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EFFECT OF PENETRATION POSITIONS BULLETS ON A PERFORATED PLATE AGAINST BALLISTIC RESISTANCE OF FIBER METAL LAMINATE (FML)

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Abstract

This study aims to examine the phenomena that occur due to projectile penetration on fiber metal laminate. Ballistic testing was carried out experimentally according to National Institute of Justice standards (NIJ Standard 0101.06 level III-A) using a 9 mm full-metal jacket projectile with a normal angle of attack (90° to the target). The results showed that fiber metal laminate could withstand the projectile rate by penetrating the first layer (aluminum plate) and the second layer (aramid/epoxy), while the last layer was deformed to form a bulge. The pierced aluminum plate is characterized by petalling failure. Meanwhile, the aramid/epoxy was penetrated by the projectile with failure of the primary yarn to break the fiber.

Keywords: *Ballistic Impact, Fiber Metal Laminates, Aramid Fiber, Aluminum, Epoxy Matrix.*

1. INTRODUCTION

Recently, the development of bulletproof vest materials has been discovered using new materials, compositional combinations, and the manufacture of composites of both metals and ceramics, as well as fiber- or particle-reinforced polymers. Ballistic behavior with high-speed impact loads is a relevant issue in a variety of structural applications. Many studies have been conducted on impact ballistics both experimentally and numerically to analyze the target material's resistance and performance in terms of penetration and residual velocity of the projectile. However, characteristics such as depth of penetration, damage, failure and microstructure in ballistic impact areas have not been explored in depth.

A wide variety of materials and structures have been produced to increase the demand for the transport sector's light and strong properties. Fiber metal laminate (FML) has attracted a lot of attention due to its outstanding mechanical properties, including excellent fatigue properties and impact resistance [1-4]. Fiber metal laminate (FML) is a fiber-reinforced polymer matrix composite with metal on top and bottom [9]. FML is made by depositing and bonding adhesives on relatively thin layers of metal and fiber-reinforced polymer composites. Various types of metals and composites have been explored to construct FMLs. For the metallic coating, light alloys of aluminum [5], titanium [1,6], and magnesium [7] have been used. For composite coatings, various types of reinforcing fibers, including aramid [8], carbon [9], and glass [10] fibers in a thermosetting or thermoplastic matrix have been investigated.

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Corderley *et al* performed ballistic experimental tests to determine the failure model of epoxy and carbon fiber reinforced titanium (FML). The test was carried out using a projectile with a speed of 2000 m/s. The test results show that one of the mechanisms for the failure of titanium is the formation of adiabatic shear bands. At the same time, the lamination sequence influences the failure model of composite materials [11]. Zu *et al* conducted a ballistic study of composite kevlar fiber reinforced rubber composite armor (KFRRCA) using practical methods to determine the depth of penetration of KFRRCA with a diameter of 56 mm. The results showed that KFRRCA can be used as an armor material because it has excellent protection capabilities, especially when the material is at 30° and 68° [12].

The emergence of very high modulus polyethylene fibers has increased the protective effectiveness of fabrics and generated interest in the protective ballistic performance of composites made of fibers. Many studies have been conducted on various versions of high-strength ceramic laminated fibers. But very few investigations have attempted to explore combinations of high strength metal and laminated fibers [9]. In the present work, the ballistic performance of a FML consisting of an aluminum constituent material and a composite made of an aramid fiber reinforced epoxy matrix was investigated in terms of ballistic impact on a target using scanning electron microscopy (SEM). This study used a 9 mm full metal jacket (FMJ) caliber projectile with a lead core protected by brass and a normal angle of attack (90° to the target).

2. MATERIALS AND METHODS

In this research, a fiber metal laminate is crafted with a triple-layer arrangement, com-prising two layers of Al 5083 plate on the external surfaces and a core consisting of four layers of kevlar/epoxy. A perforation is introduced in the initial layer of Al 5083 plate, featuring a square pattern with a circular center and a hole diameter of 3 mm. Kevlar fibers are employed in a woven form, specifically a plain weave, with an orientation angle of 0°/90°. The Kevlar fiber sheet is tailored to match the dimensions of the fiber metal laminate specimen and is then organized into four layers. The thickness of the specimen aligns with the number of layers of the Kevlar fiber sheet. The specimens are created using the vacuum-assisted resin infusion method, as illustrated in Figure 1, with the outcomes of the specimen creation process depicted in Figure 2.

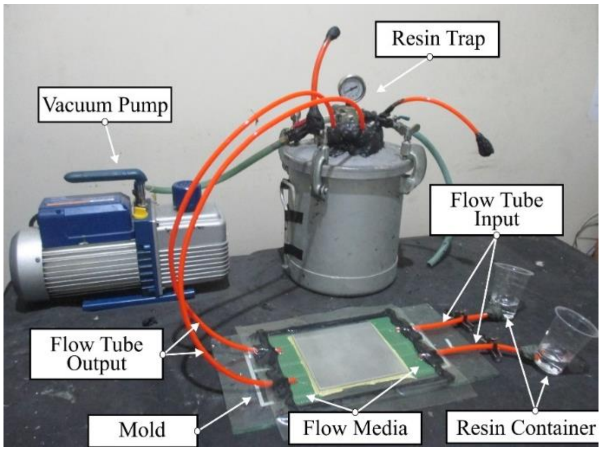
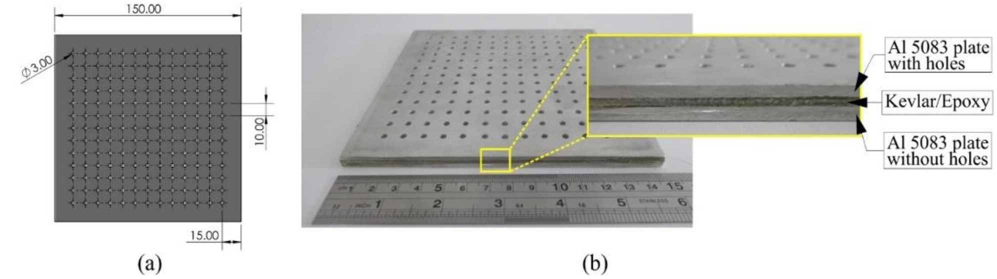


Figure 1. The procedure for fabricating fiber metal laminate through the vacuum-assisted resin infusion technique

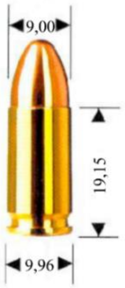


(a) (b)

Figure 2. Manufacture specimens (a) plate perforated pattern (b) fiber metal laminate configuration

Conducting ballistic tests adhering to the National Institute of Justice standard (NIJ Standard 0101.06 level III-A), utilizing a 9 mm caliber full metal jacket (FMJ) pistol with a hemispherical nose shape, as outlined in Table. 1. The bullets are fired with a veloc-ity of 426 m/s, measured using a chronograph. The ballistic tests are executed from a distance of 5 meters, employing a standard angle of attack (90° to the target sample). The ballistic testing arrangement is illustrated in Figure 3.

Table 1. Bullet spesifications

	Caliber	: 9 mm FMJ (Full Metal Jacket)
	Catridge	
	Weight	: 12,40 g
	Rim thickness	: 1,25 mm
	Extractor	: 8,60 mm
	Bullet	
	Length	: 15,70 mm
	Weight	: 8,00 g
	Material	
	Core	: Lead Antimony
	Jacket	: Brass 72 (CuZn28)

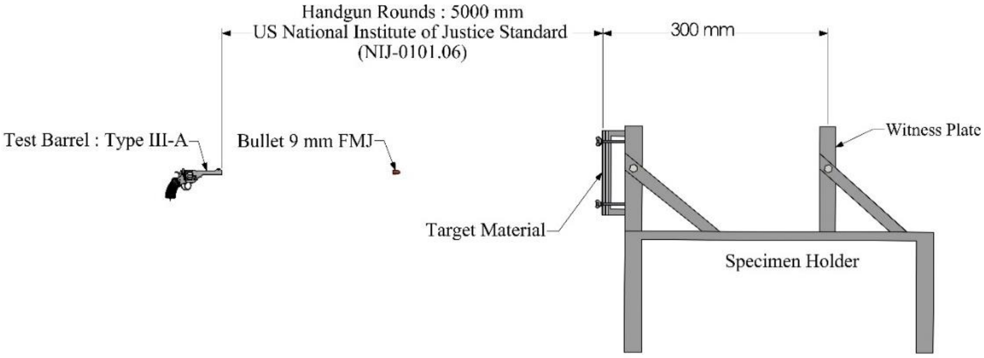


Figure 3. Ballistic testing scheme according to NIJ Standard 0101.06 level III-A

The specimen holder functions as a support or target location for specimens during ballistic testing, as depicted in Figure 4. Ballistic tests are conducted on fiber metal laminate with perforated plates to examine the material's response to penetration, par-ticularly when the bullet penetrates at different positions, such as the center of the hole, the center of the square pattern, and between ligament holes. The bullets utilized have a diameter of 9 mm, and the perforated plate features holes with a 3 mm diameter ar-ranged in a square center pattern with a 10 mm distance between holes. The bullet firing positions on the fiber metal laminate with a perforated plate are detailed in Table 2.

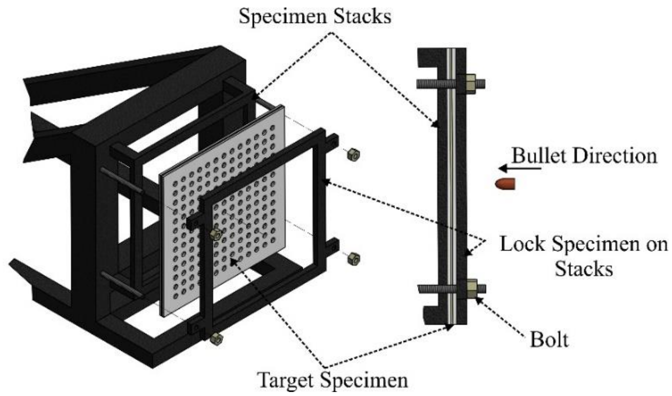
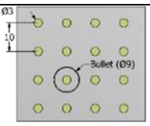
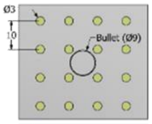
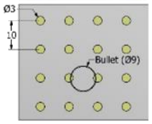


Figure 4. Specimen holder

Table 2. The bullet penetration position in the fiber metal laminate is perforated

Penetration Position	Geometry	Configuration Code
Center of the hole		FML 3A
Center of the square pattern of the hole		FML 3B
Between ligament holes		FML 3C

3. RESULTS AND DISCUSSION

The visible characteristics resulting from the ballistic impact of consecutive 9 mm FMJ caliber bullets on the Fiber Metal Laminate (FML), perforated with 3 mm diameter holes positioned at the center of the hole, within the center of the square pattern of the hole, and between ligament holes, are illustrated in Figure 5, Figure 6, and Figure 7.

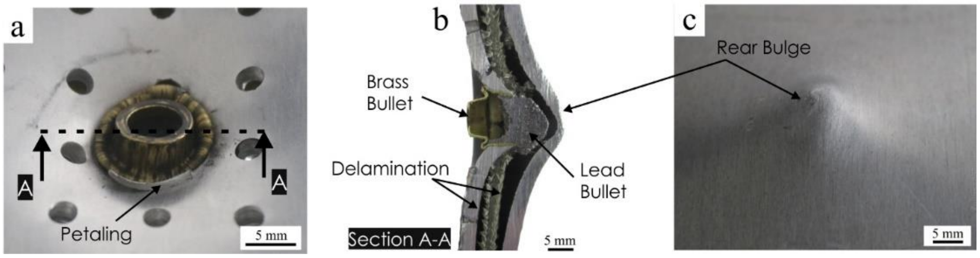


Figure 5. Ballistic impact on the FML 3A configuration (a) front face in front plate, (b) cross section and (c) rear face in back plate

Creating a circular hole with a 3 mm diameter on the frontal plate, arranged in a square center pattern with a 10 mm spacing between holes, aims to prevent full bullet penetration into the target. Instead, it induces partial bullet penetration while causing a deformation, resulting in a bulge on the backplate. When the bullet penetrates the center of the hole, it adheres to the target, as depicted in Figure 5 (a). The damage incurred on the front side of the perforated plate resembles petal-like formations around the bullet's edge, showcasing plastic deformation originating from the frontal plate. The resilient nature of the front side plate causes it to be pushed backward, leading to deformation on the backplate’

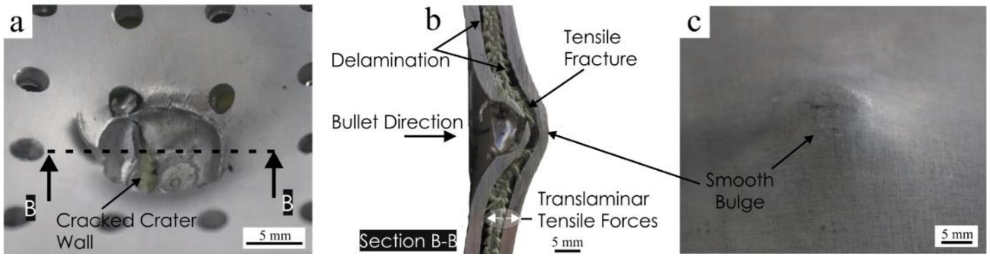


Figure 6. Ballistic impact on the FML 3B configuration (a) front face in front plate, (b) cross section and (c) rear face in back plate

Figure 6 illustrates the damage resulting from ballistic impact loads when a bullet penetrates the center of the square pattern of the hole, leading to the formation of a crater on the front side with a specific depth. This failure mode involves the creation of a ductile hole, pushing the material in the direction of the bullet and forming a bulge on the backplate. The compression of the bullet on the first layer causes tensile failure and fracture of the fibers in the second layer. The failure of the perforated Fiber Metal Lam-inate (FML) is further attributed to delamination, signifying the separation between the Al plate and kevlar/epoxy layers. This separation occurs because the bullet collisions in each layer draw the material toward the bullet's point of contact, causing the layers to overlap. The growing delamination between layers contributes to the development of a deeper and more pronounced bulge.

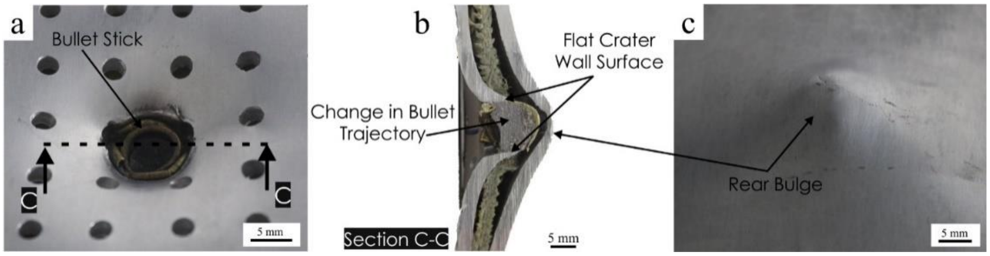


Figure 7. Ballistic impact on the FML 3C configuration (a) front face in front plate, (b) cross section and (c) rear face in back plate

During ballistic impact on a Fiber Metal Laminate (FML) with 3 mm perfora-tions, penetration between ligament holes results in a similar outcome to penetration at the center of the hole. In both instances, the bullet adheres to the target, and petals form around the bullet's edge on the front side of the perforated aluminum plate. These petals take shape due to the bullet tip's configuration, allowing it to penetrate the surface of the front layer plate. The bullet is unable to breach the final layer of the target, which is the aluminum plate, but it does create a bulge. Additionally, the bullet undergoes defor-mation, manifesting as a mushroom-like form on the top side. In Figure 7 (c), the change in directional positioning is evident, resulting in asymmetrical deformation on the back-plate (bulge) between the top and bottom of the bullet coordinate point. The bullet ve-locity for penetration into the target and the formation of the bulge on the backplate of the perforated FML is depicted in Figure 8.

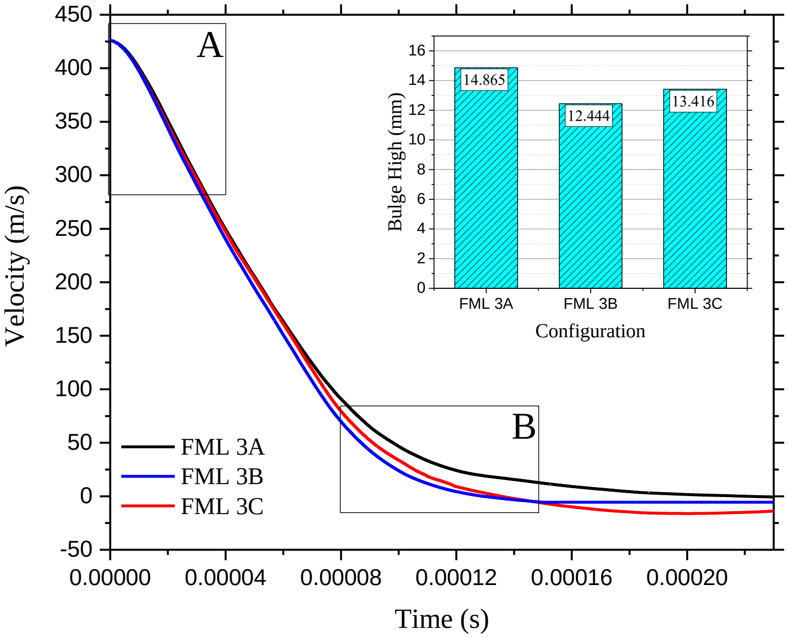


Figure 8. Bullet velocity for penetration on the target and the bulge on the backplate

Figure 8 illustrates the initial bullet velocity of 426 m/s, which gradually decreases as penetration time increases. The bullet's penetration induces deformation in the Fiber Metal Laminate (FML), and this deformation impedes the bullet's velocity, eventually halting it with a final velocity of 0 m/s. The bullet comes to a stop and reverses its direc-tion upon penetrating the first layer (Al Plate) and the second layer (kevlar/epoxy). The impact effect varies depending on the bullet's penetration position on the perforated plate. The smallest bulge is observed when the bullet penetrates at the center of the square pattern (FML 3B), followed by the position between ligament holes (FML 3C), and the last is the center of the hole (FML 3A). Specifics of the bullet velocity during penetration in the first layer (box A) are detailed in Figure 9 (a), while the bullet's velocity details after it comes to a complete stop with a final velocity of 0 m/s (box B) are pre-sented in Figure 9 (b).

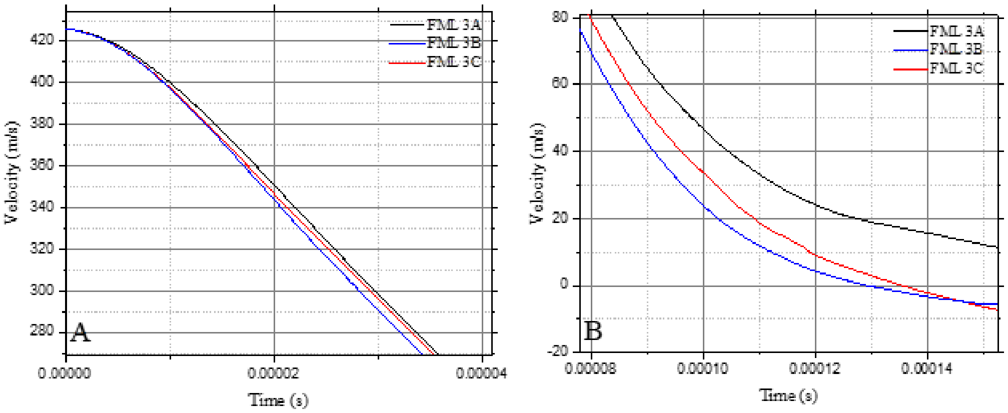


Figure 9. (a) Details initial bullet velocity penetration on the target (b) details bullet velocity after a stop at the target

Figure 9 (a) depicts the initial bullet penetration into the FML target, specifically piercing the first layer (perforated Al plate). The bullet's rate of deceleration is quicker when it penetrates the center of the square pattern (FML 3B), followed by the position between the ligaments (FML 3C) and the center of the hole (FML 3A). The cessation of the bullet's velocity at the culmination of the impact (Fig 9b) also illustrates that the penetration position at the center of the square pattern (FML 3B) achieves a faster re-duction in bullet velocity to a final velocity of 0 m/s at 1.2927 x 10-4 seconds. Converse-ly, the penetration of the bullet in the center of the hole (FML 3A) results in a longer time for the bullet's velocity to drop to a final velocity of 0 m/s, taking 2.2036 x 10-4 seconds. Energy absorption during the ballistic impact event can be calculated by utilizing the initial and final bullet velocities along with the bullet's mass. The equation for this calcu-lation is provided as follows [15]:

$$E_{absorption} = \frac{1}{2} m \left(v_i^2 - v_r^2\right) \qquad (1)$$

With $E_{absorption}$ = the energy absorption by the target (J), m = bullet mass (kg), vi = bullet initial velocity (m/s) and vr = bullet final velocity (m/s). Kinetic energy from bullets and energy absorption during the penetration process is shown in Figure 10.

Figure 10 illustrates the kinetic energy of a bullet and the energy absorption at the target. The bullet causes damage to the target due to its kinetic energy, with an initial value of 721.09 J. Upon impacting the perforated Fiber Metal Laminate (FML), the bullet's kinetic energy diminishes while the energy absorption by the target increases. The target absorbs the bullet's kinetic energy by reducing its velocity, and as the bullet veloci-ty decreases over time, the kinetic energy reaches a constant value. The trend in energy absorbed by the target is inversely proportional to the bullet's kinetic energy; as the bul-let's velocity decreases after the collision, the absorbed energy by the target increases. Penetration of the bullet at the center of the square pattern (FML 3B) results in a more rapid decrease in kinetic energy and faster energy absorption, followed by penetration between ligaments (FML 3C) and at the center of the hole (FML 3A). The bullet's kinetic energy is completely absorbed by the target, reducing it to zero, preventing the bullet from further penetration or movement within the target.

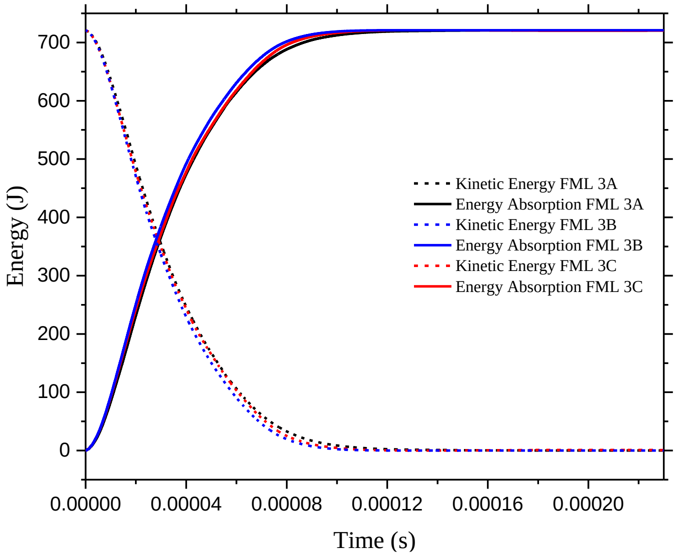


Figure 10. Kinetic energy and energy absorption during the process of penetrating the target

4. CONCLUSIONS

Introducing a hole in the initial layer of Fiber Metal Laminate (FML) and vary-ing the bullet penetration position on the perforated plate results in distinct impact ef-fects. Specifically, when the bullet penetrates the center of the square pattern hole, there is a more rapid decrease in both initial and final bullet velocities, leading to quick ab-sorption of the bullet's entire kinetic energy. At a macroscopic level, this penetration position showcases a discernible alteration in the bullet's direction back to its initial tra-jectory after perforating the plate, resulting in an asymmetrical appearance of the bulge in the last layer (backplate) between the top and bottom. In contrast, when the bullet penetrates the center of the hole, the effect is a slower reduction in bullet velocity, as there is less hindrance for the bullet when piercing the perforated plate. Although visible deviations from the bullet's original path occur after the impact event, evidenced by bullet erosion when the direction changes, this alteration does not significantly diminish the bullet's penetration capability. This resilience is attributed to the delamination effect occurring in the last layer (backplate), causing the bulge in the backplate to grow more pronounced.

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