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ANALYSIS OF THE CAPABILITY OF FIBER METAL LAMINATE COMPOSITES AS BULLETPROOF VEST MATERIAL USING FINITE ELEMENT METHOD

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ABSTRAK

Penelitian ini menganalisis kemampuan komposit Fiber Metal Laminate (FML) sebagai material rompi antipeluru menggunakan metode Finite Element Method (FEM) dengan memvariasikan posisi lapisan aluminium seri 1100 pada komposit bermatriks resin epoksi. Model terdiri atas 26 lapisan dengan konfigurasi aluminium di bagian depan, tengah, dan belakang. Simulasi dilakukan menggunakan perangkat lunak ABAQUS, dengan model material Johnson–Cook untuk aluminium dan Hashin Damage untuk komposit. Tumbukan disimulasikan menggunakan proyektil 9 mm Full Metal Jacket Round Nose (FMJ RN) sesuai standar peluru 9×19 mm untuk menganalisis penyerapan energi impak. Hasil menunjukkan bahwa konfigurasi aluminium di bagian depan menghasilkan energi kinetik sisa terendah sebesar 128,726 J, diikuti konfigurasi belakang (129,585 J) dan tengah (156,566 J). Seluruh konfigurasi menghasilkan energi sisa di bawah 170 J, yang mengindikasikan kemampuan penyerapan energi yang baik dan potensi yang lebih rendah dalam menyebabkan cedera tumpul. Posisi lapisan aluminium terbukti memengaruhi distribusi energi impak melalui mekanisme matrix cracking, fiber fracture, dan delaminasi. Berdasarkan hasil simulasi, komposit FML menunjukkan potensi untuk dipertimbangkan sebagai material alternatif rompi antipeluru ringan, meskipun validasi eksperimental masih diperlukan untuk mengonfirmasi kinerja balistiknya pada kondisi nyata.

Kata kunci: aluminium, komposit, proyektil, rompi, simulasi

ABSTRACT

This study analyzes the capability of Fiber Metal Laminate (FML) composites as bulletproof vest material using the Finite Element Method (FEM), varying the position of 1100 series aluminum layers in an epoxy resin matrix composite. The model consists of 26 layers with aluminum configured at the front, middle, and back. Simulations were carried out using ABAQUS *software, employing the Johnson–Cook material model for aluminum and the Hashin Damage model for the composite. Impact was simulated using a 9 mm Full Metal Jacket Round Nose (FMJ RN) projectile in accordance with the 9×19 mm bullet standard to analyze impact energy absorption. The front aluminum configuration provided the highest energy absorption capability, resulting in a residual kinetic energy of 128.726 J, which is 17.8% lower than that of the middle configuration (156.566 J) and 0.66% lower than that of the rear configuration (129.585 J). All configurations produced residual energy below 170 J, indicating good energy absorption capability and a lower potential for causing blunt trauma. The position of the aluminum layer was shown to influence the distribution of impact energy through mechanisms such as matrix cracking, fiber fracture, and delamination. Based on the simulation results, FML composites demonstrate potential for consideration as alternative lightweight bulletproof vest materials, although experimental validation is still required to confirm their ballistic performance under real-world conditions.*

Keywords: *aluminum, composite, projectile, vest, simulation.*

1. INTRODUCTION

A bulletproof vest is a protective device designed to reduce the potential for serious injury from the impact of bullets or explosion fragments. These vests play a critical role in defense, law enforcement, and civil security due to their ability to absorb the kinetic energy of bullets through layered materials such as aramid fibers, polyethylene, or metal composites. This layered design is focused on distributing impact forces so that bullet penetration can be reduced and the risk of blunt trauma minimized. Conventional materials such as steel and ceramics offer good ballistic protection, but have the drawback of relatively high mass, thereby reducing mobility and increasing wearer fatigue [1]. Advances in material technology continue to be directed toward producing lighter, more flexible vests that still provide high levels of protection, allowing the wearer to move freely without compromising safety [2].

Ballistic protection in modern vests is constructed from two main categories of materials: soft body armor based on high-performance synthetic fibers, and hard body armor made of ceramics or composites. Aramid fibers and UHMWPE remain favored for soft body armor due to their high strength-to-weight ratios and their ability to dissipate impact energy through a layered construction model [3]. Hard body armor uses engineered alumina ceramics, silicon carbide, and boron carbide combined with UHMWPE backing or metal plates to absorb fragments and reduce back-face deformation [4]. To enhance flexibility without sacrificing protection, recent research has explored hybrid approaches such as impregnating fibers with shear thickening fluid (STF), interlayer reinforcement with nanoparticles/graphene, and engineering the structure of fiber metal laminate (FML) composite layers [5].

Fiber Metal Laminate (FML) composites are hybrid materials that combine layers of high-performance fibers with thin metal layers, usually aluminum or titanium, yielding a superior combination of tensile strength, toughness, and ballistic resistance. This layered structure enables a more even distribution of impact energy compared to monolithic materials, so projectile penetration can be minimized without significant added weight. Among the metallic constituents used in FML structures, aluminum is one of the most widely employed materials because of its low density, high ductility, and excellent specific strength. During ballistic impact, the aluminum layer undergoes significant plastic deformation, allowing a considerable portion of the projectile's kinetic energy to be dissipated before it is transferred to the composite layers. Recent research shows that FML has great potential as a bulletproof vest material because it balances the strength-to-weight ratio crucial for wearer mobility. Studies conducted by Zhang et al. indicate that the combination of UHMWPE layers with titanium sheets in an FML configuration can withstand 9 mm projectiles with a back-face signature below NIJ standards [6]. Fadly et al. found that a fiber metal laminate consisting of aramid-epoxy layers could withstand 9 mm projectiles using both simulation and experimental methods, with a difference of ~4.37% [7]. In addition, Majzoobi et al. investigated the effect of the sequence of aluminum and titanium layers in hybrid FMLs and showed that the configuration of metal stacking influences the ballistic limit, energy absorption, and material failure mechanisms [8]. Other research conducted by Sharma et al. reported that the distribution of metal layers in titanium-based FMLs affects the pattern of delamination, deformation, and damage mechanisms from high-velocity impacts, although the impact on overall ballistic resistance is relatively minor [9]. Another study on the ability of composites to withstand bullet velocities was conducted by Rudi et al. They found that carbon fiber reinforced polymer composites with 25 and 30 layers were able to withstand 9 mm diameter bullets using the finite element method [10].

Nonetheless, most previous studies have focused on the effects of material type, metal combination, thickness, or different metal layer sequences. Investigations into the influence of the position of the aluminum layer with constant material type and number of layers on the distribution of impact energy and residual kinetic energy of the projectile are still very limited, particularly for FMLs based on 1100 aluminum and epoxy resin carbon fiber composites. Therefore, this research is focused on analyzing the effect of the position of the aluminum layer (front, middle, and back) on energy absorption capability, residual kinetic energy, and failure mechanisms using the Finite Element Method (FEM).

2. METHOD

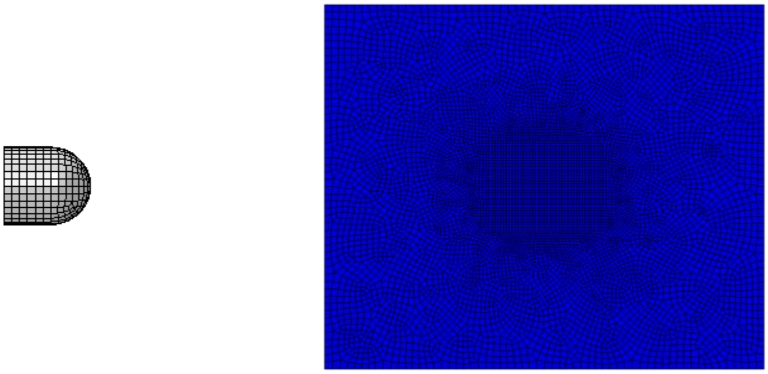
The research began with tensile testing of 1100 aluminum plate specimens to determine the tensile strength and elastic modulus. These material properties were used as the primary input parameters for the finite element analysis. The geometrical models of the Fiber Metal Laminate (FML) plate and projectile were developed using ABAQUS. The FML plate had dimensions of 250 mm × 300 mm with a total thickness of 26 mm, consisting of one 1100 aluminum layer and twenty-five CFRP layers. Both the aluminum and CFRP layers had a uniform thickness of 1 mm. To investigate the effect of the aluminum layer position on the ballistic performance of the FML structure, three laminate architectures were considered while maintaining identical plate dimensions, total thickness, and number of layers. The laminate configurations, summarized in Table 1, consisted of aluminum positioned at the front, middle, and rear of the laminate. These configurations were evaluated to determine their influence on the ballistic response, energy absorption capability, and failure mechanisms of the FML structure. The projectile was modeled as a standard 9 × 19 mm Full Metal Jacket Round Nose (FMJ RN) bullet with a diameter of 9 mm. The geometrical models of the FML plate and projectile used in the numerical simulations are presented in Figure 1.

Table 1. Laminate architectures of the Fiber Metal Laminate (FML) specimens.

Configuration	Stacking Sequence	Aluminum Layer Position	Total Layers	Plate Dimensions (mm)	Total Thickness (mm)
Front	$Al/CFRP_{25}$	Front (impact surface)	26	250 × 300	26
Middle	$CFRP_{12}/Al/CFRP_{13}$	Middle	26	250 × 300	26
Rear	$CFRP_{25}/Al$	Rear (back face)	26	250 × 300	26

The composite plate and projectile were subsequently discretized using three-dimensional eight-node linear brick elements with reduced integration (C3D8R). This element type was selected because it provides good computational efficiency and numerical stability for explicit dynamic impact analyses while accurately representing the deformation and damage behavior of the materials. Since the accuracy of finite element analysis is strongly influenced by mesh quality, an appropriate mesh density was employed to ensure reliable simulation results [11].

Boundary conditions were then defined, as illustrated in Figure 2. The composite plate was fully constrained along all four edges by restricting translational degrees of freedom in the X-, Y-, and Z-directions (U1 = U2 = U3 = 0), representing a rigidly clamped support condition. The projectile was positioned normal to the center of the front surface of the laminate and assigned an initial velocity of 374.5 m/s in the negative Z-direction. All ballistic impact simulations were performed using the ABAQUS/Explicit solver. The interaction between the projectile and the composite plate was modeled using a surface-to-surface contact formulation. A hard contact algorithm was applied in the normal direction, while a penalty friction formulation with a friction coefficient of 0.30 was used in the tangential direction. The interfaces between the aluminum and CFRP layers were modeled using tie constraints, assuming perfect interfacial bonding without debonding during impact. The aluminum layer was modeled using the Johnson–Cook constitutive model, whereas the CFRP layers were modeled using the Hashin damage criterion.



(a) **(b)**

Figure 1. Model (a) projectile and (b) composite plate

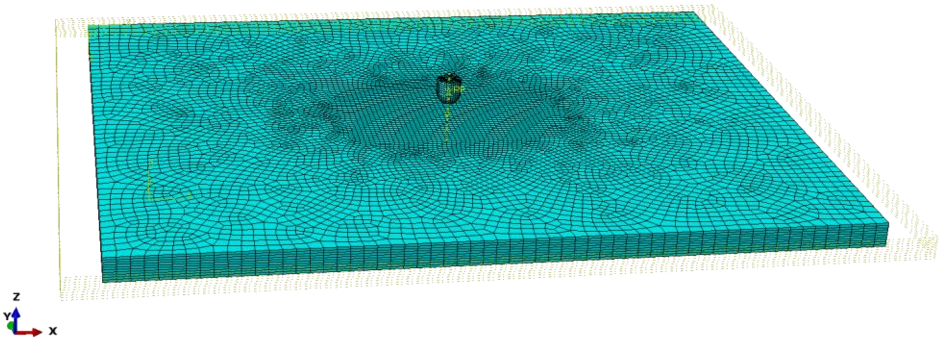


Figure 2. Boundary condition

3. RESULTS AND DISCUSSION

The kinetic energy of the bullet decreases when it collides with the composite plate, and its energy continues to decrease until the bullet stops. The ballistic impact process can be divided into several stages. Prior to impact, the projectile travels toward the target with an initial velocity of 374.5 m/s. At the moment of initial contact, compressive stresses are generated at the projectile–target interface, initiating localized deformation of the front surface of the laminate. As the impact progresses, the projectile transfers its kinetic energy to the laminate, resulting in maximum deformation accompanied by plastic deformation of the aluminum layer and progressive damage initiation within the CFRP layers according to the Hashin failure criterion [12]. Figure 3 shows the decrease in kinetic energy of the bullet occurring in the time range of 1.6 x 10-5 seconds and 1.96 x 10-4 seconds. A drastic decrease in the bullet's kinetic energy began to occur in the time range of 2.0 x 10-5 seconds and 1.4 x 10-4 seconds. The decrease in the bullet's kinetic energy represents the material's ability to absorb the bullet's kinetic energy [13]. The front aluminum position had the fastest trend of decrease in the bullet's kinetic energy compared to the middle and rear aluminum positions. The bullet kinetic energy values in the time range of 2.4 x 10-5 for the front, middle, and rear aluminum positions are 504 J, 507 J, and 528 J, respectively. The superior ballistic performance of the front aluminum configuration can be attributed to the high ductility of Aluminum 1100. Upon impact, the aluminum layer undergoes significant plastic deformation, dissipating a substantial portion of the projectile's kinetic energy before the load is transferred to the underlying CFRP layers [14]. This sequential energy absorption delays damage propagation and improves the overall impact resistance of the FML laminate.

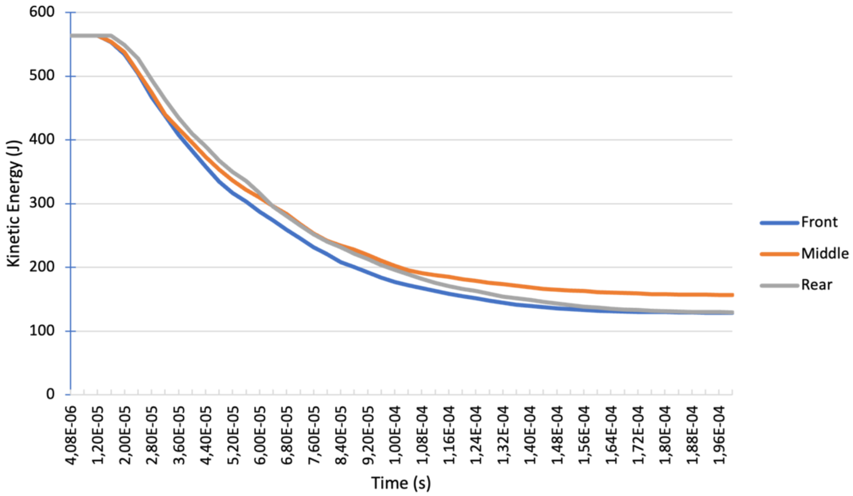


Figure 3. Reduction in kinetic energy of bullet

The kinetic energy of the bullet will be absorbed and transferred by the material to the environment even if the bullet stops. The kinetic energy transferred to the environment is residual energy that is in the same direction as the bullet's arrival. According to Hatcher's report, an impact energy of approximately 170.2 J is sufficient to cause severe injury and incapacitation [15]. Therefore, reducing the projectile's residual kinetic energy and the energy transferred to the body is an important consideration in the design of bulletproof vest materials. Figure 4 shows the residual kinetic energy of bullets for the front, center, and rear aluminum positions. Based on the graph, it can be seen that the front, center, and rear aluminum positions have residual kinetic energy that meets the requirements for the use of bulletproof vest materials. The highest residual kinetic energy is possessed by the center aluminum position and the lowest is possessed by the front position. Upon impact, the kinetic energy of the bullet will be converted into impact energy, which will then be absorbed by the vest. The absorption of bullet energy is carried out by means such as matrix cracking, fiber fracture, and delamination, as illustrated in Figure 5. Delamination can be a way out for the released energy. When delamination occurs, it will cause air gaps in the composite [16] [17].

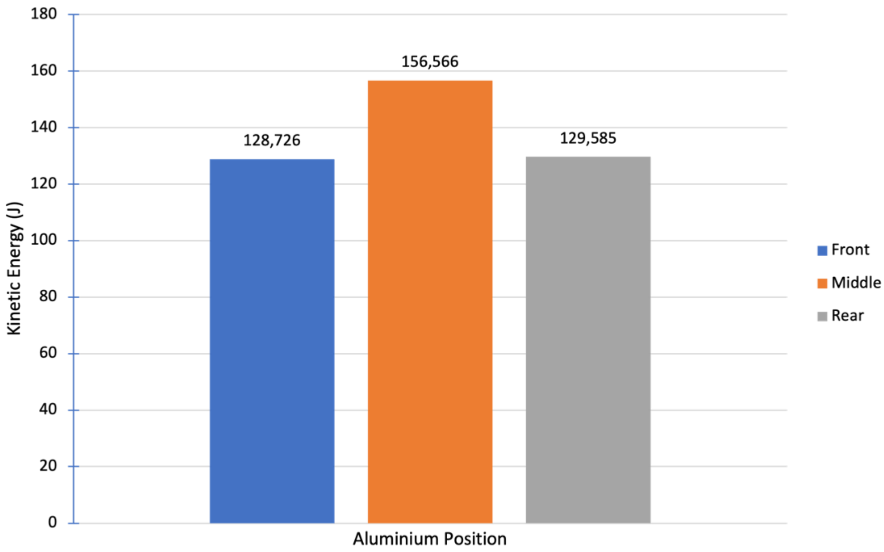


Figure 4. Residual energy kinetic of bullet

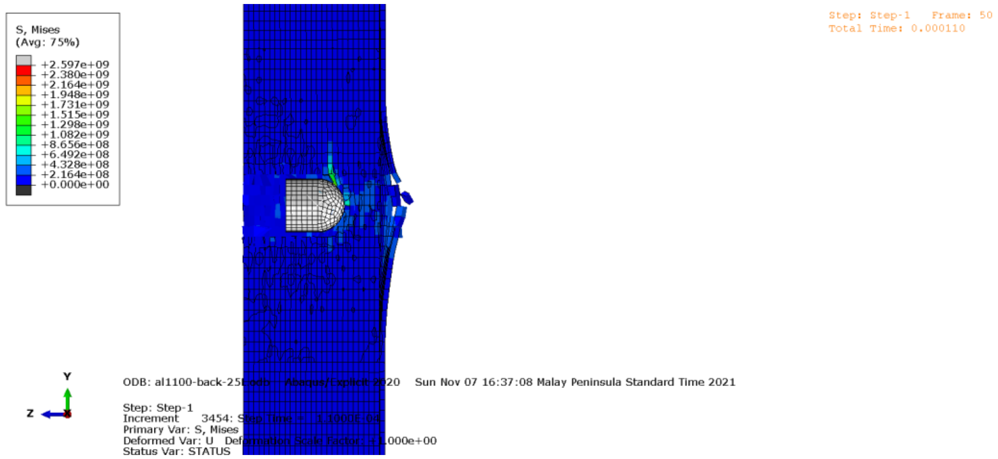


Figure 5. Matrix cracking fiber fracture and interlaminar delamination

4. CONCLUSION

This study investigated the effect of aluminum layer position on the ballistic performance of Fiber Metal Laminate (FML) composites using the Finite Element Method (FEM) in ABAQUS with the Johnson–Cook and Hashin damage models. The results show that the front aluminum configuration provided the most effective energy absorption, producing the lowest residual kinetic energy of 128.726 J, which was 17.8% and 0.66% lower than those of the middle and rear configurations, respectively. These residual kinetic energy values are below the 170.2 J threshold reported by Hatcher, indicating the potential of the proposed FML configurations to reduce the risk of blunt trauma. The findings provide useful guidance for optimizing lightweight FML structures for personal ballistic protection by appropriately positioning the aluminum layer. However, this study is limited by the absence of experimental validation and mesh-convergence analysis. Future work should include experimental ballistic testing, systematic mesh-convergence analysis, and the investigation of alternative laminate architectures and material combinations to further improve the predictive capability of the numerical model.

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