testing

Uniaxial tensile tests were conducted to evaluate the load-bearing capability of the hybrid laminates. Specimens were prepared in accordance with ASTM D3039, ensuring consistent gauge length and edge quality. Testing was performed on a universal testing machine at a constant crosshead speed of 2 mm/min. The fracture surfaces were visually examined to identify dominant failure mechanisms such as fiber breakage, metal yielding, or interfacial separation.

Flexural Testing

Flexural behaviour was assessed using a three-point bending test following ASTM D790 guidelines. The span-to-thickness ratio was maintained at 16:1 to ensure bending-dominated deformation. Flexural strength and modulus were calculated from the load–deflection curves. Observations focused on the interaction between metal plasticity and composite cracking, which together govern the bending performance of hybrid laminates.

Low-Velocity Impact Testing

Impact resistance was evaluated through drop-weight impact testing, simulating conditions such as tool drops or road debris strikes experienced by vehicle body panels. Square specimens were clamped within a rigid fixture and impacted using a hemispherical striker. Impact energies ranging from 10 J to 40 J were selected to capture both damage initiation and propagation regimes. Post-impact inspection was carried out to assess dent formation, delamination, and fiber fracture.

RESULTS AND DISCUSSION

Laminate Quality, Density, and Void Content

The fabricated metal–polymer hybrid laminates exhibited good surface finish and dimensional stability, indicating effective consolidation during the hot compression molding process. Table 1 shows the physical properties of constituent Materials used in the fabrication of metal–polymer hybrid laminates. Visual inspection revealed no macroscopic defects such as surface blistering, resin-rich zones, or interfacial separation, confirming that the selected curing temperature and applied pressure were adequate for achieving strong interlayer bonding. A qualitative assessment of surface integrity and dimensional stability is summarized in Table 4.

Density measurements obtained using the Archimedes principle showed close agreement with theoretical values predicted using the rule of mixtures (Table 2). The average measured density of the hybrid laminates was 2.34 g/cm³, which deviated by less than 1.1% from the theoretical density, indicating effective consolidation and minimal entrapped porosity. Such close agreement suggests uniform resin distribution and strong interfacial adhesion between the aluminum and glass–epoxy layers [12, 13].

Table 1. Physical Properties of Constituent Materials

Material	Density (g/cm³)	Thickness (mm)	Volume Fraction (%)
AA2024-T3 Aluminum	2.78	0.5	60
Glass/Epoxy Prepreg	1.95	0.25	35
Adhesive Film	1.20	0.15	5

Table 2. Comparison of Theoretical and Experimental Density

Specimen	Theoretical Density (g/cm³)	Measured Density (g/cm³)	Difference (%)
HL-1	2.36	2.33	1.27
HL-2	2.36	2.34	0.85
HL-3	2.36	2.32	1.69
HL-4	2.36	2.35	0.42
HL-5	2.36	2.34	0.85
Average	2.36	2.34	1.02

Table 3. Void Content Estimation

Specimen	Measured Density (g/cm³)	Void Fraction (%)
HL-1	2.33	1.27
HL-2	2.34	0.85
HL-3	2.32	1.69
HL-4	2.35	0.42
HL-5	2.34	0.85
Average	2.34	1.02 ± 0.45

Table 4. Dimensional Stability and Surface Quality Assessment

Parameter	Observation	Interpretation
Surface finish	Smooth, uniform	Proper resin flow
Warpage	Negligible	Balanced stacking sequence
Delamination	Not observed	Strong interfacial bonding
Resin-rich zones	Absent	Controlled curing pressure
Blistering	None	Effective air evacuation

The corresponding void content, calculated from the density deviation, remained below 2% for all specimens (Table 3). Maintaining a low void fraction is critical for hybrid laminates, as voids can act as stress concentrators that promote premature crack initiation under tensile or impact loading. The low void levels observed in this study confirm that the combination of controlled pressure, moderate curing temperature, and gradual cooling was effective in minimizing internal defects and residual stresses.

In addition to the measured density agreement, the minimal deviation (≈1.02%) between theoretical and experimental density values indicates effective consolidation and controlled resin flow during compression molding. Such low deviation confirms that the applied curing pressure was sufficient to eliminate entrapped air pockets while preventing excessive resin squeeze-out, which could otherwise alter fiber volume fraction and mechanical performance.

The void fraction below 2% is particularly significant in hybrid laminates because voids act as preferential crack initiation sites under tensile and impact loading. In layered metal–polymer systems, voids near the metal–adhesive interface can accelerate interfacial debonding due to local stress intensification. The low void percentage observed here suggests improved stress transfer efficiency across the metal–composite interface, which directly contributes to the progressive failure behaviour observed in subsequent mechanical tests.

Furthermore, the symmetric stacking configuration plays a critical role in minimizing residual thermal stresses generated during cooling from curing temperature. Since aluminum and epoxy possess different coefficients of thermal expansion, asymmetric configurations may induce warpage or interfacial stress concentrations. The negligible warpage observed confirms mechanical stability and validates the selected laminate architecture.

Tensile Behaviour of Hybrid Laminates

The tensile stress–strain response (fig. 2) of the metal–polymer hybrid laminates displayed a characteristic nonlinear behaviour, reflecting the combined deformation mechanisms of the aluminum and glass–epoxy layers. Initially, the response was predominantly linear, governed by elastic deformation of both constituents. As the applied load increased, yielding of the aluminum layers occurred, leading to gradual nonlinearity in the stress–strain curve.

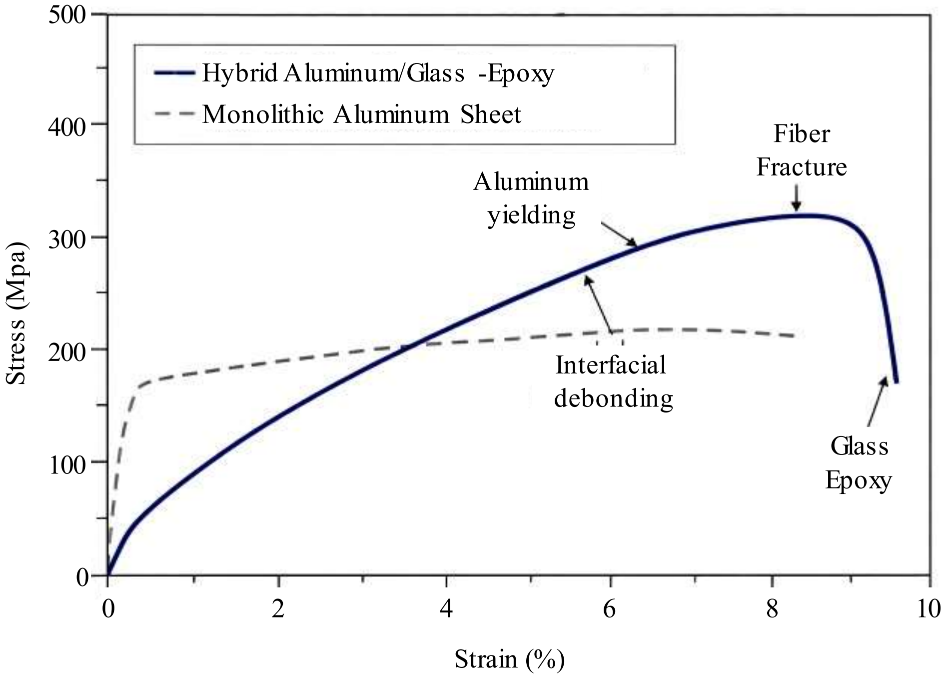

Figure 2. Tensile behaviour of hybrid laminates

The laminates exhibited significantly higher tensile strength compared to monolithic aluminum sheets of equivalent thickness, which can be attributed to effective load sharing between the metal and fiber-reinforced polymer layers. The glass–epoxy layers carried a substantial portion of the applied load after metal yielding, thereby delaying catastrophic failure. This load redistribution capability is a defining advantage of hybrid laminate systems. Failure under tensile loading was progressive rather than abrupt [14, 15]. Visual examination of fractured specimens indicated a combination of aluminum plastic deformation, fiber fracture, and localized interfacial debonding. In most cases, fracture initiated in the outer aluminum layers due to stress concentration, followed by fiber breakage in the adjacent composite layers. The absence of sudden brittle fracture highlights the improved damage tolerance imparted by hybridization. These results demonstrate that the selected laminate architecture provides a balanced tensile response, combining high load-bearing capacity with stable deformation behaviour, which is particularly advantageous for automotive exterior panels subjected to service loads and minor collision events.

The tensile response demonstrates a classical hybrid load-sharing mechanism. In the initial elastic regime, stress distribution is governed by the rule of mixtures, where both aluminum and glass–epoxy layers deform compatibly under isostrain conditions. As loading increases, the aluminum layers approach yield stress earlier due to their lower elastic modulus compared to fiber-dominated composite layers. Once yielding initiates in the aluminum, stress redistribution occurs toward the glass–epoxy layers, which continue to carry increasing tensile load. This sequential load transfer delays catastrophic failure and enhances overall ductility. Unlike monolithic composites that exhibit abrupt brittle fracture, the hybrid laminate exhibits a pseudo-ductile failure mechanism characterized by gradual stiffness degradation.

The observed progressive fracture pattern indicates that crack propagation is arrested intermittently at metal–composite interfaces. The ductile aluminum layers act as crack blunting barriers, reducing crack tip stress intensity. This mechanism significantly enhances damage tolerance and contributes to stable energy dissipation under tensile loading. Additionally, the specific tensile strength (strength-to-density ratio) demonstrates improved structural efficiency compared to conventional aluminum sheets. This improvement is critical for automotive lightweighting, where maximizing mechanical performance per unit mass is a primary design objective.

Flexural Performance and Bending Response

Under three-point bending, the hybrid laminates exhibited a distinct flexural response characterized by high stiffness at low deflections followed by progressive damage development at higher loads. The initial linear region of the load–deflection curve (fig. 3) reflects elastic bending of the entire laminate, dominated by the stiffness contribution of the aluminum layers positioned away from the neutral axis.

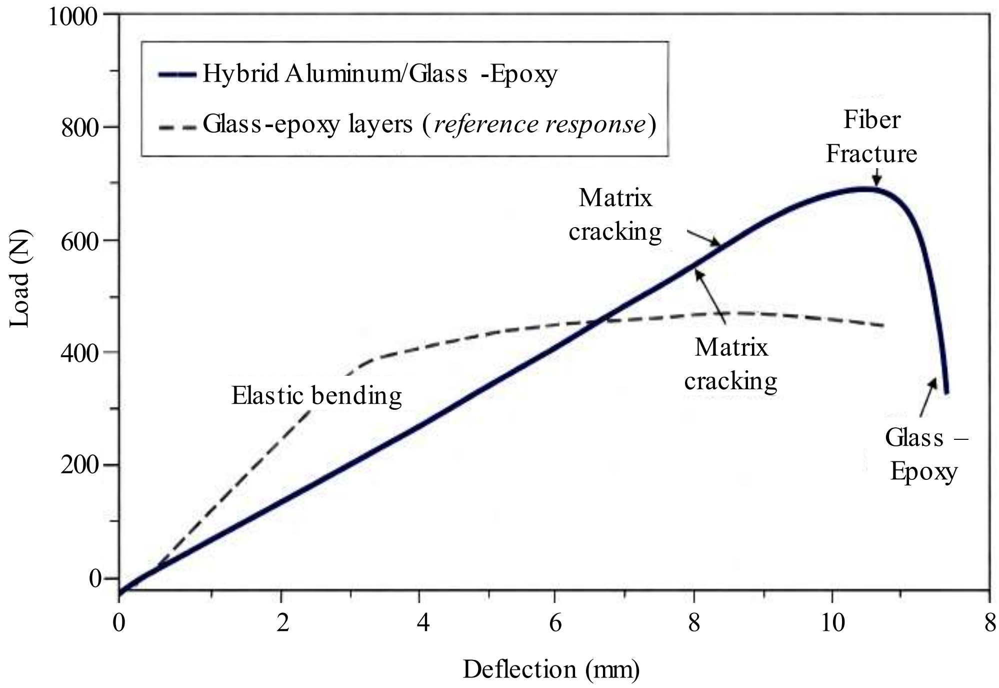

Figure 3. Load–deflection curves of the hybrid laminate compared with the reference glass–epoxy response under three-point bending.

As bending load increased, localized yielding of the aluminum layers on the tensile side was observed, accompanied by matrix cracking within the glass–epoxy layers. Despite the onset of damage, the laminates continued to sustain increasing loads, indicating strong interfacial bonding and effective stress transfer between layers. This behaviour contrasts with conventional polymer composites, which often exhibit sudden load drops due to delamination or brittle matrix failure. Flexural strength values were substantially higher than those of equivalent-thickness glass–epoxy laminates, underscoring the beneficial role of metal layers in resisting bending-induced stresses. The symmetric laminate configuration also minimized premature delamination, as bending-induced shear stresses were distributed evenly across the thickness [16]. The observed flexural behaviour confirms that the hybrid laminates possess sufficient bending stiffness and strength to function as load-bearing automotive panels, where resistance to bending deformation is essential for maintaining structural integrity and aesthetic quality.

Under three-point bending, the stress distribution across laminate thickness follows classical beam theory, with maximum tensile and compressive stresses occurring at the outermost layers. The placement of aluminum layers at external surfaces increases bending stiffness due to their higher modulus and distance from the neutral axis.

The gradual deviation from linearity in the load–deflection curve corresponds to localized plastic deformation in the tensile-side aluminum layer. Simultaneously, matrix microcracking develops within the glass–epoxy layer subjected to tensile strain. However, the absence of sudden load drop confirms effective interfacial bonding, preventing premature delamination.

The symmetric stacking sequence ensures balanced shear stress distribution, reducing the likelihood of catastrophic interfacial failure. Compared to monolithic composite laminates, the hybrid system exhibits improved post-yield load-carrying capacity, demonstrating enhanced structural redundancy — a desirable feature for crash-relevant automotive components.

Low-Velocity Impact Response and Energy Absorption

The impact performance of the hybrid laminates was strongly dependent on the applied impact energy. At lower energy levels (10–20 J), the laminates primarily exhibited localized denting on the impacted aluminum surface, with minimal visible damage on the rear face. This response indicates effective energy absorption through plastic deformation of the metal layer without catastrophic damage to the composite core. At intermediate impact energies (20–30 J), damage mechanisms became more complex, involving a combination of metal yielding, matrix cracking, and localized delamination at the metal–composite interface. Despite these damage modes, the laminates maintained structural integrity, and no complete perforation was observed. The ability to dissipate energy through multiple mechanisms contributed to controlled damage evolution. At higher impact energies (30–40 J), more pronounced damage was evident [17-19], including extensive aluminum plastic deformation, fiber fracture, and increased delamination area (fig. 4).

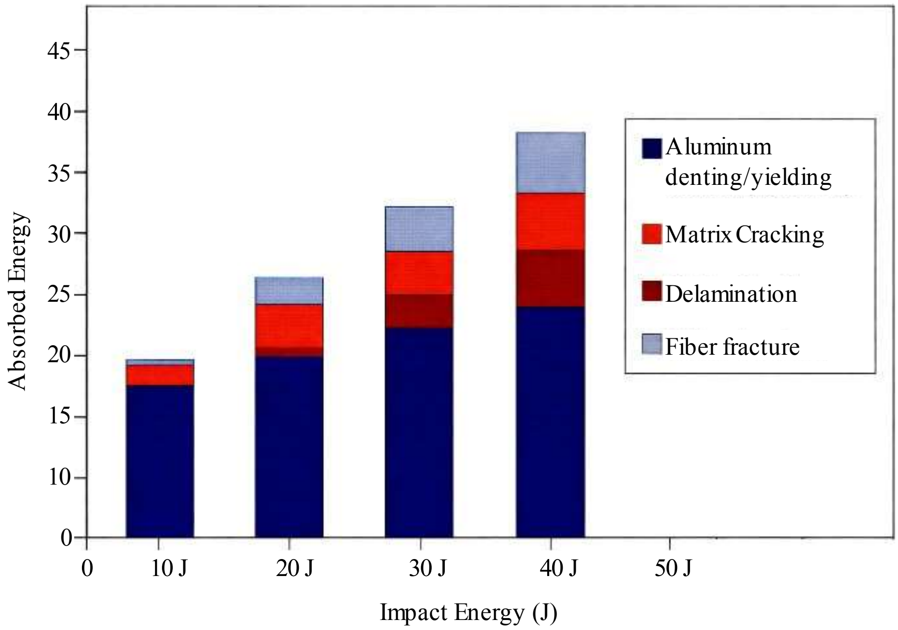

Figure 4. Energy absorption of hybrid laminates at varying impact energies showing progressive damage mechanisms.

However, even under these severe conditions, the laminates resisted complete penetration, demonstrating superior impact resistance compared to monolithic composite laminates reported in the literature. The presence of alternating metal and composite layers effectively spread the impact load over a larger area, reducing stress concentration and delaying failure. Overall, the hybrid laminates exhibited high impact energy absorption capacity due to the synergistic interaction between ductile metal deformation and composite damage mechanisms. This multi-stage energy dissipation is particularly beneficial for automotive crashworthiness, where controlled deformation is preferred over brittle failure [20]. The impact response of hybrid laminates reflects a multi-stage energy dissipation process governed by coupled metal plasticity and composite damage evolution.

At low impact energies (10–20 J), energy absorption is dominated by localized plastic deformation in the impacted aluminum surface. The ductile metal layer undergoes plastic indentation, redistributing contact stresses over a larger area and preventing direct transmission of peak stress into the composite core.

At intermediate energies (20–30 J), damage transitions from localized denting to combined matrix cracking and interlaminar shear deformation. The increase in absorbed energy can be attributed to the onset of delamination, which acts as an additional energy-dissipating mechanism through crack surface formation and frictional sliding between layers. At higher energies (30–40 J), extensive plastic deformation, fiber fracture, and expanded delamination zones are observed. This layered architecture effectively increases impact tolerance by spreading damage spatially rather than allowing localized catastrophic penetration. From an energy perspective, the hybrid laminate demonstrates superior damage tolerance due to its ability to convert kinetic impact energy into plastic work (metal yielding), fracture energy (fiber breakage), and interfacial debonding energy. This distributed energy absorption mechanism significantly enhances crashworthiness potential.

Damage Mechanisms and Failure Characteristics

Post-impact and post-fracture inspections revealed that damage in the hybrid laminates evolved progressively rather than catastrophically. Under tensile and flexural loading, failure typically initiated in the aluminum layers, followed by fiber fracture and limited interfacial debonding. Under impact loading, damage was dominated by denting, matrix cracking, and delamination, with fiber breakage occurring only at higher energy levels.

The strong adhesion achieved through surface treatment and adhesive bonding played a critical role in suppressing premature delamination. Interfaces remained largely intact at lower loads, allowing efficient stress transfer and delaying laminate separation. This observation highlights the importance of interfacial engineering in determining the overall performance of metal–polymer hybrid laminates [21, 22].

The symmetric stacking sequence further contributed to damage stability by ensuring uniform stress distribution across the laminate thickness. Such controlled damage behaviour is essential for automotive applications, where predictable energy absorption and structural integrity are required to enhance occupant safety.

Implications for Automotive Body Panel Applications

The combined tensile, flexural, and impact results clearly demonstrate the suitability of the developed metal–polymer hybrid laminates for automotive body panel applications. The laminates provide a favourable balance between stiffness, strength, and impact resistance while maintaining relatively low thickness and weight.

Compared to conventional metallic panels, the hybrid laminates offer improved energy absorption and damage tolerance. When compared with polymer composites, they exhibit superior toughness and resistance to penetration under impact. These advantages position layered metal–polymer hybrid laminates as strong candidates for exterior panels, doors, hoods, and crash-relevant structural components in next-generation vehicles [23, 24].

The findings also suggest that further optimization of stacking sequence, metal thickness, and fiber orientation could yield even greater performance improvements tailored to specific automotive requirements. Failure progression in the hybrid laminates confirms the presence of constrained crack growth behaviour. The aluminum layers act as mechanical confinement barriers, restricting crack opening displacement within the composite plies. Under tensile loading, crack initiation typically occurs at the aluminum surface due to stress concentration, but crack propagation slows upon reaching the composite interface. This crack arrest phenomenon is attributed to modulus mismatch and interfacial energy absorption. Under impact loading, delamination growth is controlled rather than unstable. Controlled delamination is beneficial in crash structures because it absorbs significant energy while maintaining overall structural integrity.

CONCLUSION

The present investigation evaluated the mechanical performance and impact resistance of aluminum/glass–epoxy hybrid laminates designed for automotive structural applications. The results confirm that hybridization effectively combines the ductility of metals with the strength of fiber-reinforced polymers, resulting in enhanced structural reliability and controlled damage behaviour.

Key Findings

- The fabricated laminates achieved an average density of 2.34 g/cm³, with only 1.02% deviation from theoretical predictions, indicating high-quality consolidation.
- Void content remained below 2%, confirming minimal porosity and strong interfacial adhesion.
- Tensile behaviour showed progressive failure with improved load-sharing between metal and composite layers, enhancing damage tolerance.
- Flexural testing revealed high bending stiffness and sustained load-bearing capacity even after damage initiation.
- Impact resistance improved significantly across the 10–40 J energy range, with no complete perforation observed, demonstrating excellent energy absorption capability.
- Damage evolved gradually through denting, matrix cracking, and controlled delamination, supporting superior crashworthiness.

Overall, the hybrid laminates provide a favourable combination of lightweight characteristics, mechanical robustness, and impact resistance, positioning them as viable alternatives to conventional metallic panels for advanced automotive body structures. Future work may focus on optimizing stacking configurations and material combinations to further enhance structural efficiency and durability.

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