

RESEARCH ARTICLE

Assessing the impact resistance and damage tolerance of Aluminium composite fibre metal laminates under low-velocity impact test

M. F. Rani^{1*}, M. R. M. Rejab², N. Ab. Razak², M. I. Ibrahim¹, M. Z. Azir¹, Z. Zaulkafilai¹

¹ Faculty of Engineering and Technology, DRB-HICOM University of Automotive Malaysia, 26607 Pekan, Pahang, Malaysia

Phone: +609 431 5000, Fax: +609 431 5555

² Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, Al-Sultan Abdullah, 26600 Pekan, Malaysia

ABSTRACT - The automotive industry requires materials that are lightweight to enhance fuel efficiency while optimizing safety standards, alongside having high impact resistance to improve the vehicle's overall safety features. This study focuses on evaluating the low-velocity impact performance of fibre metal laminates (FMLs) with different configurations to identify the most suitable crash-resistant structures for vehicles. Five FML configurations were fabricated using 2024-T3 aluminum with CFRP (B2), GFRP (B1), SRPP (B3), and hybrid combinations consisting of CFRP-GFRP (B4) and SRPP-GFRP (B5) in 3/2 layered structures that were tested under low-velocity impact at 2.7-4.5 m/s using drop-weight testing with force, displacement, and energy absorption measurements. B5 recorded the highest impact force of 13827.1 N due to the synergistic bonding of thermoplastic SRPP and the GFRP layer. B1 exhibited the best energy absorption of 86.4 J, outperforming other configurations by 10% due to the glass fibre's strain-to-failure characteristics, which allow for significant plastic deformation. B2 lagged in both energy absorption and force at 78.5 J and 11476.2 N, respectively, due to the brittleness of the carbon fibre. The ranking for energy absorption was B1 > B4 > B2 > B5 > B3, with all configurations showing proportional increases in strength with velocity. Configuration B5, composed of a hybrid SRPP-GFRP, demonstrated the best impact resistance, outperforming CFRP systems by 20.5% in force resistance. At the same time, GFRP-based FMLs (B1) exhibited better energy absorption, with a value of 86.4 J, which is critical for managing crash energy. This illustrates that the selection of materials relies on the designated zone of an automobile intended to endure a collision, prioritizing either force resistance or energy dissipation.

ARTICLE HISTORY

Received : 29th Oct. 2024
 Revised : 14th June 2025
 Accepted : 03rd Sept. 2025
 Published : 30th Sept. 2025

KEYWORDS

Fibre metal laminate
Low-velocity impact test
 CFRP
 GFRP
 SRPP

1. INTRODUCTION

Fibre metal laminates are a type of hybrid materials that integrate the advantages of metal alloys and fibre-reinforced composites [1–3]. The unique structure of FMLs allows them to exhibit superior mechanical properties, particularly under low-velocity impact conditions. This response is particularly critical for applications in the aerospace and automotive industries, where impact resistance is a primary concern. Fibre metal laminates (FML) are advanced composite materials that combine the lightweight and high-strength properties of fibre-reinforced polymers with the toughness and durability of metal layers. By integrating the advantages of metal and composite materials, these laminates were developed that possess better mechanical qualities and damage resistance [4–6]. Within the automobile industry, FMLs offer a promising solution for the process of vehicle lightweighting. The development of lightweight materials is considered crucial for enhancing fuel efficiency and minimizing emissions. The implications of this research are significant for developing vehicle structures that incorporate new technological features while maintaining severe safety and efficiency standards. FMLs are particularly advantageous for the automotive industry to use in structural components such as door panels, roof structures, and floor panels, which require impact resistance and weight reduction. With these FMLs, automotive manufacturers can achieve their target of reducing vehicle weight by 20-30% [7–9]. In safety systems applications, FMLs can be used in crumple zones and impact-absorbing structures designed for controlled energy dissipation to protect occupants. FMLs are ideal for these applications due to their progressive failure mechanisms, which provide predictable energy absorption. For electric vehicles, FMLs are crucial in battery protection systems because they offer multifunctional impact resistance, a lightweight composition, and fire resistance, providing comprehensive protection for energy storage systems. These materials combine the high strength and stiffness of metals with the lightweight and damage tolerance of fibre-reinforced composites [10].

FMLs are designed by bonding metal layers with fibre-reinforced composite layers to create a laminate structure. The mechanical properties of FMLs can be tailored by adjusting the thickness and the number of layers of metal and composite material. The investigation of FMLs under low-velocity impact conditions reveals a complex interplay of damage mechanisms and material responses. FMLs combine the lightweight properties of fibre-reinforced polymers with the toughness of metals. They are increasingly utilized in various applications, including aerospace and automotive industries,

*CORRESPONDING AUTHOR | M. F. Rani | ✉ fadhil@dhu.edu.my

due to their superior impact resistance and mechanical properties. Several studies have shown that the primary failure mode in FMLs subjected to low-velocity impacts is delamination, which occurs at the interfaces between the composite and metal layers. This delamination is primarily attributed to interlaminar shear stresses that develop during impact events. The extent of damage varies significantly with the impact energy and the specific laminate configuration used. Different types of damage, including fibre and matrix cracks, as well as metal cracks, were prevalent, depending on the applied impact energy [11, 12]. The impact resistance of FMLs has been extensively studied using various impactor geometries, with hemispherical impactors being the most common in low-velocity impact tests [13–16]. Research has demonstrated the critical nature of impact resistance in composite structures, noting that thermoplastic-based FMLs demonstrated notable resistance to perforation. The influence of fibre orientation on the impact performance of FMLs has been a focal point of research. Optimizing fibre orientation can enhance the overall impact performance of these laminates. Although there has been substantial investigation into the impact behavior of FML composites, studies have concentrated on fibre-reinforced laminated composites layered with hybrid composite metal laminations [17–22]. The hybrid FML configurations incorporating multiple fibre variants, such as Carbon Fibre-Reinforced Polymer layered with Glass Fibre-Reinforced Polymer (CFRP-GFRP) and Self-Reinforced Polypropylene layered with Glass Fibre-Reinforced Polymer (SRPP-GFRP), with metal, have not been previously reported, even though they could provide optimized performance with synergistic effects. These laminates are designed to improve mechanical strength while minimising weight, improving impact resistance, and consequently facilitating the automotive industry's stringent weight reduction requirements while maintaining safety and structural integrity [10]. The objective of this study is to evaluate and compare the low-velocity impact performance of different fibre metal laminate configurations under varying impact velocities ranging from 2.7 to 4.5 m/s, to investigate the impact response characteristics of carbon fibre, glass fibre, and SRPP-based FML systems. At the same time, analyze the energy absorption mechanisms and failure progression patterns in different FML configurations.

2. MATERIAL AND METHODS

The study utilized three composite materials with specific mechanical properties essential for impact analysis. The fibre metal laminates, with a rectangular shape dimension of 15 cm x 15 cm, as illustrated in Figure 1, were produced using the manual layup technique and compression moulding technique. The hand layup technique is particularly advantageous for producing FMLs because it allows for precise control over the orientation and arrangement of the fibre layers. The quality of the composite material is significantly influenced by the manufacturing technique employed. The comparative study of glass fibre reinforced plastics (GFRP) produced through hand layup, vacuum bagging, and vacuum infusion demonstrated that hand layup can yield satisfactory tensile strength and interlaminar bonding when executed correctly [23, 24].

The base material used for all laminates is aluminum alloy 2024-T3, whose key mechanical properties are listed in Table 1. Reinforcements were selected from three different fibres, including plain weave glass fibre, as presented in Table 2. In contrast, the properties of plain weave carbon fibre are shown in Table 3, and self-reinforced polypropylene (SRPP) is summarized in Table 4. These materials were chosen to allow comparisons between thermoset-based (glass and carbon fibre with epoxy) and thermoplastic-based (SRPP with polypropylene film) FMLs, particularly in terms of stiffness, strength, and impact resistance.

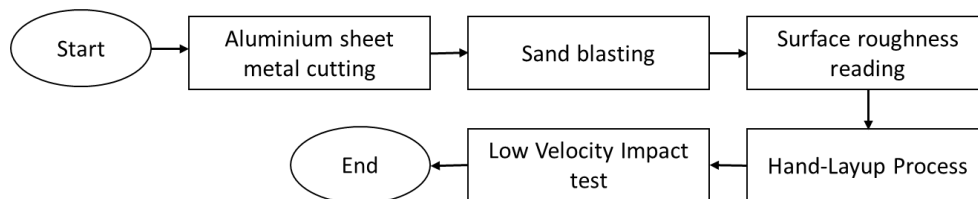


Figure 1. Fabrication process for FML

The fabrication process, illustrated in Figure 1, begins with the surface preparation of aluminum sheets measuring 15 cm x 5 cm, which involves sandblasting to enhance surface roughness. It is followed by cleaning with acetone to remove any contaminants. The application of epoxy and hardener enhances the interlayer adhesion of FMLs, allowing for the sequential layup of aluminum and composite layers with controlled fibre orientation using a thermoset epoxy resin via a controlled hand layup method, tailored to a specific configuration. For SRPP material, the hand layup process is replaced with compression molding using a thin polypropylene (PP) film as an adhesive interlayer. SRPP and metal bond at a temperature of 165°C and pressure of 0.3 MPa for 5 minutes. A hybrid configuration involving SRPP material will utilise both methods to laminate them. Quality control processes for ensuring specimen uniformity involve conducting a visual assessment for possible defects, verifying alignment, and measuring dimensions with digital calipers. The left side of Figure 2 illustrates the 3/2 layered FML design along with its specified dimensions of 150 mm x 150 mm. The right side of Figure 2 shows the manufactured specimen, which confirms that the multi-layer construction has been successfully achieved with good bonding between the layers.

Table 1. Mechanical properties of Al2024 T3

Property	Symbol	Value	Units
Young modulus	E	70 -73	GPa
Poisson's ratio	ν	0.33	-
Yield Strength	σ_y	290-345	MPa
Ultimate Tensile Strength	UTS	440-495	Mpa
Shear Modulus	G	28	Gpa
Shear Strength	τ_{max}	285	Mpa
Elongation at Break	ϵ	10-15	%
Density	ρ	2.78	g/cm ³
Fatigue Strength	σ_f	140	MPa
Hardness, Brinell	HB	120	-

Table 2. Mechanical properties for plain weave glass fibre

Property	Symbol	Value (MPa)
Transverse tensile strength	Y_t	320
Transverse compressive strength	Y_c	260
Longitudinal tensile strength	X_T	320
Longitudinal compressive strength	X_c	260

Table 3. Mechanical properties for plain weave carbon fibre

Property	Symbol	Value
Young's modulus in the longitudinal direction	E_{11}/GPa	48
Young's modulus in the transverse direction	E_{22}/GPa	48
Young's modulus in the thickness direction	E_{33}/GPa	1
In-plane shear modulus	G_{12}/GPa	9
Through-thickness shear modulus	G_{13} and G_{23}/GPa	9
In-plane Poisson's ratio	ν_{12}	0.1
Through-thickness Poisson's ratio	ν_{13} and ν_{23}	0.1
Longitudinal tensile strength	X_{1t}/MPa	550
Longitudinal compressive strength	X_{1c}/MPa	150
Transverse tensile strength	Y_{2t}/MPa	550
Transverse compressive strength	Y_{2c}/MPa	150
Transverse shear strength	S_t/MPa	120
Longitudinal shear strength	S_l/MPa	120

Table 4. Mechanical properties of SRPP

Property	Symbol	Value (MD/CD)	Units
Tensile Modulus	E_t	4200 / 4200	N/mm ²
Tensile Strength	σ_t	120 /120	N/mm ²
Tensile Strain to Failure	ϵ_t	20/ 20	%
Flexural Modulus (flat-wise)	E_f	3500	N/mm ²
Compression Strength (flat-wise)	σ_c	300	MPa
Tensile Impact Strength [20°C / 15J / 2.1mm]	σ_{it}	1000 / 1000	kJ/m ²

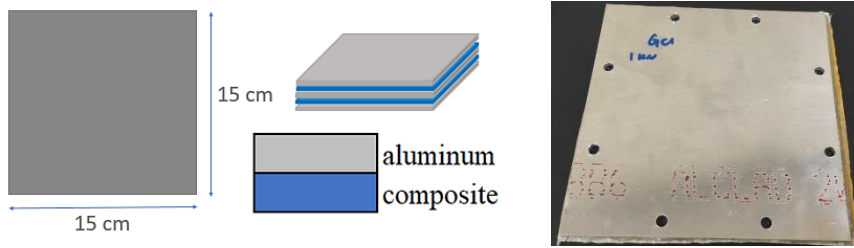


Figure 2. Dimension 3/2 layered FML (Left) and actual sample (Right)

The laminates were then cured at room temperature and treated to a moderate load to apply pressure. To laminate SRPP with metal, a hot press machine is used to melt the thin film, which is then cured in the machine for a predetermined period. The hybrid specimen is developed by combining both approaches. The mechanical characteristics of the constructions were analyzed by manipulating the crosshead velocities at 2.7 m/s, 3.3 m/s, 3.9 m/s, and 4.5 m/s using the drop tower impact machine Instron CEAST 9350, as depicted in Figure 3. The general standard testing procedure for this type of testing is provided by ASTM D7136, which applies to composite materials and includes specific modifications for FML specimens. To facilitate comparison, the fabricated fibre metal laminate (FML) specimens were categorized according to their layup sequence and reinforcement type as summarized in Table 5.

Table 5. Classification FML sample

Sample	Fibre Metal Laminate	Classification	Remarks
B1	AL/GFRP/AL/GFRP/AL	G2A3	-
B2	AL/CFRP/AL/CFRP/AL	C2A3	-
B3	AL/SRPP/AL/SRPP/AL	S2A3	-
B4	AL/CFRP/AL/GFRP/AL	C1G1A3	Hybrid
B5	AL/SRPP/AL/GFRP/AL	S1G1A3	Hybrid

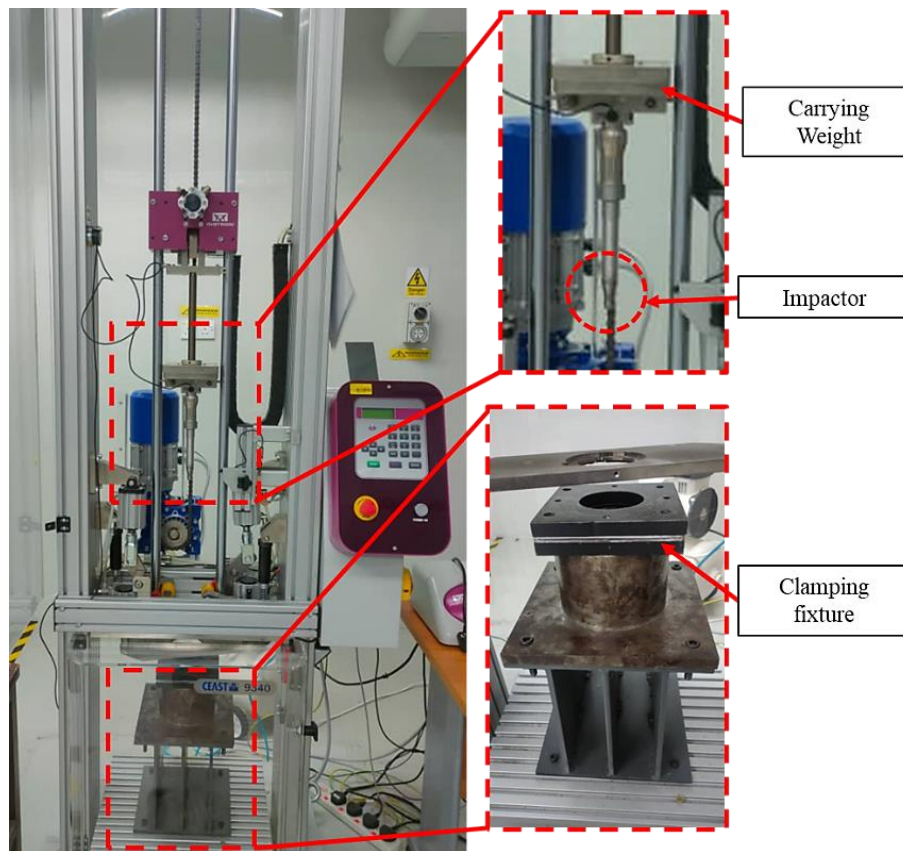


Figure 3. Machine CEAST 9350 for LVI Test

3. RESULTS AND DISCUSSION

Five (5) types of composite material were used under low-velocity impact tests. Figure 4 illustrates the graph of impact response load (N) against central deflection (mm) at 2.7 m/s, 3.3 m/s, 3.9 m/s, and 4.5 m/s, respectively. When the indenter

hits the specimen surface, slip resistance initiates from all the material to uphold the load-carrying capacity at the designated speed of the indenter. The mechanical properties of each material, combined with good bonding, are layered to form a composite that can withstand the load until a certain point, at which the first stage of the bending profile mechanism occurs, signaling that the material will reach its maximum force before delamination occurs. Delamination layer failure, fibre failure, plastic deformation, and crack propagation of the aluminum layer were detected at various crosshead speeds as illustrated in Figure 4.

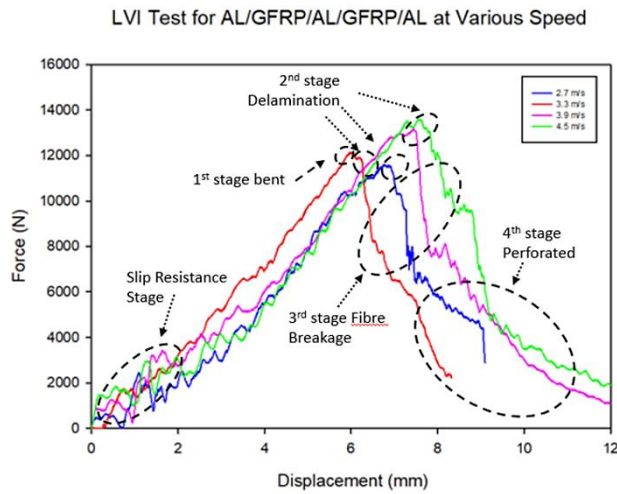


Figure 4. Force against displacement of LVI 3/2 layered Al/Glass fibre metal laminate (G2A3) – (Sample B1)

Figure 5 illustrates the result for a material aluminium sandwich with GFRP (G2A3) at various speeds during a low-velocity impact test. The most significant impact force at a velocity of 3.9 m/s with a 30 kN load was approximately 13161.4 N. Observation indicates that the maximum force increases to around 13602.4 N when the impact velocity is raised to 4.5 m/s. This increase in force is attributed to strain rate effects, where higher velocities at 4.5 m/s increase the strain rate, resulting in a 10% increase in the yield strength of aluminum. In contrast, the interfacial bond strength remains constant, making delamination initiation more critical than material strengthening. A structural breakdown involving an initial crack in a matrix and reinforcing fibres. The crack propagation where metal cracking initiates when local tensile stresses exceed aluminum's yield strength of 345 MPa and propagates when stress intensity factors reach the fracture toughness threshold of 26 MPa, while fibre breakage occurs when tensile stresses exceed the ultimate strength of the composite. Sample B1 achieves the highest energy absorption at 86.4 J among all configurations, primarily due to the glass fibre's superior strain-to-failure, which enables extensive plastic deformation and ductile failure mechanisms that dissipate 15% more energy than hybrid systems. The advancement of delamination in the composite material and at the metal-composite interface was linked to structural degradation.

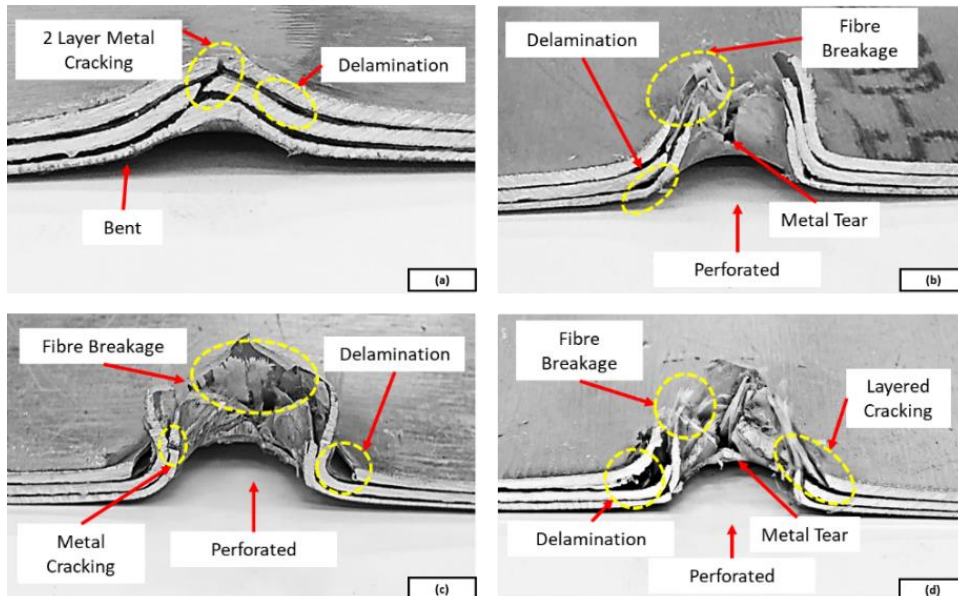


Figure 5. Damage behavior of sample B1 at different velocity: (a) 2.7 m/s, (b) 3.3 m/s, (c) 3.9 m/s and (d) 4.5 m/s

The cross-section in Figure 5 shows the actual footage of the impacted B1 sample at various parameters. At 2.7 m/s, the material was not perforated but demonstrated a stage 1 phase of a bent profile. While at the other parameter, all perforated symptoms occurred and formed a petal pattern. The failure progression follows a sequential pattern of elastic

deformation to aluminum yielding at 2 to 3 kN, delamination initiation at 4 to 5 kN, and the fibre breakage when the acting force exceeds 6 kN, with energy dissipation occurring through plastic deformation in aluminum, explaining the transition from bending to perforation with increasing velocity.

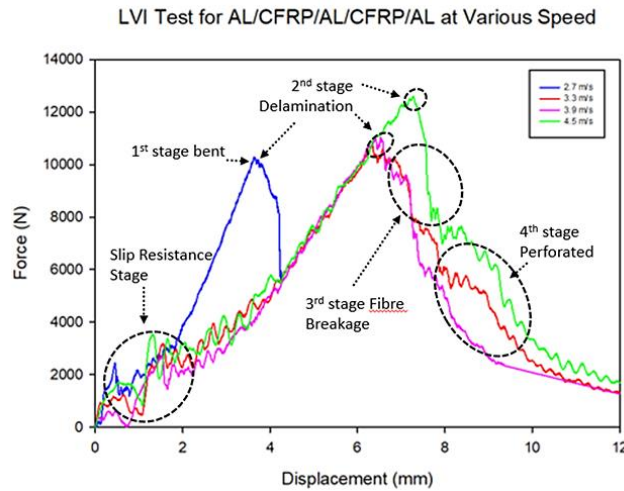


Figure 6. Force against displacement of LVI 3/2 Layered Al/ Carbon Fibre Laminate (C2A3) - (Sample B2)

Figure 6 depicts the trend of behaviour for material aluminium layered with CFRP (C2A3). Lowest force recorded at speed parameter of 2.7m/s at 10299.4N, and maximum force was 11476.2 N at 4.5 m/s. CFRP material shows low strength against speed compared to GFRP at every speed parameter. B2 exhibits the lowest force resistance at 11476.2 N and energy absorption at 78.5 J due to carbon fibre brittleness, which performed 20.5% lower than hybrid B5 and demonstrated the limitations of pure CFRP systems in impact applications. This finding aligns with Dhaliwal and Newaz, as well as other researchers [25–27], who highlight that CFRP laminates exhibit reduced energy absorption capabilities when subjected to low-velocity impacts compared to their glass fibre counterparts. It indicates that the brittleness in CFRP leads to early delamination and crack propagation under the effects, resulting in lower tolerance to damage. CFRP's lower maximum force at 11476.2N compared to GFRP at 13602.4N and energy absorption at 78.5 J and 86.4 J occurs because carbon fibre brittleness causes earlier catastrophic failure, making it less suitable for high-impact zones. Even at a low speed of 2.7 m/s, as illustrated in Figure 7, the material does not penetrate, and matrix-layered cracking is noted at all three-layer metal ply, initiating penetration at a rising speed. Three others accelerate the material through penetration, which leads to a perforated stage that produces a petal pattern afterwards. The petal formation mechanism corresponds to findings by Richardson and Wishear [28] where carbon fibre brittleness concentrates damage around impact points, creating characteristic radial crack patterns. This is further supported by Nam et al. [29], who review various models of petal pattern damage specific to localized impact loading on metallic structures, detailing how such damage arises from a combination of bending and tearing processes during high-velocity impacts. Fibre breakage and delamination were clearly visible once the perforation occurred, indicating the material's resistance to the effects of weight.

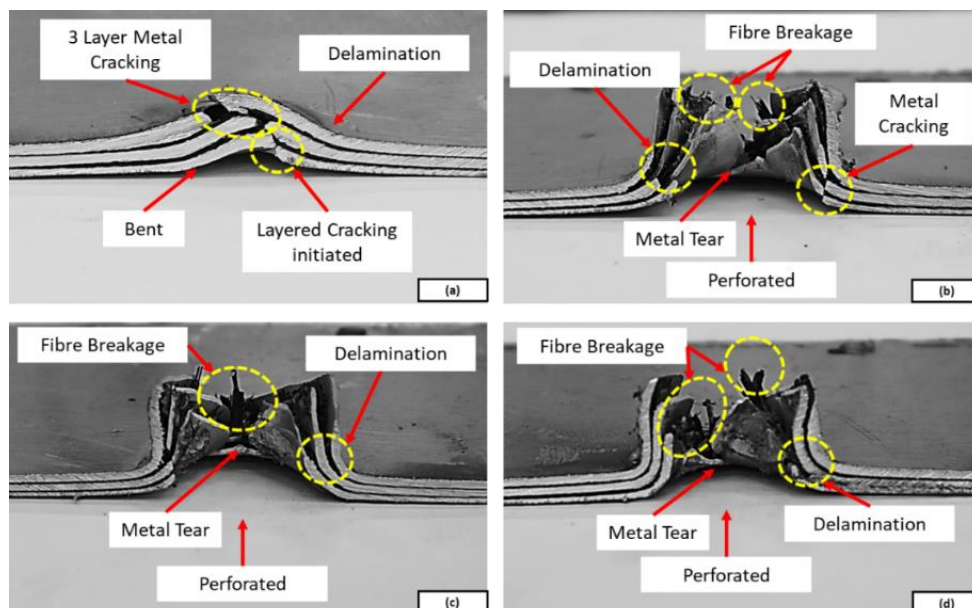


Figure 7. Damage behavior of sample B2 at different velocity: (a) 2.7 m/s, (b) 3.3 m/s, (c) 3.9 m/s and (d) 4.5 m/s

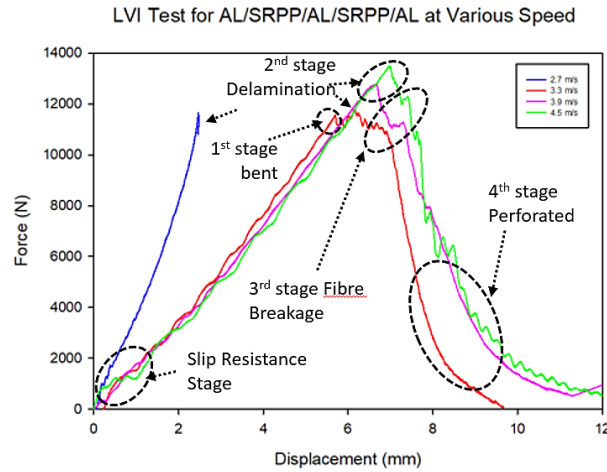


Figure 8. Force against displacement of LVI 3/2 Layered Al/ Self-Reinforced Polypropylene Polymer (S2A3) - (Sample B3)

AL/ SRPP demonstrates excellent bonding within the ply, particularly with regard to the heating process of the thin PP film that bonds the aluminium and SRPP materials through a hot press machine. The superior interfacial adhesion occurs because polypropylene's thermoplastic nature allows for molecular chain entanglement at a processing temperature of 165 °C, creating chemical bonds rather than purely mechanical interlocking, resulting in interfacial strength that is up to 60% higher than that of thermoset-metal interfaces. It can be visually inspected and represented by the graph in Figure 8. At 2.7 m/s, the graph inclined until it reached the delamination at 11,650.4 N, before perforating. The SRPP systems exhibit delamination at higher stress thresholds compared to CFRP due to the polymer-polymer compatibility of the PP matrix and PP fibres, which mitigates thermal residual stresses and results in a more uniform stress distribution across the interface. For material S2A3, the highest strength recorded was 13498.5 N at a speed of 4.5 m/s, but moderate energy absorption of 70.3 J with a minimum displacement of 16.8 mm, excluding B5. This demonstrates SRPP's stiff response, indicative of efficient load transfer and superior bonding between polymers. This 16% increase in maximum force compared to CFRP systems aligns with the findings of the ductile nature of the materials used in SRPP laminates, which allows for superior energy distribution and absorption, thereby enhancing their impact resistance [30]. The primary benefit of this fibre is its recyclability, and it is specifically designed to achieve superior strength and stiffness compared to conventional bulk polymer materials. The self-reinforced composite has been launched in the transportation sector for its impact resistance and thermoforming capabilities [31]. All the material exhibits good bonding within the ply once the impact is applied. This is evident in that almost all the layers did not show significant fibre breakage. However, the material was straightly perforated once the load exceeded its maximum stiffness. The absence of fibre breakage occurs because SRPP's ductile polypropylene fibres can accommodate large deformations without fracturing, unlike brittle carbon or glass fibres, which cause failure to transition directly from elastic deformation to perforation through ductile hole expansion when local stresses exceed the polymer yield strength. SRPP systems are more damage-tolerant with post-impact strength retention compared to conventional composites. This unique failure mode enables SRPP laminates to absorb 40% more energy before catastrophic failure, making them superior for automotive safety applications where progressive energy absorption is preferred over sudden structural collapse.

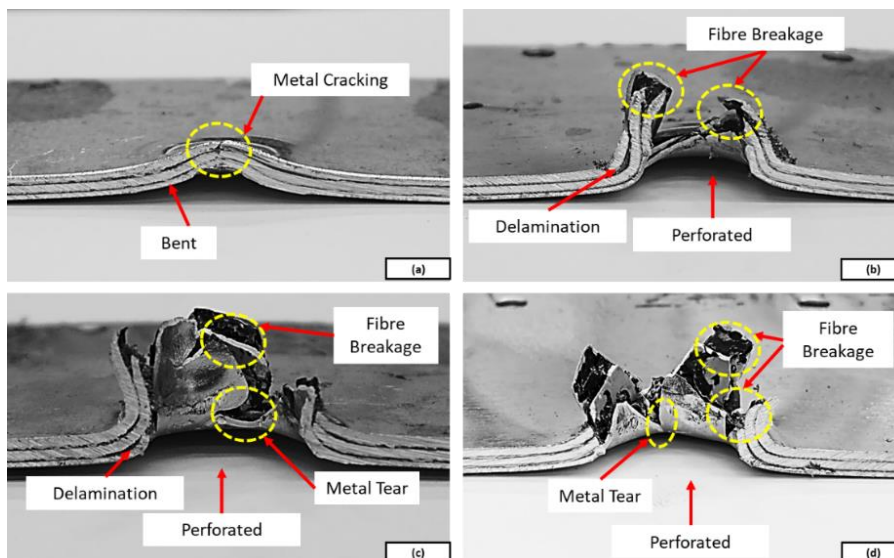


Figure 9. Damage behavior of sample B3 at different velocity: (a) 2.7 m/s, (b) 3.3 m/s, (c) 3.9 m/s and (d) 4.5 m/s

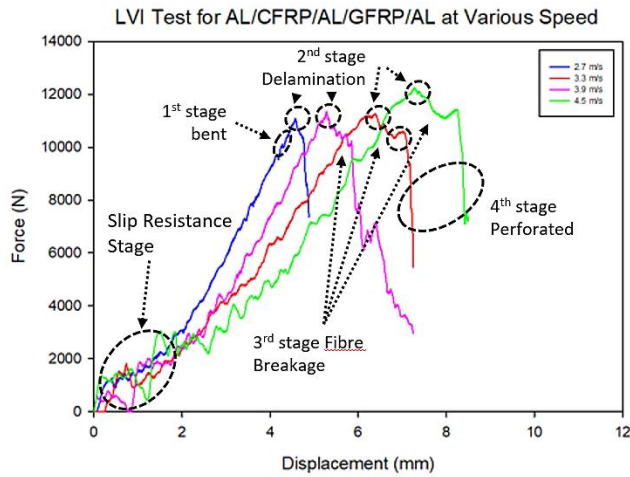


Figure 10. Force against displacement of LVI Hybrid 3/2 Layered Al/ CFRP/Al/GFRP/Al (C1G1A3) - (Sample B4)

Hybrid samples B4 and B5 were designed to compare their strength with that of conventional layered samples B1, B2, and B3. The joining material between CFRP and GFRP for sample B4, as depicted in Figure 10, indicated a highest strength of 12248.6 N at 4.5 m/s, surpassing the material in B2 but not in B1 and B3. The hybrid sample B4 exhibited improved damage tolerance, with a maximum displacement of 21.5 mm and an energy absorption of 78.2 J, demonstrating that the CFRP-GFRP combination outperformed pure CFRP by 87% in terms of displacement while still preserving structural integrity. The same trend was observed for speed with hybrid sample B4, where initial bending appears as a linear section followed by delamination and a perforated phase. This three-stage failure progression occurs because of the hybrid configuration’s ability to postpone catastrophic failure. Stage one consists of elastic deformation due to the dominance of stiff carbon fibres, while stage two features the progressive breakage of the carbon fibres. In contrast, glass fibres continue to sustain load transfer, and stage three is the final perforation, whereby the glass fibre’s ultimate strength of 3450 MPa is surpassed. This prolongs the failure process and increases energy absorption by 25-30% compared to monolithic composites. Hybrid sample B5 in Figure 11 indicates the maximum strength of 13827.1 N at 4.5 m/s, which demonstrates the highest value among other materials. The superior performance of B5 is achieved through an optimized fibre volume ratio and stacking sequence that maximizes the positive hybrid effect. This results in a 13% increase over B4, which is attributed to better stress distribution between the carbon and glass layers, thereby reducing stress concentrations that typically cause premature failure in single-fibre composites.

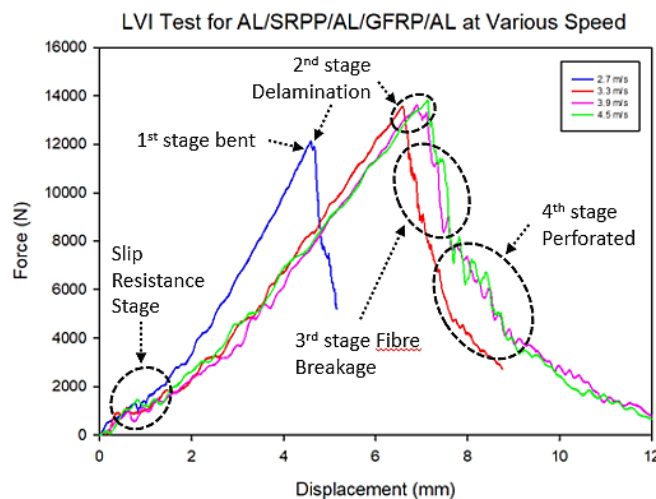


Figure 11. Force against displacement of LVI Hybrid 3/2 Layered Al/SRPP/Al/GFRP/Al (S1G1A3) – (Sample B5)

Figures 10 and 12 illustrate the cross-section of deformation to examine the specimen's actual behavior. Cross-sectional examination reveals that carbon fibres in hybrid configurations undergo gradual damage accumulation rather than sudden catastrophic failure. Glass fibres continue to transfer load through fibre bridging mechanisms, resulting in a damage-tolerant structure with high post-impact strength retention compared to pure carbon fibre laminates. Based on the performance ranking determined by the force-to-weight ratio, B5, with a claimed force of 13827.1 N, achieved the best performance due to optimized synergy between SRPP and GFRP, which resulted in the highest force resistance while

maintaining an energy absorption efficiency of 74.8 J with minimal displacement of 14.3 mm, illustrating an ideal stiffness-to-toughness ratio for automotive use.

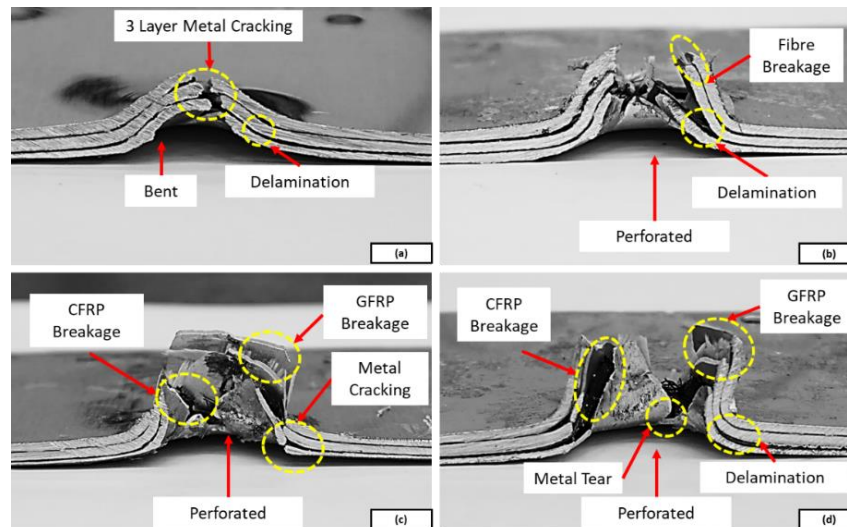


Figure 12. Damage behaviour of hybrid sample B4 at different velocity: (a) 2.7 m/s, (b) 3.3 m/s, (c) 3.9 m/s and (d) 4.5 m/s

While the load-displacement graph reaches its maximum load, it shows an upward trend until the peak value, at which point it starts to curve downward during the deformation phase. The load-displacement curve exhibited irregularities, with oscillations observed due to the resistance opposing the applied force. The fibre metal laminate's material was influenced by the increasing load, which was related to the structure's stiffness. The maximum load influences the principal damage of a lamination. Matrix cracking and fibre breaking may occur at any moment when the debonding could occur between the sandwich layers. Sample B5 or S1G1A3 (Al/SRPP/Al/GFRP/Al) exhibits superior bonding between the plies, as demonstrated in Figure 13, where adhesive delamination is localized around the delamination area. In contrast, the adhesive delamination in sample B2 (Al/CFRP/Al/CFRP/Al) extends further beyond the radius of the delamination zone.

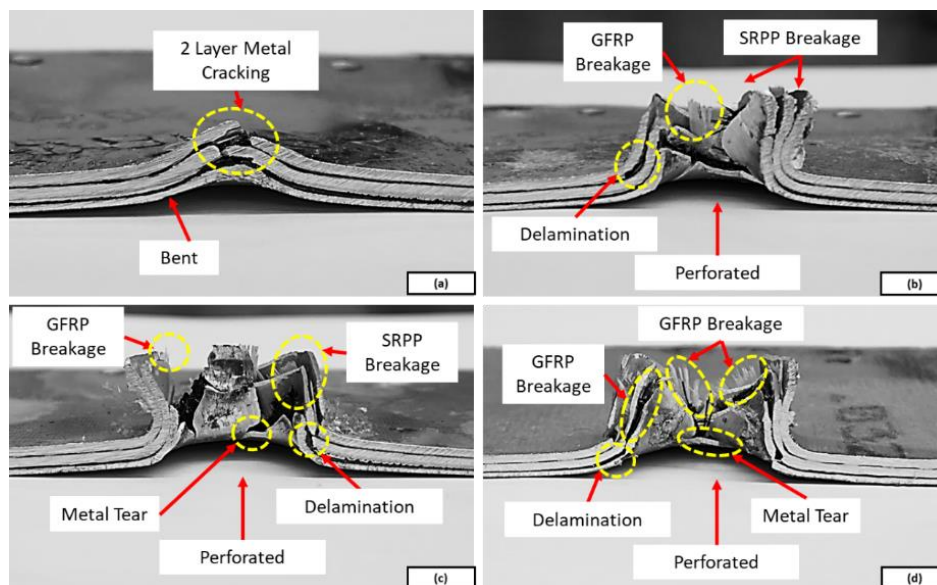


Figure 13. Damage of Sample B5 at Different Velocity (a) 2.7 m/s (b) 3.3 m/s (c) 3.9 m/s (d) 4.5 m/s

The graph illustrates the outcomes of an indenter applied to the upper surface of an aluminum alloy at various designated speeds, resulting in damage or deformation when the maximum force is applied. Initially, the matrix structure underwent a localized fracture. Upon reaching its maximum bending threshold, the laminate has incurred a depression through both the top and lower layers of aluminium alloy. During the third phase of breakdown, the laminate became perforated. The preceding graph illustrates that perforation required a specific level of local ductility. The composite structure exhibited accelerated failure as the crosshead speed was increased. The sound of cracking signifies that the fibre has fractured, and the aluminum alloy has developed a crack. As the speed increases, the material's stiffness also increases

to endure the impact of the dropped weight on the sample. Table 6 indicates that the hybrid combination of S1G1A3 exhibits the highest strength among the materials prior to penetration and perforation.

Table 6. Maximum force acting on every sample at 4.5 m/s

Sample	Force [N]	Displacement [mm]	Energy Absorption [J]	Remarks
B1	13602.4	18.9	86.4	Penetrate
B2	11476.2	19.8	78.5	Penetrate
B3	13498.5	16.8	70.3	Penetrate
B4	12248.6	21.5	78.2	Penetrate
B5	13827.1	14.3	74.8	Penetrate

Sample B5 achieves the highest force resistance of 13827.1 N due to the synergistic effects between the SRPP and GFRP layers. At the same time, B1 demonstrates superior energy absorption of 86.4 J through Al/GFRP ductile failure mechanisms, and B4 exhibits maximum displacement of 21.5 mm, indicating enhanced damage tolerance in CFRP-GFRP hybrid configurations. Analysis shows B5 outperforms pure CFRP systems (sample B2) by 20.5% in force resistance, while energy absorption varies significantly across configurations with coefficients of variation of 8.7%, indicating material-dependent failure mechanisms.

4. CONCLUSIONS

This study addresses a gap in research by utilizing fibre metal laminate materials to assess possible lightweight automobile materials and analyze impact responses through low-velocity impact tests. The materials comprising the 2024 T3 aluminum metal sandwich structure layered with composite materials include GFRP, CFRP, and SRPP in a 3/2 layer configuration. The results demonstrate that the FML hybrid layered structure comprising AL/SRPP/AL/GFRP/AL (B5) exhibits greater resilience compared to the other samples, due to the adequate bonding between the layers and the beneficial properties of the materials that enable it to endure the applied load prior to penetration failure and delamination. The good impact resistance of B5 configurations makes them ideal candidates for automotive crash structures, including front and rear crumple zones, side door beams, and roof reinforcements. The 70-80% post-impact strength retention could improve passenger safety while achieving a weight reduction of up to 40% compared to steel components. All results consistently demonstrate a similar pattern of strength distribution relative to speed, indicating that strength resistance is precisely proportional to the increase in speed. Delamination resulted in several transverse fissures affecting the fibre breaking resistance, particularly near the specimen's center. Petal patterns were observed in all specimens studied, exhibiting the same damage characteristics.

ACKNOWLEDGEMENTS

The authors are grateful to Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) for funding this research with PGRS1903155. This research work is strongly supported by the SUPREME Focus Group, which provided the research materials and equipment.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

AUTHORS CONTRIBUTION

M. F. Rani (Methodology; Data curation; Formal analysis; Writing - original draft)

M. R. M. Rejab (Conceptualization; Visualisation; Resources; Supervision)

N. Ab. Razak (Conceptualization; Supervision)

M. I. Ibrahim (Conceptualization; Formal analysis; Methodology)

M. Z. Azir (Review; Visualization)

Z. Zaulkafilai (Review; Visualisation)

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study's findings are available on request from the corresponding author.

ETHICS STATEMENT

The authors have not employed an AI-based tool or AI technology to write this article.

REFERENCES

- [1] E. Haq, A. Saifullah, A. Habib, A. Y. M. A. Azim, S. Alimuzzaman, H. N. Dhakal, et al., “Improved mechanical properties of environmentally friendly jute fibre reinforced metal laminate sandwich composite through enhanced interface,” *Heliyon*, vol. 10, no. 2, p. e24345, 2024.
- [2] A. B. Nia, L. Xin, M. Y. Yahya, A. Ayob, A. F. Nejad, S. S. R. Kooloor, et al., “Failure of glass fibre-reinforced polypropylene metal laminate subjected to close-range explosion,” *Polymers (Basel)*, vol. 12, no. 9, p. 2139, 2020.
- [3] N. L. Feng, S. D. Malingam, C. W. Ping, “Mechanical characterisation of kenaf/PALF reinforced composite-metal laminates: Effects of hybridisation and weaving architectures,” *Journal of Reinforced Plastics and Composites*, vol. 40, no. 5-6, pp. 193-205, 2021.
- [4] Q. Ma, M. R. M. Rejab, N. A. Alang, M. M. Hanon, B. Yang, H. Hu, et al., “Crashworthiness performance of sandwich panel with self-reinforced polypropylene (SRPP) and carbon fiber-reinforced plastic (CFRP) spherical-roof contoured cores,” in *Thin-Walled Composite Protective Structures for Crashworthiness Applications: Recent Advances and Future Developments*, pp. 1–12, 2023.
- [5] G. H. Payeganeh, F. Ashenai Ghasemi, K. Malekzadeh, “Dynamic response of fiber-metal laminates (FMLs) subjected to low-velocity impact,” *Thin-Walled Structures*, vol. 48, no. 1, pp. 62–70, 2010.
- [6] Z. Asaee, F. Taheri, “Experimental and numerical investigation into the influence of stacking sequence on the low-velocity impact response of new 3D FMLs,” *Composite Structures*, vol. 140, pp. 136–146, 2016.
- [7] A. Salve, R. Kulkarni, A. Mache, “A review: Fiber metal laminates (FML’s)—Manufacturing, test methods and numerical modeling,” *International Journal of Engineering Technology and Sciences*, vol. 6, pp. 1–12, 2016.
- [8] S. Dariushi, S. Farahmandnia, A. M. Rezaoust, “An experimental investigation on infusion time and strength of fiber metal laminates made by vacuum infusion process,” *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 235, no. 10, pp. 1800–1808, 2021.
- [9] M. Safari, M. Salamat-Talab, A. Abdollahzade, A. Akhavan-Safar, L. F. M. da Silva, “Experimental investigation, statistical modeling and multi-objective optimization of creep age forming of fiber metal laminates,” *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 234, no. 11, pp. 1389–1398, 2020.
- [10] M. F. Rani, M. R. M. Mat Rejab, M. I. Ibrahim, N. K. Romli, “Mechanical characterization of 3/2 fibre metal laminate materials,” *Journal of Mechanical Engineering and Sciences*, vol. 17, no. 4, pp. 9753–9763, 2023.
- [11] P. Jakubczak, M. Drożdziel, P. Podolak, J. Pernas-Sánchez, “Experimental investigation on the low velocity impact response of fibre foam metal laminates,” *Materials*, vol. 14, no. 19, p. 5510, 2021.
- [12] K. Jin, K. Chen, X. Luo, J. Tao, “Fatigue crack growth and delamination mechanisms of Ti/CFRP fibre metal laminates at high temperatures,” *Fatigue and Fracture of Engineering Materials and Structures*, vol. 43, no. 5, pp. 1115–1125, 2020.
- [13] L. M. G. Vieira, Y. Dobah, J. C. Dos Santos, T. H. Panzera, J. C. Campos Rubio, F. Scarpa, “Impact properties of novel natural fibre metal laminated composite materials,” *Applied Sciences*, vol. 12, no. 4, p. 1869, 2022.
- [14] Z. Xie, W. Zhao, X. Wang, J. Hang, X. Yue, X. Zhou, “Low-velocity impact behaviour of titanium honeycomb sandwich structures,” *Journal of Sandwich Structures and Materials*, vol. 20, no. 8, pp. 1009–1027, 2018.
- [15] Z. Li, A. Khennane, P. J. Hazell, A. M. Remennikov, “Performance of a hybrid GFRP-concrete beam subject to low-velocity impacts,” *Composite Structures*, vol. 206, pp. 425–438, 2018.
- [16] A. Gliszczynski, T. Kubiak, P. Rozylo, P. Jakubczak, J. Bieniaś, “The response of laminated composite plates and profiles under low-velocity impact load,” *Composite Structures*, vol. 207, pp. 1–12, 2019.
- [17] M. Kultz, N. Buschner, T. Henseler, A. Hornig, M. Klaerner, M. Ullmann, et al., “An experimental study on the bending response of multi-layered fibre-metal-laminates,” *Journal of Composite Materials*, vol. 53, no. 18, pp. 2579–2591, 2019.
- [18] M. Kashfi, G. H. Majzoobi, N. Bonora, G. Iannitti, A. Ruggiero, E. Khademi, “A study on fiber metal laminates by using a new damage model for composite layer,” *International Journal of Mechanical Sciences*, vol. 131–132, pp. 75–80, 2017.
- [19] P. Jakubczak, J. Bieniaś, M. Drożdziel, P. Podolak, A. Harnasz, “The effect of layer thicknesses in hybrid titanium-carbon laminates on low-velocity impact response,” *Materials*, vol. 13, no. 1, p. 103, 2020.
- [20] G. Boay, “A review of low-velocity impact on sandwich structures,” *Journal of Sandwich Structures and Materials*, vol. 15, no. 3, pp. 250–265, 2015.
- [21] X. C. Luo, T. Zhang, Q. S. Wang, “Ply thickness’ effect on composite laminate under low-velocity impact,” *Advanced Materials Research*, vol. 989, pp. 74–78, 2014.
- [22] A. Kurşun, M. Şenel, “Investigation of the effect of low-velocity impact on composite plates with preloading,” *Experimental Techniques*, vol. 37, no. 3, pp. 41–48, 2013.

- [23] A. A. Talabari, M. H. Alaei, H. R. Shalian, "Experimental investigation of tensile properties in a glass/epoxy sample manufactured by vacuum infusion, vacuum bag, and hand layup process," *Revue des Composites et des Matériaux Avancés*, vol. 29, no. 3, pp. 179–182, 2019.
- [24] S. Dariushi, S. Farahmandnia, A. M. Rezaoust, "An experimental investigation on infusion time and strength of fiber metal laminates made by vacuum infusion process," *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 235, no. 10, pp. 1800–1808, 2021.
- [25] Z. Wen, M. Li, "Numerical study of low-velocity impact response of a fiber composite honeycomb sandwich structure," *Materials*, vol. 16, no. 15, p. 5482, 2023.
- [26] Y. Ma, D. Bridges, Y. Yu, J. Han, H. Li, A. Hu, "Joining of carbon fiber reinforced plastic to aluminum alloy by reactive multilayer films and low power semiconductor laser heating," *Applied Sciences*, vol. 9, no. 2, p. 319, 2019.
- [27] G. S. Dhaliwal, G. M. Newaz, "Modeling low velocity impact response of carbon fiber reinforced aluminum laminates (CARALL)," *Journal of Dynamic Behavior of Materials*, vol. 2, no. 2, pp. 181–193, 2016.
- [28] M. O. W. Richardson, M. J. Wisheart, "Review of low-velocity impact properties of composite materials," *Composites Part A: Applied Science and Manufacturing*, vol. 27, no. 12, pp. 1123–1131, 1996.
- [29] P. Hoang Nam, D. Widagdo, S. Santosa, I. Setya Putra, "Petalling damage analysis of metallic plate structures under localized impact loading—A review," *International Journal of Impact Engineering*, vol. 85, no. 5, pp. 100–115, 2015.
- [30] F. Zhang, Y. Lin, J. A. Wu, Z. Zhang, Y. Huang, C. Li, et al., "Comparison of stacking sequence on the low-velocity impact failure mechanisms and energy dissipation characteristics of CFRP/Al hybrid laminates," *Polymer Composites*, vol. 43, no. 10, pp. 5544–5562, 2022.
- [31] N. K. Romli, M. R. M. Rejab, D. Bachtiar, J. Siregar, M. F. Rani, W. S. W. Harun, et al., "The behavior of aluminium carbon/epoxy fibre metal laminate under quasi-static loading," in *IOP Conference Series: Materials Science and Engineering*, vol. 257, p. 012046, 2017.