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BALLISTIC IMPACT RESPONSE OF FIBRE METAL LAMINATES BASED ON RAMIE FIBRE WOVEN REINFORCED POLYESTER

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ABSTRACT

This research focused on evaluating the ballistic impact behavior of polyester-reinforced woven ramie fibers combined with aluminum fiber metal laminates (FMLs). The materials were structured in four specific configurations: two types of ramie composites (2-layer and 3-layer) and two FML configurations FML 2/2 and FML 2/3. Ballistic performance was assessed through both experimental and numerical testing under a controlled firing angle of 90 degrees with 9 mm projectiles. The findings clearly showed that the FMLs had superior energy absorption capabilities compared to pure ramie composites, with the FML 2/3 configuration standing out, absorbing 52.69 J of energy. This highlights the enhanced ballistic resilience of hybrid laminates, especially with increased composite layers. Therefore, the FML, particularly the FML 2/3, exhibits a significantly higher energy-absorbing capacity, making it more effective in reducing projectile performance post-penetration. The FML 2/3 configuration showed the greatest reduction in residual velocity in both experimental and simulation results, indicating superior effectiveness in absorbing ballistic energy compared to the other configurations. This finding suggests that adding layers to the composite, especially in the FML configuration, enhances the material's resistance to projectile penetration and effectively decreases the projectile's residual velocity. However, additional research is necessary to gain a comprehensive understanding of the high-velocity performance of thermoplastic fiber metal laminates (FMLs), particularly for their potential use in industrial applications.

Keywords: fiber metal laminate, ballistic impact, ramie woven, aluminium, polyester, composite.

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INTRODUCTION

In the last century, the demands stipulated by various application areas in the automotive and aerospace industries such as the need for lightweight structures, material damage resistance, and low fuel consumption have, if not changed, at least significantly increased, necessitating the design of new structural systems (Allah *et al*., 2023; Etri *et al*., 2022; Fadly, Bakri, *et al*., 2023). Fiber Metal Laminates (FMLs) offer a promising solution, as they can be designed by combining metal layers with fiber-reinforced polymers (FRP). FMLs are hybrid structures that mechanically combine the properties of their constituents. They not only possess the mechanical properties of metals but also exhibit improved fatigue and impact resistance compared to standard FRPs (Etri et al., 2022; Qureshi, 2022; Bakri *et al*., 2023; Asyraf *et al*., 2022; Reichenbach *et al*., 2021; Krajangsawasdi *et al*., 2021; Fadly, Purnowidodo, *et al*., 2023; Tao *et al*., 2023). These enhanced properties have led to the use of FMLs as structural components in aircraft (Ulus & Kaybal, 2023; Wang *et al*., 2024; Costa *et al*., 2023).

Due to the potential applications of FMLs, various constructions have been developed with different numbers of layers, metal thicknesses, and fiber preform layouts combined with overall configurations (Serubibi *et al*., 2023; Kavitha *et al*., 2020; Smolnicki *et al*., 2023). Recent studies have investigated FMLs with metal layer thicknesses ranging from 0.2 to 0.6 mm (Sharma *et al*., 2021; Kakati & Chakraborty, 2020; Zarezadeh-mehrizi *et al*., 2022; Megeri & Naik, 2021; Ferrante *et al*., 2016). In quasi-static and low-velocity impact studies, metal layers with thicknesses ranging from 0.2 to 0.6 mm were utilized, whereas thicker metal layers of 0.8 mm were specifically used for high-velocity impact studies (Khoramishad *et al*., 2018).

FML construction has been studied using a variety of metals and other composites. Light metal layers such as aluminum alloys (Antipov *et al*., 2012), titanium (Nassir *et al*., 2020), and magnesium (Cortés & Cantwell, 2005) have been applied. Both thermoset and thermoplastic matrices have been experimented with for the composite layers, along with different types of reinforcing fibers, including carbon (Alderliesten, 2017), aramid (Bellini *et al*., 2020), and glass fibers (Jalali Aghchai & Khatami, 2018). Fiber metal laminates (FMLs) have been widely researched under different loading conditions, including quasi-static bending and denting, blast loading, low-velocity impact, and high-velocity impact. For instance, Reyes (2010) conducted uniaxial tensile tests on thermoplastic-based FMLs, which were constructed with layers of aluminum alloy sandwiched between glass fiber-reinforced polypropylene. Their findings indicate that FMLs follow a rule of mixtures regarding elastic moduli and ultimate strength, depending on different stacking sequences. In general, the tensile strength of fiber metal laminates (FMLs) tends to increase as the volume fraction of composite material rises, while the tensile modulus decreases accordingly.

Carrillo *et al* (2019) investigated the low-velocity impact behavior of fiber metal laminates (FMLs) composed

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of polypropylene reinforced with aramid fibers and aluminum alloy Al 5052-H32. Their findings revealed that the 3/4 layer configuration (consisting of 3 aluminum layers and 4 composite layers) achieved the highest specific energy absorption [J/(kg)] at both the damage threshold and first perforation, outperforming other configurations in the study. Optical analysis revealed that the primary damage modes included plastic deformation and tearing of the aluminum layers, accompanied by delamination; these phenomena led to fiber failure, which contributed to energy dissipation. In a similar study, Kaboglu *et al*. (2018) utilized a light-gas gun to assess the bending capacities and low-velocity impacts (~270 m/s) in the quasi-static regime on fiber metal laminates (FMLs) made of glass fiber-reinforced epoxy composite with laminated aluminum. The study highlighted that strong adhesion between the metal and composite layers was key to enhancing the tensile strength of the FMLs, confirming the effectiveness of bonding techniques. Furthermore, the FML properties showed slight improvements as the number of alternating layers of aluminum alloy and fiber composite increased.

In recent years, numerous studies have explored the use of thermoplastic materials as the matrix phase for fiber metal laminates (Santiago *et al*., 2017. The adoption of thermoplastic composites has the potential to reduce manufacturing times, which in turn lowers production costs. Thermoplastic-based FMLs have shown superior impact resistance and energy absorption mechanisms compared to their thermoset-based counterparts (Sexton *et al*., 2014). For instance, Carrillo *et al* (2019) investigated the low-velocity impact behavior of FMLs composed of aluminum and self-reinforced polypropylene (SRPP), noting that the thinning and cracking of SRPP layers contributed to high energy absorption rates. Similarly, Cortés (2014) found that while the onset of damage, indicated by minimum perforation impact energy, was higher in plain composites than in SRPP FMLs and aluminum alloy FMLs, the latter still demonstrated strong performance. Santiago et al. examined the impact response of thermoplastic-based FMLs, revealing improved mechanical behavior compared to FMLs made with epoxy chop glass fibers.

Building on the existing literature and acknowledging the limited understanding of the dynamic behavior of thermoplastic FMLs incorporating woven ramie fiber, this study focuses on an experimental and numerical modeling investigation of the ballistic impact response of FMLs made from polyester-reinforced woven ramie fiber and aluminum plates. Two specific configurations of thermoplastic FMLs and their constituent materials were explored. Tensile and ballistic impact tests were conducted across various impact energy levels, with a detailed analysis of the energy absorption mechanisms during the impact.

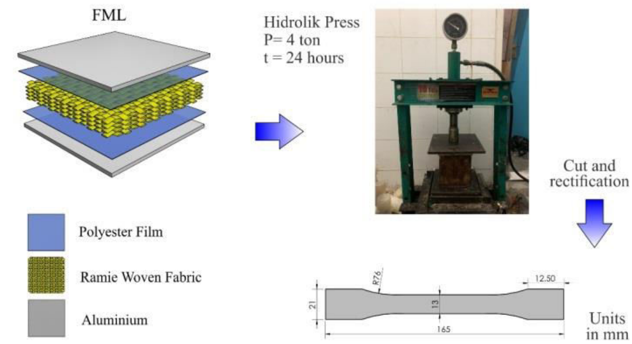

Figure-1. FML stacking sequence and specimen geometry for tensile testing.

MATERIALS AND METHODS

Materials and Manufacture

The FML used consists of aluminum plates with a thickness of 0.4 mm in the outer layers. The sample dimensions are 150 x 150 mm. The ramie fiber reinforcements were woven into plain weave fabric with orientations of 0°/90° in varying numbers of layers. In this study, the composite matrix of the fiber metal laminate (FML) is a thermoplastic polymer, specifically polyester, which also acts as the adhesive between the metal and composite layers through a polyester film. The composite component is constructed using two woven fabrics with a volume fraction of 40%. The specific configurations of the FMLs and their constituent materials, used for mechanical and ballistic testing, are detailed in Table 1. In these FML configurations, the first digit represents the number of metal layers, while the second digit denotes the number of composite layers.

Table-1. Confugiration specimen.

Material	Stacking Sequence
Ramie/polyester 2 layer	$[0/90]_2$
Ramie/polyester 3 layer	$[0/90]_3$
FML 2/2	[Al. 0/90, 0/90, Al]
FML 2/3	[Al. 0/90, 0/90, 0,90, Al]

The stacking sequence of the FML and composite materials, as detailed in Table-1, outlines the number and arrangement of both the aluminum and composite layers. Figure-1 provides a visual representation of the FML fabrication process, which was carried out using the hand lay-up method. Additionally, it illustrates the geometry of the tensile test specimen, prepared according to ASTM D638-03 standards for tensile testing.

Ballistic Test

The ballistic testing aims to observe the phenomena resulting from projectile penetration in the target material. This testing is conducted by the National

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Institute of Justice (NIJ) Standard 0101.06 Level III-A. The ballistic tests are performed at a distance of 5 meters with a normal impact angle (90° to the target sample). The ballistic testing setup is illustrated in Figure-2. Using a 9 mm pistol with full metal jacket (FMJ) hemispherical nose projectiles, as shown in Figure-3. The initial and final velocities of the bullets are measured using a chronograph.

Figure-2. Schematic representation of a ballistic test.

Numerical Modelling

The geometry of the projectile and FML model was developed based on the experimental testing. Modeled in Autodesk Inventor Professional 2016, the projectile and FML models were then exported to ANSYS 18.1 Workbench for simulation. Figure-4 shows the shape and size of the projectile. The FML was meshed with a body sizing of 2 mm in the ballistic impact area, while the projectile jacket and core were meshed with a size of 0.5 mm using tetrahedral meshing (Figure-5). The material data was input based on the tensile strength characteristics of the material.

Figure-3. Gun and projectile.

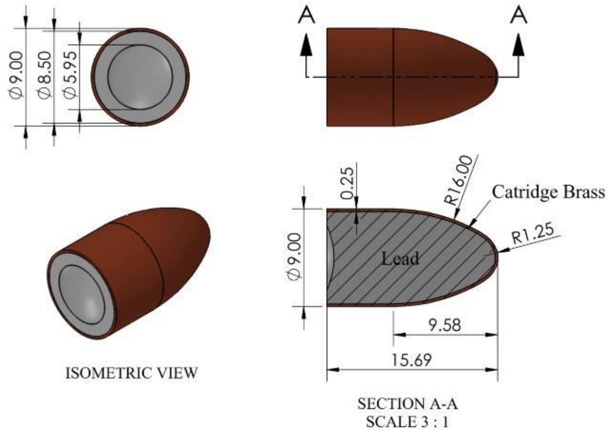

Figure-4. Geometry and measurements of the projectile.

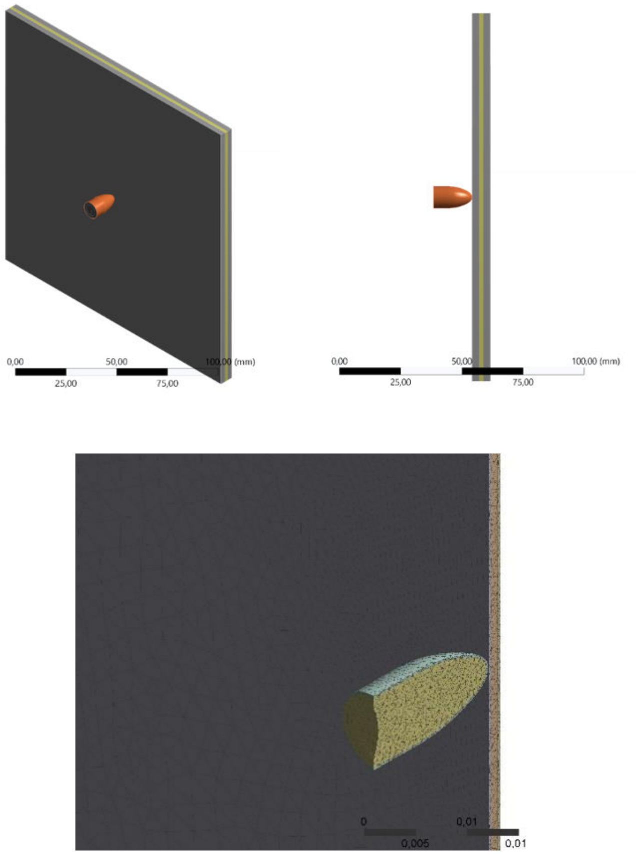

Figure-5. Simulation model and mesh configuration of the specimen

RESULTS AND DISCUSSIONS

Table-2 outlines the material properties used in this study. The experimental findings provided in this paper can serve as valuable data for future numerical studies and model validation, contributing to a deeper understanding of the behavior of thermoplastic FMLs under ballistic impact conditions.

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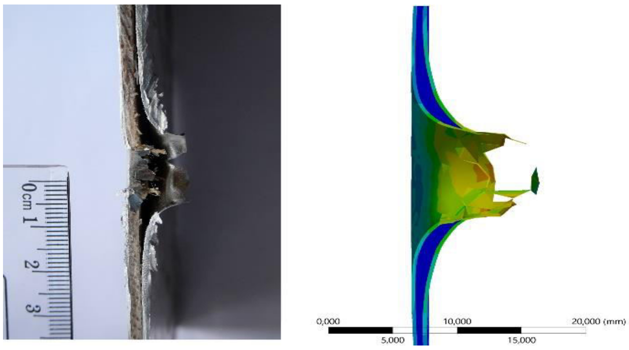
Table-2. Tensile properties material.

Material	Young's modulus (MPa)	Yield strength (MPa)	Ultimate Tensile strength (MPa)	Strain at UTS (mm/mm)
Aluminium	40.36	63.39	120.65	0.056
Ramie Composite	16.06	-	67.35	0.044

The numerical simulation was verified through various test experiments to compare the ballistic impact results between the experiments and the simulation. Figure-6 presents the results of both the experimental and simulation calculations concerning the ballistic effects.



(a) (b)

Figure-6. Results of ballistic tests, (a) experimental; (b) simulated.

The validation of the experimental and simulation results is based on the projectile velocity as it penetrates the material. The final velocity from the experiment, obtained through chronograph measurements, is compared with the simulation results, as shown in Table-3.

The delamination observed in the simulation is greater than that in the experimental results, resulting in a higher final projectile velocity in the simulation compared to the experiment. This discrepancy is due to the lack of bonding between the final layer (backplate) and the preceding layers, causing the last layer to move more easily. According to I. Crouch (2017), delamination failure facilitates membrane stretching, which involves plastic deformation.

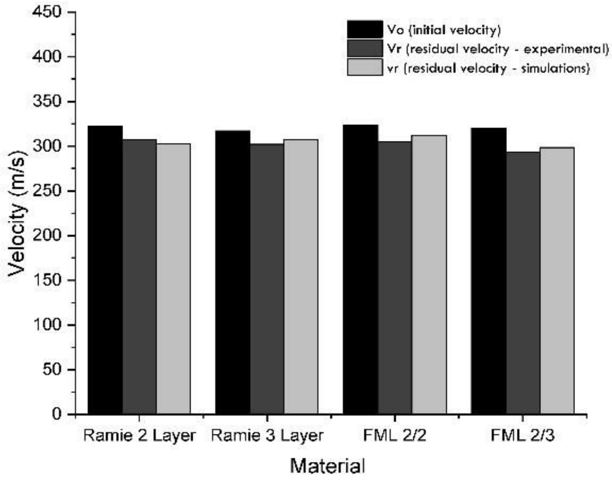


Figure-7. Initial and residual velocity of the material configuration.

Table-3. Comparison of the measured projectile velocity after ballistic impact

Material	Residual velocity (m/s)		%Error
	Exsperimental	Simulations	
Ramie/polyester 2 layer	307.5	302.68	1.59
Ramie/polyester 3 layer	302.1	307.33	1.73
FML 2/2	304.5	311.96	2.44
FML 2/3	293.4	298.56	1.75
Average			**1.88**

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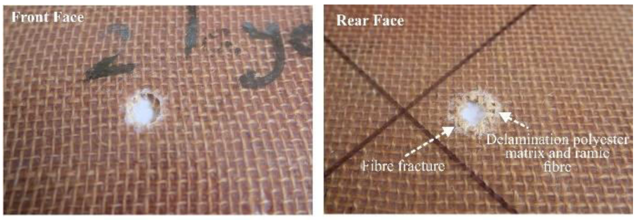
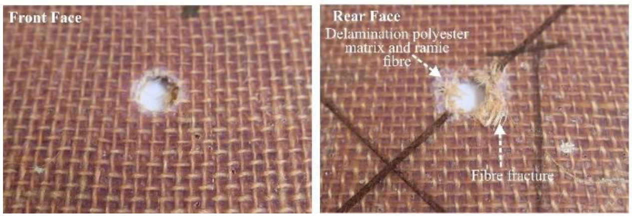
Figure-7 shows that the FML 2/3 configuration exhibits the most significant reduction in residual velocity in both the experimental and simulation results, indicating greater effectiveness in absorbing ballistic energy compared to other configurations. This suggests that adding layers to the composite, particularly in the FML configuration enhances the material's ability to withstand projectile penetration and effectively reduces the projectile's residual velocity.

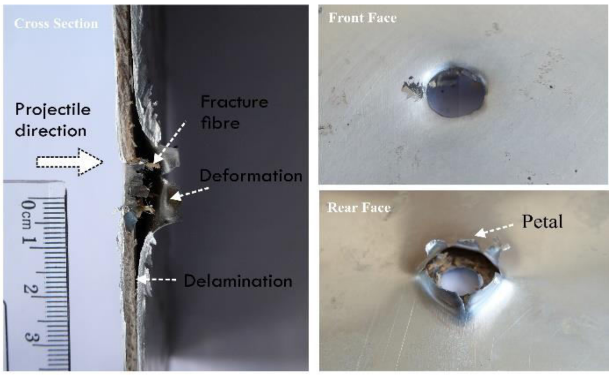


(a)

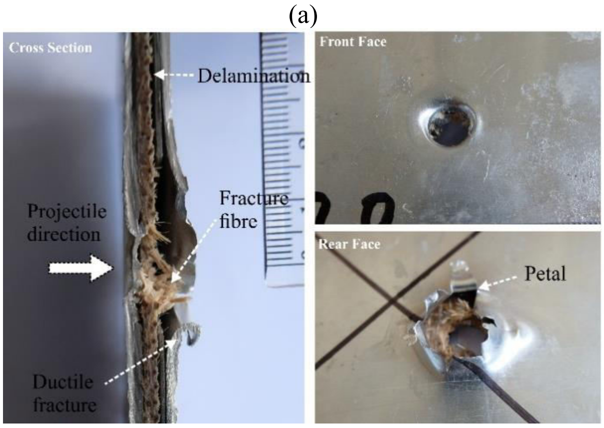


(b)

Figure-8. Ballistic impact in the ramie woven composites, (a) 2 layer, (b) 3 layer.



(a)



(b)

Figure-9. Ballistic impact in the FML, (a) FML 2/2, (b) FML 2/3.

Figure-8 shows that the direct penetration by the projectile indicates areas where the composite has undergone local damage. A clear hole is visible as a result of the projectile's penetration. The image also shows fiber fractures occurring when the projectile's penetration force exceeds the tensile strength of the fibers, causing them to break. A distinct fiber fracture area is visible around the projectile hole. The polyester matrix exhibits cracks due to the stress experienced during penetration, indicating adhesion failure between the fibers and the matrix. Cracks in the matrix can be seen around the projectile hole. There is also potential for delamination between the fiber layers, leading to interlaminar failure.

Figure-9 shows that the projectile penetrates the FML in the direction indicated by the arrow in the image. The projectile causes direct penetration through both the metal and fiber layers, resulting in localized damage. The force exerted by the projectile surpasses the tensile strength of the fibers, leading to fiber breakage. Clear evidence of fiber fracture can be observed around the penetration area, marking the failure points. Additionally, the aluminum layer exhibits plastic deformation, which is visible in the image, further highlighting the material's response under ballistic impact.

This deformation demonstrates how the metal layer absorbs and distributes the energy from the projectile. The formation of 'petals' in the aluminum layer indicates the tensile force exerted by the projectile during penetration, revealing failure mechanisms such as bending and tearing. As shown in Figure-10, at the initial stage of penetration, the projectile impacting the 2-layer ramie composite has an approximate velocity of 320 m/s. Over a brief period of around $1\text{x}10^{-4}$ seconds, this velocity gradually decreases to about 315 m/s, demonstrating that the 2-layer ramie composite is capable of absorbing the projectile's kinetic energy through material deformation, effectively dissipating the impact force. The projectile targeting the 3-layer ramie composite begins penetration with a velocity of approximately 315 m/s and experiences a faster decrease in velocity compared to the 2-layer ramie, reaching 305 m/s after $1\text{x}10^{-4}$ seconds.

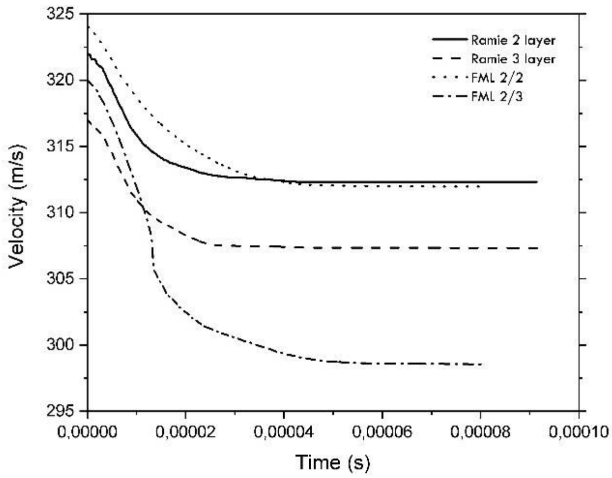


Figure-10. Velocity versus time.

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The FML 2/2 begins penetration with a projectile velocity of about 323 m/s, gradually decreasing to 312 m/s after $1x10^{-4}$ seconds, indicating its effective ability to reduce the projectile's velocity, which reflects the efficient combination of fiber and metal layers in absorbing energy. The FML 2/3, starting penetration with a velocity of 317 m/s, shows the most significant velocity reduction compared to the other targets, reaching about 297 m/s after $1x10^{-4}$ seconds. This demonstrates that the FML 2/3 has the highest resistance to penetration, with the additional metal layer providing greater resistance.

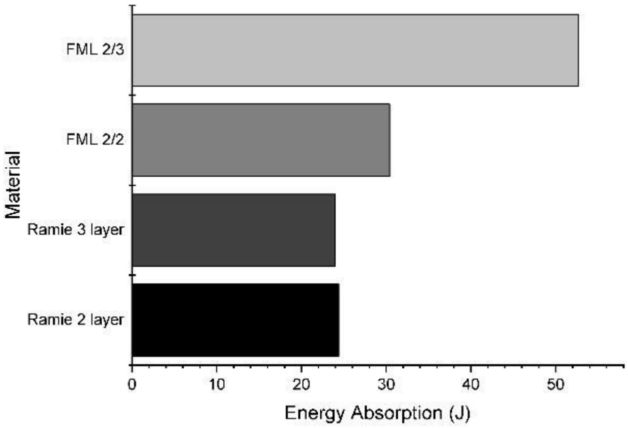

Figure-11. Energy absorbed after a ballistic impact.

Figure-11 shows that the FML exhibits higher energy absorption performance compared to the composite. FML 2/2 absorbs 30.42 joules of energy, while FML 2/3 absorbs the highest energy at 52.69 joules. This demonstrates that the FML configuration, particularly FML 2/3, has a significantly greater energy absorption capacity, making it a more effective material for reducing the impact of projectile penetration.

The penetration process of the projectile at time t (seconds) and the residual velocity of the projectile v (m/s) are shown in Figure-12, 13, 14, and 15. The color changes indicate the magnitude of stress experienced by the material (MPa). A decrease in stress concentration is represented by a change in color, with lower stress levels appearing as a bluer shade. The deformation of the material is greater than that of the projectile, leading to penetration in all material configurations. The projectile successfully penetrates the target, while the target undergoes deformation around the penetration hole. This process results in the formation of petals around the penetration hole.

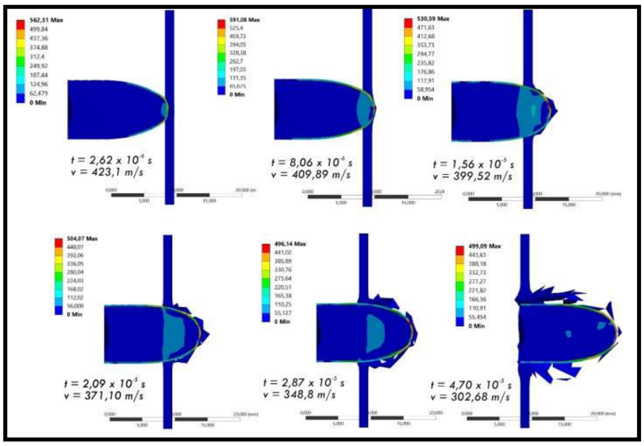

Figure-12. Distribution of equivalent stress and residual velocity of projectiles in 2-layer ramie composite

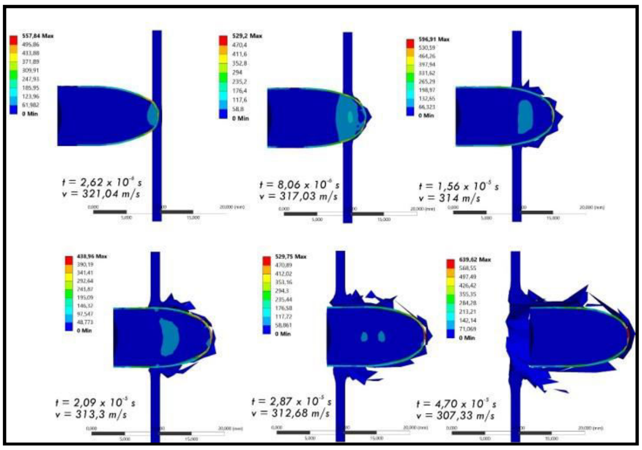

Figure-13. Distribution of equivalent stress and residual velocity of projectiles in 3-layer ramie composite.

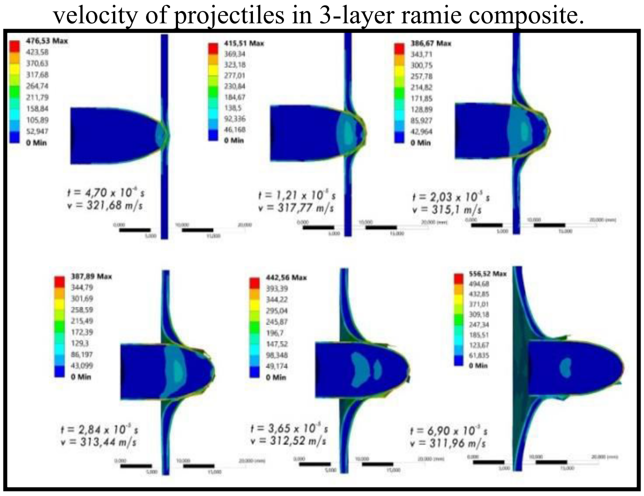

Figure-14. Distribution of equivalent stress and residual velocity of projectiles in FML 2/2.

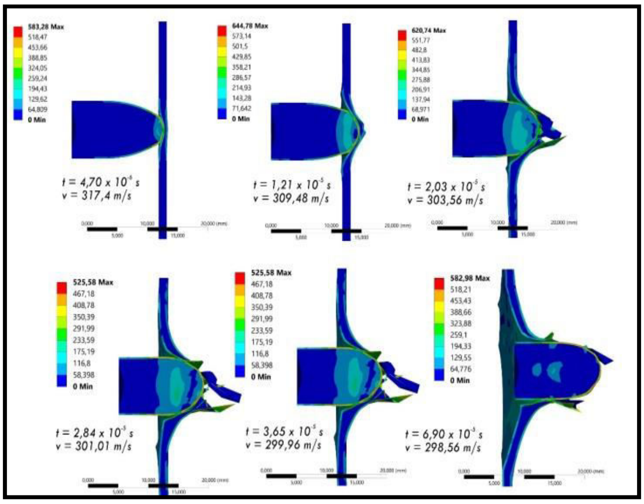

Figure-15. Distribution of equivalent stress and residual velocity of projectiles in FML 2/3.

CONCLUSIONS

The 2-layer and 3-layer ramie composites exhibit fiber fractures and matrix cracking when the projectile penetrates the target. In contrast, FML 2/2 and FML 2/3 display similar characteristics, such as petal failure with ductile fracture and delamination between layers. FML 2/3 demonstrates the best ability to reduce projectile velocity, followed by the 3-layer ramie composite, FML 2/2, and the 2-layer ramie composite. Increasing the number of layers in both the ramie composite and the fiber metal laminate (FML) significantly improves the material's capacity to absorb penetration energy, thereby offering greater resistance to projectile penetration. This enhanced layer structure helps distribute the impact energy more effectively, leading to better protection against penetration. This indicates that adding layers, whether in the ramie composite or FML, improves the material's efficiency in absorbing the projectile's kinetic energy, with FML 2/3 being the most effective material in resisting and reducing projectile velocity during penetration.

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