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RESEARCH ARTICLE

Mechanical characterization of 3/2 fibre metal laminate materials

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ABSTRACT - Development of lightweight materials onto vehicle bodies, especially in the automotive sector is seen as one of the best alternative solutions in order to reduce fuel consumption and decrease harmful emissions produced by the emission. Reducing in weight of a vehicle can improve fuel efficiency with no prejudice to safety strength requirements. Fibre metal laminate (FML) is hybrid composite structure based on thin sheet of metal alloys and plies of fibre reinforced polymeric materials which offer the ability of superior mechanical properties such as lightweight, high fatigue growth resistance and high strength and stiffness. Multi-material auto bodies will allow optimal material selection in structural components for higher performance and lower cost. This study aims to fabricate and investigate the failure behaviour of a 3/2 layer fibre metal laminate subjected to the quasi-static indentation test. The FML is constructed from aluminium 2024-T3 and layered with composite materials CFRP, GFRP and SRPP. The crosshead speed test analysis ran in different parameters on 1 mm/min, 5 mm/min, 10 mm/min and 50 mm/min, respectively in quasi-static indentation test. The experimental performances of each specimen were compared to predict the behaviour and performance of the FML composite. The test indicates that varying crosshead speeds have influenced the affected region of the FML, causing debonding on the laminate as a result of continued loading.

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1.0 INTRODUCTION

Weight reduction approach onto car body is one of the significant moves made by car makers with the aim to improve car performance, reduce fuel efficiency and as well as to give benefits to environmental impact. Aluminium alloy, magnesium and several types of lightweight automotive bodies are developed by using composite material combined with aluminium alloys or other high-strength steels which can offer the desired potential to reduce vehicle fuel consumption and emission [1]. As studied by Lotus Engineering on Toyota Venza, it determines that achievement of 33% in weight reduction in a vehicle can contribute to only 3% from the component cost. Lightweight materials derived from different materials sources can be utilized in the vehicle structure especially in the car body. The key to this objective is to employ the right multi-material to be integrated at the right location without impairing the car's primary function [2]. Within the research scope, hybrid composite reinforced materials were constructed by combining two or more different materials through sandwiching methods between aluminium and specific fibre composite material, expecting to improve the strength of the material. The FML allows for the application of numerous combinations of lamination materials, taking into consideration of parameters including fibre type, layer thickness, layer number, and orientation complexity [3, 4]. By reducing vehicle weight it is possible to increase fuel economy as much as 8% by reducing vehicle weight about 10%. Furthermore, the efficiency of the battery can be increased even further when weight is reduced by 10% [5, 6]. Delamination is a type of damage that can significantly reduce the ability of laminates to carry loads, therefore limiting their lifespan. In order to enhance the ability of composites to withstand damage, it is necessary to customize the microstructure to be tough and replace brittle damage mechanisms with ductile ones [7].

Given its mechanical properties of corrosion resistance and lightweight properties, aluminium is frequently chosen over other metals for metal ply in developing fibre metal laminate. Through FML, material behaviour is improved because the mechanical properties in their constituents are combined to improve ductility, fatigue strength, and impact resistance [8, 9]. Typically, for composite side, GLARE is made of glass-reinforced aluminium laminate, ARALL is made of aramid-reinforced aluminium laminate (ARALL), and CARALL is made of carbon-reinforced aluminium laminate [10-12]. By combining their mechanical properties into one material, FML improves the strength of the material.

A separate investigation conducted by Velumayil and Palanivel [13], an examination was carried out on the mechanical characteristics of hybrid composite laminates composed of basalt, Kevlar, and epoxy materials. The mechanical qualities of pure laminate configurations were compared with hybrid designs that incorporated a blend of natural and synthetic fibres by the researchers. The mechanical characterization tests yielded findings indicating that the hybrid composite laminates composed of kenaf, kevlar, and epoxy had improved mechanical properties in comparison to the pure laminate configurations. The cross-head impact will damage the matrix between the material lamination, and the interaction between matrix-fibre will start to degrade. The epoxy resin would be stiff and offers slight resistance to the

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propagation of cracks. There has also been research of an analysis of FML failure behaviour regarding the effect of adhesive quantities, implying that the adhesive layer substantially impacts the interlaminar features of FML. On the other hand, the optimal amount of adhesive has been proven, with the correct quantity increasing the laminate's mechanical characteristics of the FML constituent [3].

Fibre metal laminate (FML) is a composite material that integrates alternating layers of fiber-reinforced plastic (FRP) and metal. The design aims to optimize the utilization of the superior strength and stiffness exhibited by the metal layers, while simultaneously capitalizing on the lightweight nature and corrosion-resistant characteristics of the FRP layers. Fibre metal laminates (FMLs) find widespread application within the aerospace and automotive sectors, owing to their desirable attributes of high strength, low weight, and durability. The precise arrangement of FMLs may exhibit variability contingent upon the specific application and the desired characteristics. In general, FMLs are composed of alternating layers of metal and FRP materials. The metal layers primarily contribute to the structural integrity of the FML, while the FRP layers serve to enhance reinforcing and safeguard against corrosion. The metallic layers commonly consist of aluminium or titanium, whilst the FRP layers may comprise materials such as carbon fiber-reinforced polymer (CFRP) or glass fiber-reinforced polymer (GFRP). In Figure 1, FML's most common fibres are from carbon, glass and aramid. When sandwiching with metal mostly made from aluminium, it is then called carbon-reinforced aluminium laminates (CARAL), glass-reinforced aluminium laminates (GLARE) and aramid-reinforced aluminium laminates (ARALL).

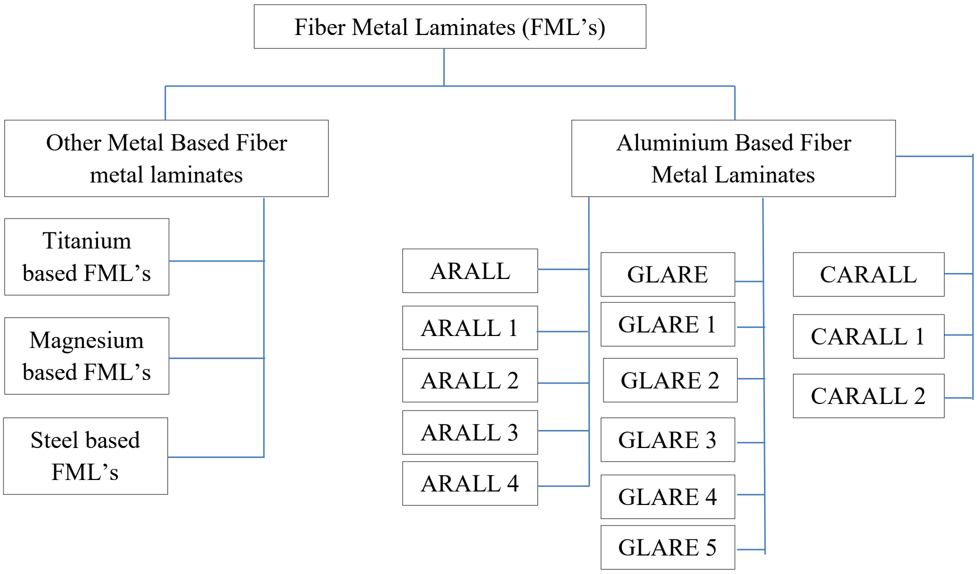


Figure 1. Classification of metal in FML [11]

The combination of metal and FRP layers in FMLs offers several advantages. The metal layers provide high strength and stiffness, allowing FMLs to withstand high loads and resist deformation. The FRP layers enhance the material's fatigue and impact resistance, making it more durable and damage-tolerant. Additionally, the lightweight nature of the FRP layers helps to reduce the overall weight of the structure, leading to improved fuel efficiency and performance. FMLs have been extensively studied in terms of their mechanical properties and performance. Many elements of FMLs, such as their production, structural behaviour, impact resistance, and fatigue qualities, have been the subject of scientific inquiry. Carbon, glass, and basalt fibre interlayer hybrid composite laminates were tested for their response to low-velocity impacts [14]. The study looked at how hybridization and fabric structure affect FMLs' ability to withstand low velocity impacts and the effects of hybridization and fabric structure on the material's performance were evaluated by performing low-velocity impact tests on interply hybrid specimens made using a vacuum-assisted resin infusion moulding technique.

Fibre metal laminates (FMLs) have a range of advantages in comparison to traditional metallic alloys and composites. The FMLs are composite materials that possess a combination of beneficial properties derived from both metals and fiber-reinforced composites. One of the primary advantages of fibre metal laminates (FMLs) is in their enhanced mechanical qualities, it has been demonstrated that FMLs possess superior impact strength, indentation characteristics, tensile strength, and flexural strength in comparison to both non-hybrid and hybrid laminates [15]. The utilization of thin metal sheets in conjunction with fiber-reinforced layers in FMLs leads to the development of components that exhibit notably enhanced particular qualities, including strength and stiffness, in comparison to traditional monolithic materials. The FMLs exhibit a notable capability for absorbing high levels of energy, rendering them well-suited for use in crash structures [16].

An additional advantage of FMLs lies in their ability to withstand high temperatures. Titanium/carbon fibre-reinforced polymer (Ti/CFRP) FMLs have the ability to endure elevated temperatures, rendering them suitable for use in hypersonic aircraft scenarios [17]. Functional materials, commonly referred to as FMLs, has the capability to be tailored to exhibit specific qualities that align with the unique demands of a given application. For example, fibre-reinforced composite laminates using kenaf and pineapple leaf fibres were created using various weaving patterns and stacking arrangements in order to examine their mechanical characteristics [15]. The selection of materials and manufacturing methods enables the customization of the FMLs properties to fulfil unique requirements. FMLs provide enhanced resistance to damage and contribute to the reduction of weight in lightweight structures. Fatigue-resistant materials of FMLs, such as Glass Laminate Aluminium Reinforced Epoxy (GLARE), have been specifically engineered to enhance the capacity of metallic lightweight structures to withstand damage. The incorporation of both metallic and fibre-reinforced layers in fibre metal laminates (FMLs) confers improved durability against fatigue fractures, delamination, and impact loading [18-20]. Fatigue-induced material failures of FMLs have been found to play a significant role in the reduction of weight in structures, hence resulting in enhanced fuel efficiency and improved overall performance.

Furthermore, in addition to possessing desirable mechanical and thermal qualities, the FMLs can be fabricated via cost-effective manufacturing techniques. The conventional method of manufacturing fibre metal laminates using autoclaves has been associated with high prices. However, there is a growing interest in exploring alternative manufacturing procedures that can retain the quality of laminates while also reducing expenses. The investigation of hybrid laminates using thermoplastic matrices has been conducted as a potential solution to address the drawbacks associated with thermosetting matrices, including elevated manufacturing costs and limited recycling capabilities. Fibre metal laminates offer several benefits, including improved mechanical properties, heat resistance, damage tolerance, weight reduction, and cost-effective manufacturing processes.

The present research aims to analyze the impact behaviour of several fibre metal laminates under the conditional test of quasi-static indentation (QSI). Using different constant speed, failure mechanisms of the FML with different composite layer materials of CFRP, GFRP and SRPP material laminate can be determined. Finally, the characterization of the fracture pattern of QSI behaviour between the different layers will be discovered by using microstructure analysis.

1.1 Fabrication of Fibre Metal Laminate

In this study, three types of fibre metal laminate containing composite material 3/2 configuration layup with aluminium alloy 2024-T3 (Table 1) were fabricated by using 3/2 configuration through compression moulding technique. The formation of the FML consists of AL/CFRP/AL/CFRP/AL, AL/SRPP/AL/SRPP/AL and AL/GFRP/AL/GFRP/AL. The stacking configuration is illustrated in Figure 2. The square specimen dimension size is 150mm x 150mm.

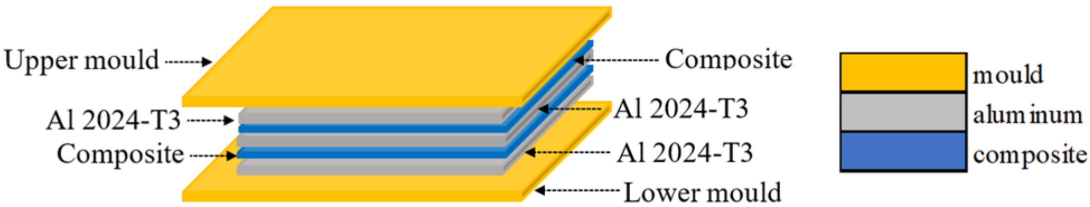


Figure 2. Illustration of the compression moulding process for preparing the FML specimen

These materials were bonded to the aluminium alloys with epoxy as adhesive between the layers. the preparation of the specimen was using hand layup method. preparation of specimens included with surface roughness by using sandblasting process type abrasive blasting. Sandblasting is a process of surface finishing by forcibly propelling against the metal surface which it will remove paint, rust or any unwanted foreign material on aluminum surface in order to improve the bonding with the preferable selected composite. The surfaces of the aluminium alloy were treated by high air pressure sandblasting technique using brown aluminum oxide (Al_2O_3) as a medium sand which provide harder abrasive to lower dust level. Through sandblasting process, it aims to improve surface texture toughness bonding between the composite fibres subject to material CFRP and GFRP with aluminium alloy sheet metal. In other hand as for SRPP material, an adhesive layer and interlayer of polypropylene film were used to bond sheet metal with the srpp. all specimens were utilized and evaluated using quasi-static indentation tests. The SRPP sandwich structure is suggested as a viable lightweight and recyclable material for future application in alternative constructions, with a focus on investigating the energy-absorbing properties of sandwich structures with honeycomb cores [21].

Table 1. Physical properties of aluminium 2024-T3

Properties	Value
Melting Temperature (ºC)	502
Density (kg/m^3)	2770
Heat Capacity (K/kg K)	875

1.2 Quasi-Static Indentation Test

Quasi-static indentation tests are commonly used to evaluate the mechanical properties of materials, including composite materials. These tests involve applying a controlled and slowly increasing load to a material surface, typically using a sharp indenter, and measuring the resulting deformation or indentation depth. The tests are performed at a slow loading rate to ensure that the material response is predominantly elastic and to minimize the effects of dynamic loading. Quasi-static indentation tests can provide valuable information about the hardness, stiffness, and deformation behaviour of materials. The indentation depth can be used to calculate the material's hardness, which is a measure of its resistance to permanent deformation under an applied load. The load-displacement curve obtained from the test can also be used to determine the material's elastic modulus, which represents its stiffness or resistance to elastic deformation. These tests are particularly useful for characterizing the mechanical properties of composite materials, which consist of two or more distinct materials combined to achieve specific performance characteristics. By performing quasi-static indentation tests on different regions or layers of a composite material, it can assess the individual contributions of each component and evaluate the overall mechanical behaviour of the composite [22].

The damage behaviour of composite laminates during low-velocity impact tests can be described using a four-stage impact model, as illustrated in Figure 3 [23-25]. This model categorizes the level of impact damage based on the surface contact during the test. The first stage is the indentation stage, where the impactor initially contacts the surface of the laminate. At this stage, there is no material breakage, and the damage is very narrow. The indentation depth is typically small, and the laminate primarily undergoes elastic deformation. As the impactor continues to move deeper into the specimen, carrying increased energy, the partially perforated stage is reached. At this stage, internal damage is created within the laminate. The impactor causes the fibres in the composite to break, resulting in transverse cracks at the centre of the impact point. These cracks are approximately the same size as the diameter of the impactor. The laminate experiences both elastic and plastic deformation, and the damage area expands beyond the initial indentation. The fully perforated stage occurs when cracks propagate throughout the thickness of the laminate. Cracks extend from the impact point and spread laterally, causing delamination and fibre breakage. The laminate experiences significant damage, and the load-carrying capacity is reduced. The damage area is larger compared to the partially perforated stage. Finally, the penetration stage is reached when the impactor penetrates through the entire thickness of the laminate. This stage occurs when the impact energy is sufficient to overcome the strength of the laminate. The impactor passes through all the surface layers, resulting in complete perforation.

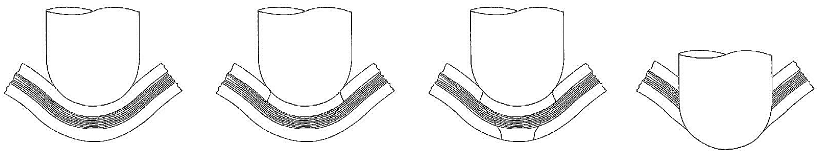


Figure 3. Level of damage associated with: (a) indented, (b) moderate perforated, (c) wholly perforated, and (d) penetrated [3]

2.0 TESTING PROCEDURE

An assessment for quasi-static indentation (QSI) was carried out using an Instron Universal Testing machine. The quasi-static test is not designed to be performed by using the compression plate alone, leading to the fabrication of the indenter with a diameter of 12.7 mm. The material clamper's outside and inner diameters are 160 mm and 127 mm, respectively. Figure 4 shows the Instron type 3369 universal testing machine for the QSI test together with the indenter and material clamper.

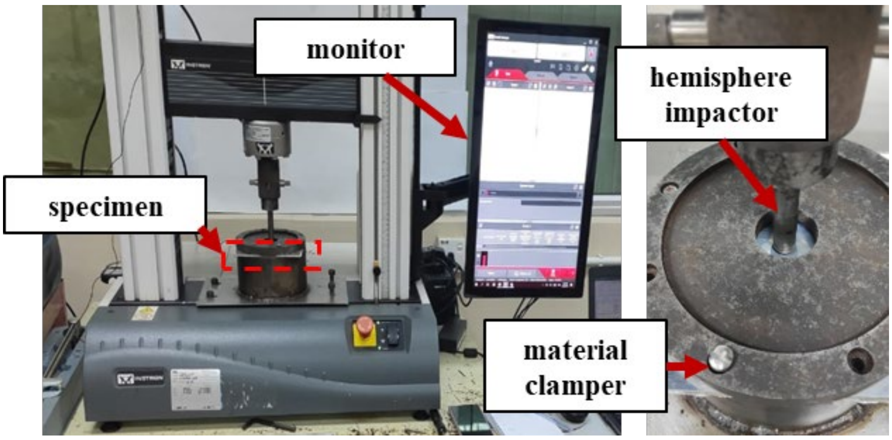


Figure 4. Indentation test setup using Instron type 3369 machine

The analysis of the mechanical response observed during testing is often influenced by the characteristics of the metal, while the ductility of the material components also contributes to the mechanism of failure. In the QSI test, the measurement of the response can be conducted using damper models, while particular attention should be given to the assessment of flexural displacement. The computation of the energy resulting from the flexural deformation caused by the contact of a projectile on a plate can be determined by analyzing the stress and strain of the plate. The development of an analytical model relies on the flexural behaviour of a plate. Following on that, the plate exhibits two distinct regions: the damaged region and the undamaged zone. As depicted in Figure 4, quasi-static indentation samples were tested with the Instron 3369 universal testing machine at cross-head speeds of 1, 5, 10, and 50 mm/min, respectively. The computer numerical control (CNC) machine was used to fabricate a hemispherical nose indenter for the testing equipment. During testing, the indenter had a diameter of around 12.7 mm, and the QSI sample was clamped with a clamper. Three type of specimens 3/2 layer FML consisting of AL/CFRP, AL/GFRP and AL/SRPP, size 150 mm x 150 mm as per Figure 5 below, was fixed using a material clamper with an outside and inner diameter of 160 and 127 mm, respectively. The results of the QSI test were gathered and analyzed in a load-displacement trace. The load (N) versus central deflection (mm) data was compiled and captured for interpretation. Characteristic of the fracture pattern in perforation behaviour between the different layers of FML by using microstructure analysis.

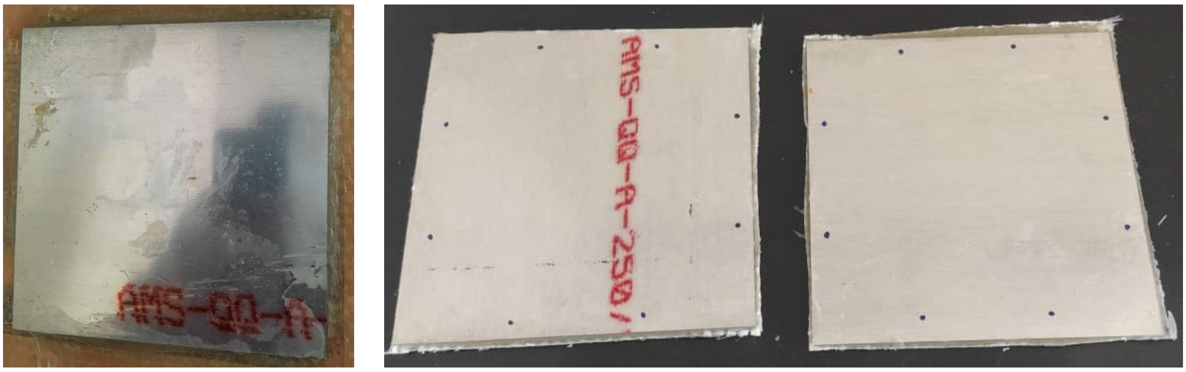


Figure 5. The FML specimens for QSI test

3.0 RESULTS AND DISCUSSION

3.1 Results of Fibre Metal Laminate 3/2 Configuration

Three types of FML were evaluated in the experiment, particularly Carbon Fibre Reinforced Polymer (CFRP), Glass Fibre Reinforced Polymer (GFRP), and Self Reinforced Polypropylene (SRPP). The variables of cross-head speed (mm/min) and type of material were held constant while the maximum load cell was set at 30 kN. The graph displays the relationship between Load (kN) and Displacement (mm), with all the observed results being presented. To acquire reliable results, every parameter was tested on three specimens. The dimensions of the specimen were established at 150 mm × 150 mm.

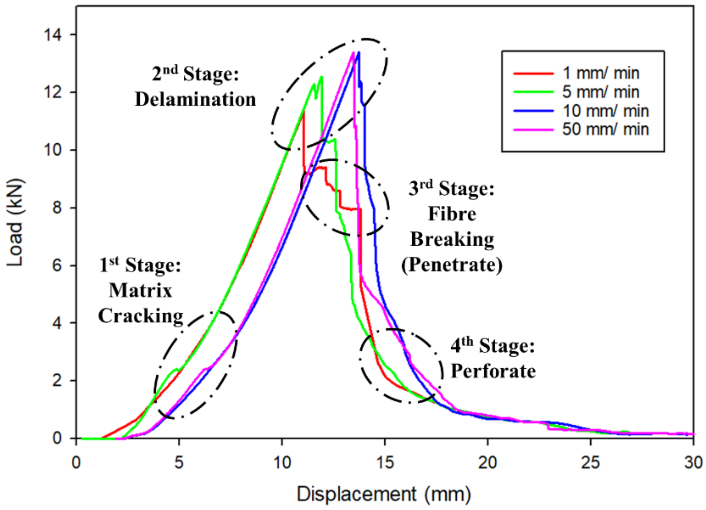
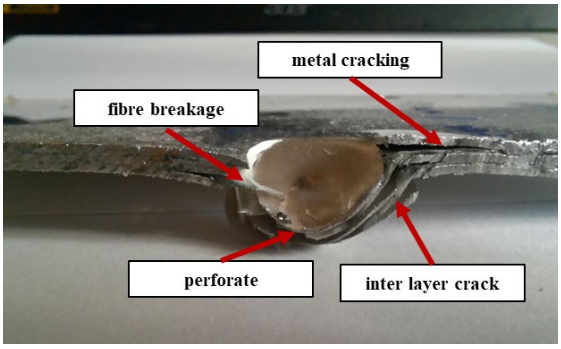


Figure 6. Load against central deflection in 3/2 layer aluminium/GFRP

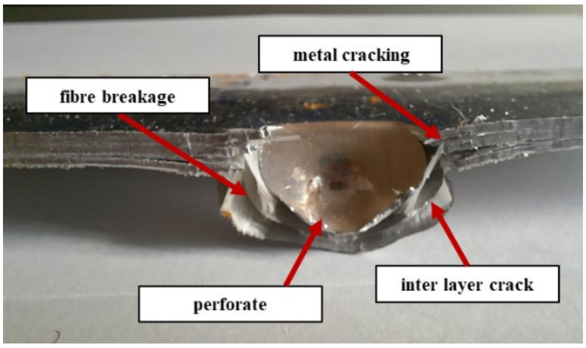
The FML responded with the highest yield load when three specimens were tested at one cross-head speed. In terms of force (kN) shown in Table 2, 50 mm/min can withstand greater than other parameters of 1, 5 and 50 mm/min, at 11.40 kN, 12.65 kN and 13.40 kN, respectively. Continued loading caused matrix cracking, which was happening in a stable state. When the value exceeded 11.40 kN, the parameter of speed 1mm/min in FML fracture began to form. In contrast, FML can withstand a load of 13.41 kN at 50 mm/min before it begins to shatter. The load-central deflection curve showed a little residual displacement at the contact area. The 5 mm/min crack growth started at a value above 12.65 kN, but the 10 mm/min cross-head speed crack growth started at a value beyond 13.40 kN. The breakage patterns exhibit a noticeable spike in their pattern when the speed of the head is above a certain threshold and produces a petal pattern. The specimen subjected at velocity of 50 mm/min exhibited superior performance as compared to the FML specimens affected at velocities of 1 mm/min, 5 mm/min, and 10 mm/min. As depicted in Figure 6, the fracture of the laminate resulting from cracking and the degradation of the interface between the matrix and the fibre are observed. The aluminium's cracking and the fibres' rupture behaviour are both indicated by the sound of fracture.

Table 2. The 3/2 layer of aluminium/GFRP experimental data

Speed (mm/min)	Maximum Force (kN)	Energy (J)	Observations
1	11.40	72.18	Penetrate
5	12.65	76.17	Penetrate
10	13.40	80.83	Penetrate
50	13.41	76.72	Penetrate



(a)



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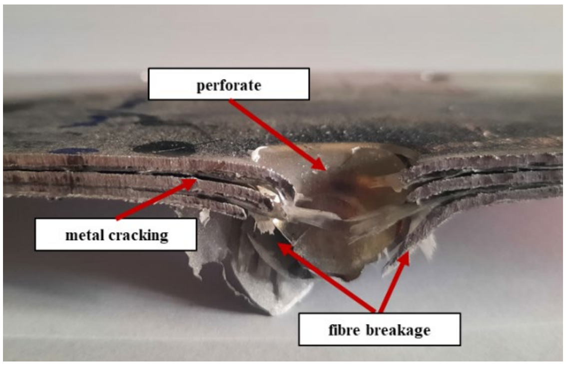

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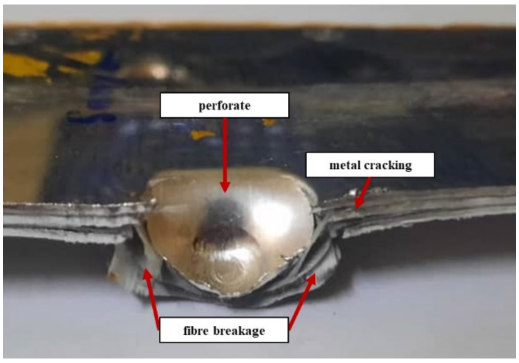


(d)

Figure 7. Fractured cross-sectional view of glass fibre metal laminate at four different cross-head speeds: (a) 1 mm/mm, (b) 5 mm/mm, (c) 10 mm/mm and (d) 50 mm/mm

Figure 7 displays a cross-sectional view of a fracture in a glass fibre metal laminate. It indicates that all specimens tested were penetrated by an indenter with a diameter of 12.70 mm. Maximum force increased due to the FML reinforcement with Epoxy's strong interlaminar bonds.

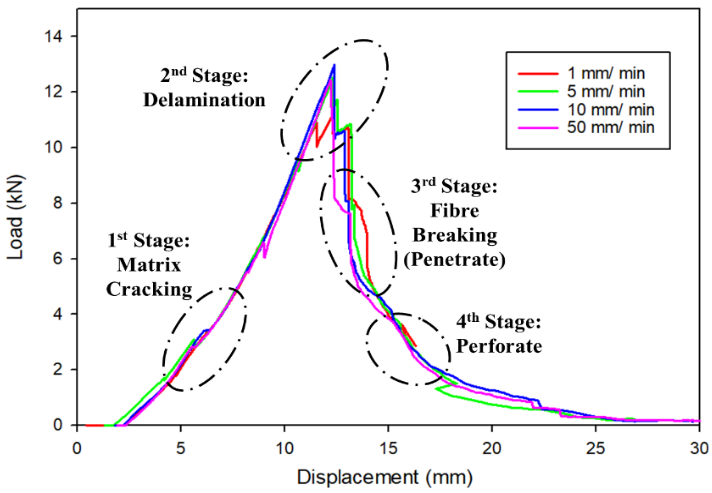


Figure 8. Load against central deflection in 3/2 layer aluminium/CFRP

The graph in Figure 8 illustrates a positive correlation between the increase in cross-head speed and the degradation of the material. The delamination process persists until it reaches the perforated stage. During the testing process, a sequence of crack sounds were observed, indicating the rupture of the interlayer within the layer. The fracture cross section of carbon fibre metal laminate exhibits consistent damage morphologies, including petal cracking. The demonstration of a high maximum force indicates a significant amount of residual energy remaining in the impactor subsequent to its complete penetration of the specimen. The occurrence of the crack is associated with an increased transverse shearing stress, which is linked to the applied contact force. The specimen underwent penetration during the third stage of failure, following a progressive rise in stress until it reached the point of plastic deformation. The dissipated energy would signify the energy expended in overcoming the resistance of the indenter. The evaluation of the performance of the aluminium carbon fibre laminate was conducted using a QSI test with varying cross-head speeds. Dry carbon fibre fabric is employed as a composite material in conjunction with thermoset resin. The resin is carefully mixed with an appropriate percentage of hardener to provide a strong binding between the aluminium metal and the composite matrix. According to the Figure 8, there is a clear correlation between the rise in cross-head speed and the degradation of the material. The delamination process persists until it reaches the perforated stage. Several series of crack sounds were audible throughout the testing, indicating that the FML's interlayer was about to rupture.

Table 3. The 3/2 layer aluminium/CFRP experimental data

Speed (mm/min)	Maximum Force (kN)	Energy (J)	Observations
1	11.14	73.23	Penetrate
5	12.51	80.30	Penetrate
10	12.98	82.88	Penetrate
50	12.43	78.30	Penetrate

The energy utilized in fracturing the specimen was determined by analyzing the Load-Displacement graph depicted in Figure 9, which was derived from data in Table 3 which obtained during a QSI test. The independent variable in this study is the cross-head speed, which was manipulated at four levels: 1, 5, 10, and 50 mm/min. The specimen subjected to a cross-head speed of 10 mm/min exhibited a higher force tolerance compared to the specimen tested at a speed of 5 mm/min, with values of 12.98 kN and 12.51 kN, respectively. The fracture of the FML occurs at a rate of 1 mm/min, with a load exceeding 11.14 kN. In contrast, when subjected to a speed of 50 mm/min, FML exhibits the ability to withstand a load of 12.43 kN before showing signs of cracking.

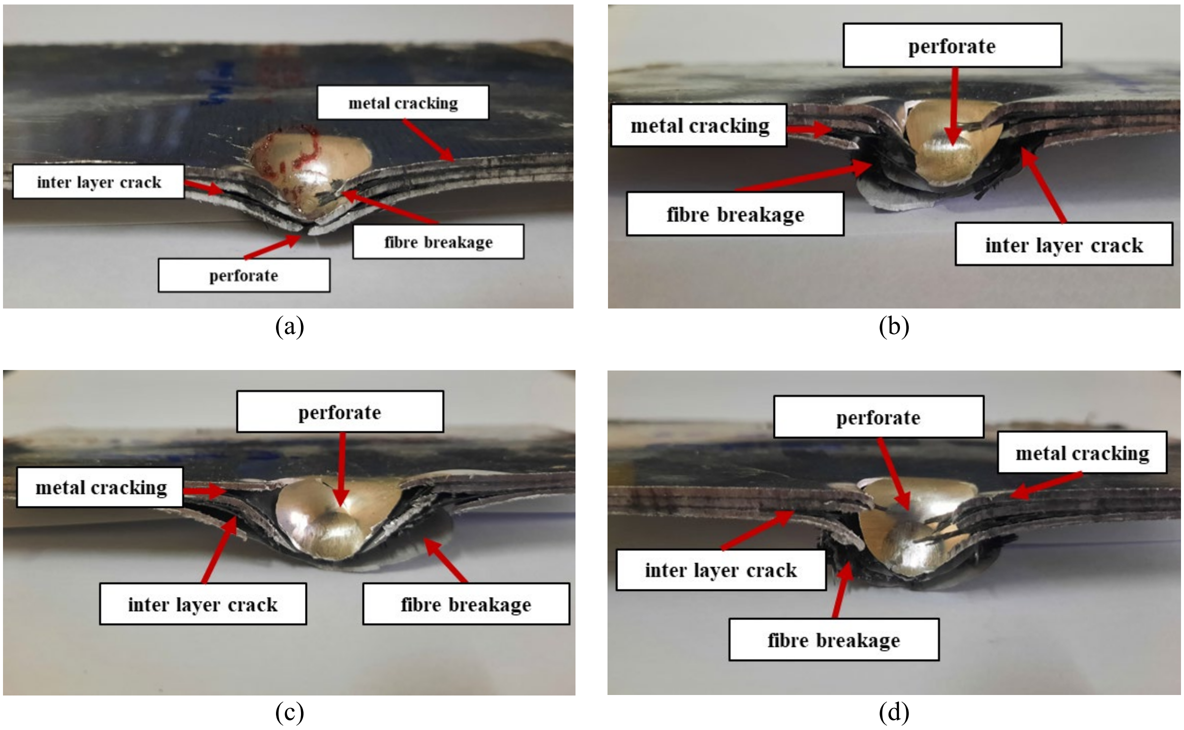


Figure 9. Fractured cross-sectional view of carbon fibre metal laminate at different speeds: (a) 1 mm/mm, (b) 5 mm/mm, (c) 10 mm/mm and (d) 50 mm/mm

Figure 9 presents a cross-sectional view of the indentation damage observed in the aluminium/carbon fibre laminate. The damage is depicted for various cross-head speeds employed during the indentation process. The assessment of a composite construction is conducted by analyzing the damage cross-section. Delamination is a common occurrence observed in the interface between a sheet metal and a fibre layer, typically arising subsequent to the occurrence of matrix and fibre breaking. The analysis of the damage cross section on the fibre metal laminates was conducted, afterwards followed by the progressive increase in the cross-head speed during the indentation process.

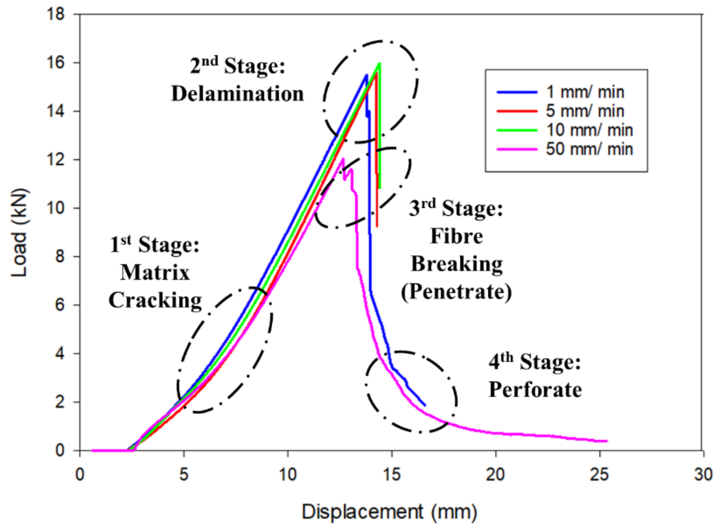


Figure 10. Load against central deflection in 3/2 layer aluminium/SRPP

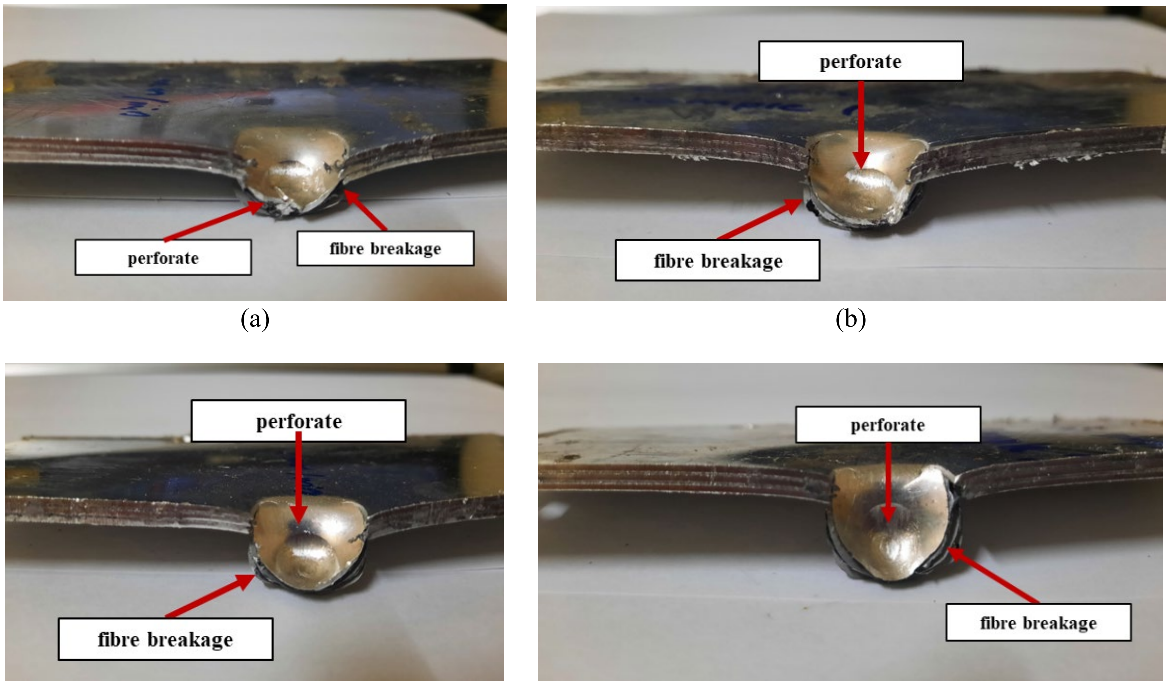
The degradation of structure manifests in a range of failure modes, including delamination, matrix cracking, and fibre breakage. Upon application of force from the indenter, the upper surface of the specimen exhibited bending. According to the Figure 10, it can be shown that the load resistance of FML at a cross-head speed of 5 mm/min exhibited superior performance compared to that at 1 mm/min, with values of 15.61 kN and 15.00 kN, respectively. During the initial phase, the specimen experienced material deformation at a rate of 50 mm/min from the beginning until it reached its maximum load of 12.05 kN. The distortion was a result of the application of a maximum load on the specimen. The third stage, is characterized by the occurrence of fibre splitting. At this juncture, the indenter successfully pierced the specimen under load of 7.21 kN. A summary of the experimental data as in Table 4. The fibre metal laminate exhibited four distinct stages of failure. Upon the application of force by the indenter onto the fibre metal laminate, the laminate experiences a pre-load prior to the subsequent load, causing a transition in the behaviour of the laminate from elasticity to plasticity, resulting in permanent deformation.

Table 4. The 3/2 layer aluminium/SRPP experimental data

Speed (mm/min)	Maximum Force (kN)	Energy (J)	Observations
1	15.00	87.82	Penetrate
5	15.61	75.85	Penetrate
10	15.20	79.48	Penetrate
50	12.05	77.66	Penetrate

The interlayer's behaviour involves the maintenance of a bond between the sheet metal and the SRPP through the presence of a melted adhesive film. The application of force exerted by the impactor would result in structural failure in some areas. However, cohesion between layers would be compromised if the bonding between substrates collapsed. An increase in cross-head speed would lead to the breakdown of the composite structure. The structural degradation occurred within the central region, where the indenter exerted a perpendicular force on the top surface of the fibre metal laminate.

The delamination layer failure stage, fibre failure phase, plastic deformation, and cracking propagation of the aluminium layer were observed at cross-head speeds of 1, 5, 10, and 50 mm/min, as shown in Figure 10. The energy utilized to rebound the indenter would be made up as energy loss. The graph displays the results of an indenter applied to the top surface of an aluminium alloy under a progressive load, causing damage or deformation on the surface once the maximum force acts on it. In the beginning, the matrix structure experienced a localized fracture. After the laminate has been stressed to its maximum bending point, an indentation has been produced through the upper and bottom ply of the aluminium alloy. In the third phase of failure, the laminate perforated. As can be seen in the preceding graph, perforation necessitated a certain degree of local ductility. The composite structure began to fail at a faster rate as the cross-head speed was increased. The sound of cracking indicates that the fibre has broken and the aluminium alloy has cracked. Following its passage through the target, the indenter leaves a hole with the same diameter as itself. All specimens were perforated at the range of and the highest force act to 3/2 AL/CFRP before delamination was reported at 12.43 kN, AL/ GFRP at 13.41 kN and AL/ SRPP at 15.61 kN. Even though SRPP reaches the highest force between the specimens but its shows low stiffness characteristic. The SRPP graph shows that, once the delamination stage occurred, there was only slight resistance of fibre-breaking penetration from the material to perforated.



(d)

Figure 11. Fractured cross-sectional view of SRPP/FML at four different speeds: (a) 1 mm/mm, (b) 5 mm/mm, (c) 10 mm/mm and (d) 50 mm/mm

The cross-section views are shown in Figure 11 to investigate the actual failure pattern of the specimens. The SRPP indicated a good bonding within the ply due to thin PP film heating process to strongly bond the aluminium and the SRPP material through hot press machine. Furthermore, the AL/SRPP graph shows that the matrix cracking stage is slightly indicated due to this good bonding layer but has low stiffness characteristics.

4.0 CONCLUSION

This study fills a gap in the research field by applying fibre metal laminate materials to evaluate potential lightweight automotive materials and analyze perforation responses through quasi-static indentation tests. When the load reaches its maximum value, the load-displacement graph exhibits an ascendent trend until the peak value and starts to curve down once the deformation phase occurs. The load-displacement line was not smooth, and some fluctuations were discovered due to the resistance act towards the acting force. The material of the fibre metal laminate was affected by the loading as the load was raised, which was attributed to the rigidity of the structure. Maximum loading has an impact on the primary damage of a lamination. It is possible for matrix cracking and fibre breaking to occur at any time. The AL/GFRP presents the better bonding layer between the ply, in which the adhesive delamination is affected nearby the delamination area, whereas the AL/CFRP delamination area spreads wide from the radius of the delamination area. Due to the delamination of the laminate in AL/GFRP, there were a number of transverse cracks of the fibre breakage resistance, particularly at the centre of the specimen. Also, petal patterns were spotted in all specimens tested where the same damage characteristic was visible. These studies highlight the importance of hybridization and fabric structure in determining the mechanical properties, impact resistance, and fatigue behaviour of FMLs. The combination of different fibre types and metal layers allows for optimising the material's performance for specific applications. Understanding the behaviour of FMLs under different loading conditions is crucial for their successful implementation in various industries.

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6.0 REFERENCES

[1] M. Heibeck, M. Rudolph, N. Modler, M. Reuter, and A. Filippatos, “Characterizing material liberation of multi-material lightweight structures from shredding experiments and finite element simulations,” *Minerals Engineering,* vol. 172, p. 107142, 2021.

[2] G. Kopp, E. Beeh, R. Schšll, A. Kobilke, P. Stra§burger, and M. Krieschera, “New Lightweight Structures for Advanced Automotive Vehicles–Safe and Modular,” *Procedia - Social and Behavioral Sciences,* vol. 48, pp. 350-362, 2012.

[3] N. K. Romli, M. R. M. Rejab, D. Bachtiar, J. Siregar, M. F. Rani, W. S. W. Harun, S. M. Salleh, and M. N. M. Merzuki, "The behavior of Aluminium Carbon/Epoxy fibre metal laminate under quasi-static loading," *IOP Conference Series: Materials Science and Engineering,* vol. 257, p. 012046, 2017.

[4] M. Quanjin, M. Merzuki, M. Rejab, M. Sani, and B. Zhang, "A review of the dynamic analysis and free vibration analysis on fiber metal laminates (FMLs)," *Functional Composites and Structures*, vol. 5, p. 012003, 2023.

[5] D. Ganesarajan, L. Simon, S. Tamrakar, A. Kiziltas, D. Mielewski, N. Behabtu, and C. Lenges, "Hybrid composites with engineered polysaccharides for automotive lightweight," *Composites Part C: Open Access,* vol. 7, p. 100222, 2022.

[6] Y. Chu, L. Sun, and L. Li, "Lightweight scheme selection for automotive safety structures using a quantifiable multi-objective approach," *Journal of Cleaner Production,* vol. 241, p. 118316, 2019.

[7] U. A. Shakil, M. R. Mat Rejab, N. Sazali, S. A. Hassan, M. Y. Yahya, and Q. Ma, "Damage characterisation of amine-functionalized MWCNT reinforced carbon/epoxy composites under indentation loading," *Journal of Materials Research and Technology,* vol. 24, pp. 6713-6729, 2023.

[8] N. R. J. Hynes, N. J. Vignesh, J. T. W. Jappes, P. S. Velu, C. Barile, M. A. Ali, M. U. Farooq, and C. I. Pruncu, "Effect of stacking sequence of fibre metal laminates with carbon fibre reinforced composites on mechanical attributes: Numerical simulations and experimental validation," *Composites Science and Technology,* vol. 221, p. 109303, 2022.

[9] Q. Ma, M. Rejab, S. A. Hassan, H. Hu, M. Azeem, and A. Y. Nasution, "Impact behaviour of spherical-roof contoured-core (SRCC) sandwich panel under the low-velocity impact (LVI): A numerical investigation," *Materials Today: Proceedings*, 2023.

[10] B. M. C. Rajan, A. Kumar, T. Sornakumar, and A. S. Kumaar, "Impact response and damage characteristics of carbon fibre reinforced aluminium laminates (CARAL) under low velocity impact tests," *Materials Today: Proceedings,* vol. 5, no. 9, pp. 20070-20077, 2018.

[11] T. Sinmazçelik, E. Avcu, M. Ö. Bora, and O. Çoban, "A review: Fibre metal laminates, background, bonding types and applied test methods," *Materials & Design,* vol. 32, no. 7, pp. 3671-3685, 2011.

[12] L. M. G. Vieira, J. C. dos Santos, T. H. Panzera, J. C. C. Rubio, and F. Scarpa, "Novel fibre metal laminate sandwich composite structure with sisal woven core," *Industrial Crops and Products,* vol. 99, pp. 189-195, 2017.

[13] S. S. Saravanakumar, A. Kumaravel, T. Nagarajan, and I. G. Moorthy, "Investigation of physico-chemical properties of alkali-treated Prosopis juliflora fibers," *International Journal of Polymer Analysis and Characterization,* vol. 19, no. 4, pp. 309-317, 2014.

[14] D. Chen, Q. Luo, M. Meng, Q. Li, and G. Sun, "Low velocity impact behavior of interlayer hybrid composite laminates with carbon/glass/basalt fibres," *Composites Part B: Engineering,* vol. 176, p. 107191, 2019.

[15] N. L. Feng, S. D. Malingam, and 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, 2020.

[16] M. Kuhtz, N. Buschner, T. Henseler, A. Hornig, M. Klaerner, M. Ullmann, H. Jäger, L. Kroll, and R. Kawalla, "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.

[17] K. Jin, K. Chen, X. Luo, and J. Tao, "Fatigue crack growth and delamination mechanisms of Ti/CFRP fibre metal laminates at high temperatures," *Fatigue & Fracture of Engineering Materials & Structures,* vol. 43, no. 6, pp. 1115-1125, 2020.

[18] X. Li, M. Y. Yahya, A. Bassiri Nia, Z. Wang, and G. Lu, "Dynamic failure of fibre-metal laminates under impact loading – experimental observations," *Journal of Reinforced Plastics and Composites,* vol. 35, no. 4, pp. 305-319, 2015.

[19] A. Davar, S. M. R. Khalili, and K. M. Fard, "Assessment of different higher order theories for low-velocity impact analysis of fibre-metal laminate cylindrical shells," *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications,* vol. 228, no. 3, pp. 160-189, 2013.

[20] P. Jakubczak, M. Drozdziel, P. Podolak, and J. Pernas-Sanchez, "Experimental investigation on the low velocity impact response of fibre foam metal laminates," *Materials,* vol. 14, no. 19, p. 5510, 2021.

[21] Q. Ma, and M. Rejab, "The energy-absorbing characteristics of two-dimensional periodic self-reinforced polypropylene (SRPP) sandwich panel," *Science Talks,* vol. 6, p. 100170, 2023.

[22] G. Bold, M. Langer, L. Bornert, and T. Speck, "The protective role of bark and bark fibers of the giant sequoia (Sequoiadendron giganteum) during high-energy impacts," *International Journal of Molecular Sciences,* vol. 21, p. 3355, 2020.

[23] T. Trzepiecinski, A. Kubit, R. Kudelski, P. Kwolek, and A. Obłój, “Strength properties of aluminium/glass-fiber-reinforced laminate with additional epoxy adhesive film interlayer,” *International Journal of Adhesion and Adhesives,* vol. 85, pp. 29-36, 2018.

[24] A. Vlot, E. Kroon, and G. La Rocca, “Impact response of fiber metal laminates,” *Key Engineering Materials,* vol. 141-143, pp. 235-276, 1997.

[25] M. Salvetti, A. Gilioli, C. Sbarufatti, A. Manes, and M. Giglio, “Analytical model of the dynamic behaviour of CFRP plates subjected to low-velocity impacts,” *Composites Part B: Engineering,* vol. 142, pp. 47-55, 2018.