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Experimental investigation of perforated multi-layered composite armor subjected to ballistic impact

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ABSTRACT

Ballistic protection of vehicles has become an important endeavor, as it concerns how occupants can possess a comfortable feeling together with a high level of protection during a shooting incident. In recent years, numerous forms of armor have employed several kinds of distinct materials to produce a new generation of panels to address the crucial issues in the structure of armor, such as how to provide high protection with reduced density combined with further increasing the stacking and bond strength between the layers of the panel. This study attempts to use a different approach represented by engineering design to combine with the high impact resistance and low weight, as well as high bonding between the laminate of the structure. The structure of the suggested armor consists of five main layers made of different materials: FRP composite materials, then two perforated layers of steel, followed by one perforated layer of rubber, and finally, one layer of aluminum. These layers were tested via 9 mm caliber to specify the ability of each layer to absorb the energy of the projectile and then the configuration of the layers depending on the function of each layer. However, the results offer a significant ballistic performance with reasonably reduced mass and excellent bonding strength between the layers of the structure.

1. Introduction

In recent years, the development of protective shell techniques, especially in the light armor structure has become important and indispensable for humans, buildings as well as vehicles [1]. Extensive experimental and numerical studies have been conducted on the high-speed impact and plastic deformation of multi-layered material structures [2, 3]. However, the balance between protection and the low weight of armor is complex and faces many challenges. One of these is the trade-off principle [3], which refers to increasing the protection and maximizing the energy absorbed as well as the density of the shell [4, 5]. In general, the multi-layered armor technique is one of the most advanced mechanisms to increase protection and reduce weight [6]. On the other hand, monolithic panels such as steel sheets have high protection with high density [7]; also, this structure is insufficient to protect the vehicle against the high energy of explosion besides high shock waves with debris compared to the multi-layered system [8]. The best structure that can resist the blast is the structure that deforms while maintaining the ability to control the impact force [1, 9]. Hence, preserving appropriate space around the occupants to prevent them from injury during any type of fire or explosion attack [10].

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Nomenclature:

E	Young's modulus (GPa)
FRP	Fibre-Reinforced Polymer
G	Shear modulus (GPa)
KEL	kinetic Energy Loss
K	Fitting constant
UHMWPE	Ultra-High Molecular Weight Polyethylene
Greek symbols	
ΔE	Kinetic Energy Absorbed
λ	Coefficient of Projectile geometry
ν	Poisson Ratio
ρ	Density (Kg/m^3)
Subscripts	
m_p	Mass of The Projectile
m_{pl}	Mass of The Plug
V_b	Ballistic Velocity
vi	Initial Velocity
vr	Residual Velocity

Many researchers have investigated the blast-worthy single panels that have many geometries and materials, such as curved structures both experimentally and numerically [2, 11, 12], V-shape structures [13], stiffened structures [14], and sandwich structures [15], or using MS hybrid Polymers to bond between the parts of the armor [16, 17]. There was limited research on multilayer structures, especially with the perforated plates [18]. Indeed, one of the defects of multilayer structures is the strength of the bond between the layers compared to monolithic plates [19]. Many techniques have been used to reduce armor density, such as selecting lightweight materials [20, 21]. Another technique employs the engineering design by using perforation plates [22]; however, the big size of the perforated holes probably contributes negatively to the ability of the structure to resist the high impact of the projectile, fatigue, and fracture mechanics[23-25]. Thus, two types of geometry, steel and rubber plate, were used in this study. These geometries contribute significantly to increasing the stacking and homogenization between the layers and also reducing the weight of the panel while considering the arrangement and direction of plates. After this, ballistics tests of different thicknesses of monolithic plates of aluminum, composite material, and rubber were performed to design the optimum structure of armor. This work presents a new shell of lightweight layers that are combined with layers of steel to reduce the effect of high-speed impact on the protected object with low-density structure of armor. The following section includes the experimental setup utilized for this work followed by specimen preparation and finally, selected results are presented.

2. Experimental approach

The experimental approach of this work has three main steps: preparing the investigating specimen, lab setup, and analysis of the experimental data.

2.1. Design and preparation of composite armor

The proposed composite protection armor consists of five layers: one aluminum sheet, two steel sheets, a rubber layer, and finally, one FRP. The main factor of this work is to reduce the total weight of the heavy armor and increase the dynamic energy absorbed. The sheets are stacked together using tiny layers of adhesive with little pressure, as shown in Fig. 1. The resulting multilayer composite was left to fully cure and dry for a few days. The aluminum-6065 sheets were placed on the outside of the composite, and the steel sheets were inside. The layer of aluminum, rubber, and steel were made from $\mathbf{150 \times 150 \times 1}\boldsymbol{mm}$, and the FRP layer $\mathbf{150 \times 150 \times 10}\boldsymbol{mm}$. The final dimensions of the composite protection armor were $(\approx \mathbf{150 \times 150 \times 20})\boldsymbol{mm}$. The material sheet stacking sequence mainly depends on the required goals of each layer in the structure. Furthermore, the rubber sheet is made with holes of $\mathbf{6}\boldsymbol{mm}$ in diameters distributed on the surface to cover the most contact area. The mesh of holes is $\mathbf{30.7}\ \boldsymbol{mm}$, in horizontal and $\mathbf{35.7}\ \boldsymbol{mm}$ in vertical steps respectively, Fig.2a.

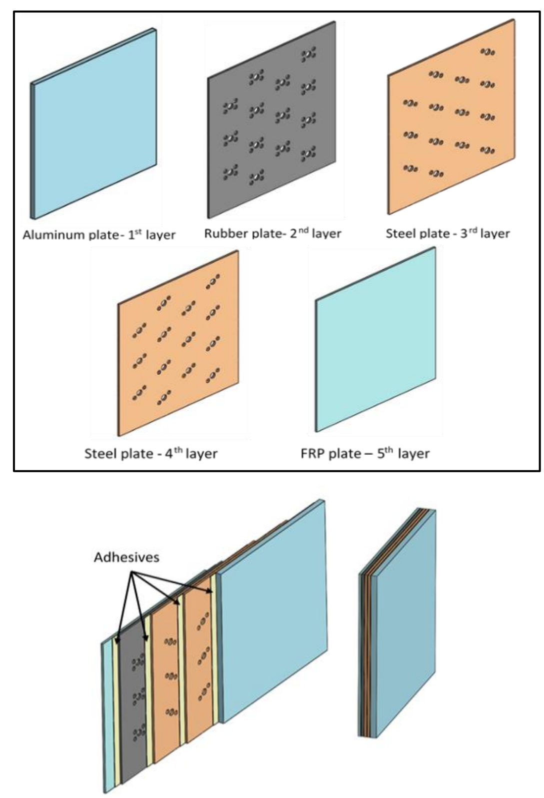


Figure 1. Schematic of the steps of stacking five layers used to make the composition of the protective armor

For the rubber sheet, the small holes with $\mathbf{4}\ \boldsymbol{mm}$ in diameter were added and distributed around the 6 *mm* holes, Fig. 2a. In total, the rubber has 14 large holes and 56 small holes, which provided more than $\approx \mathbf{1100}\ \boldsymbol{mm}$ as a cemented-contact area. For the steel plate, Fig. 2b, $\mathbf{6}\ \boldsymbol{mm}$ in diameter mesh holes were made with a mesh of $\mathbf{30.9}\ \boldsymbol{mm}$ horizontally and $\mathbf{21.18}\ \boldsymbol{mm}$ vertically. The steel plates were arranged in a way to be sure that there are no holes in the overall composite, i.e. the rotation angle between the steel plates is $\mathbf{90}^{\circ}$. The holes were filled with glue to enhance the total strength of the armed structure. Fig. 3 shows the details of the preparation and assembly of the armed specimen. Also, it can be observed that the amount of mass that was reduced by holes directly affected the total weight of armor that might be used with cars, and eventually decreasing the full consumption is not the scope of this work. Thus, the multilayer structure makes a total mass reduction of about 10% in weight.

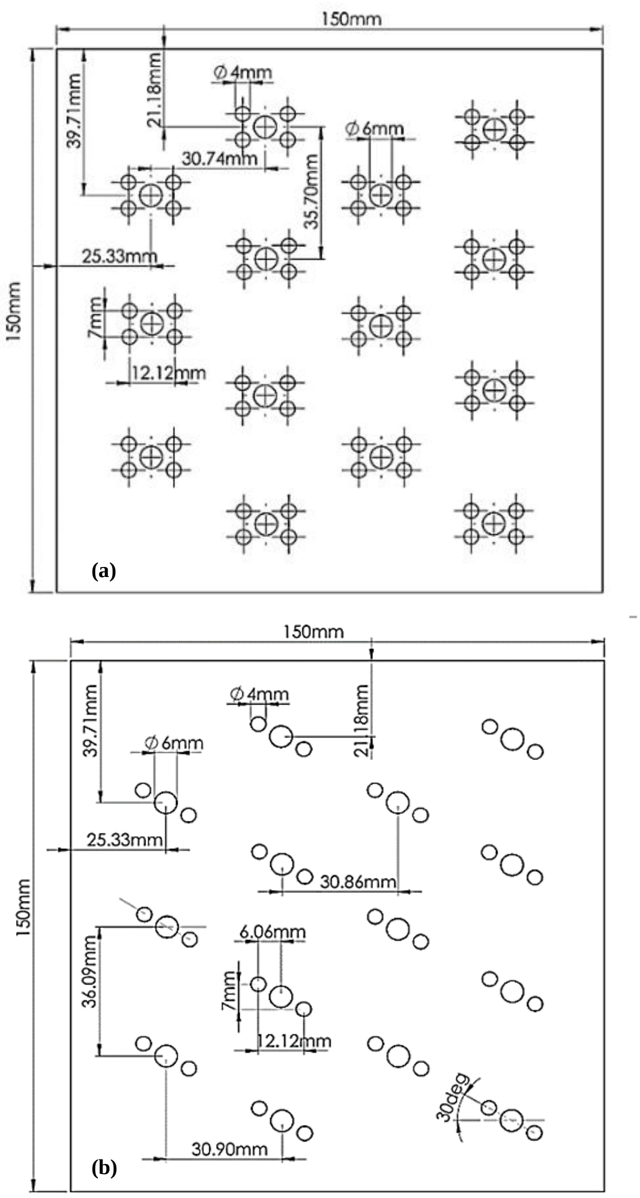


Figure 2. Dimensions of the perforated plastic (a) Rubber plate and (b) Steel plate

2.2. Experimental setup

The experimental setup used in this work has been done inside the training of the shooting building in Baghdad. Fig. 4 shows two chronograph devices were used to measure the bullet speed before and after the plate impact. In the middle, at the point 5 m from the shooting point, the specimen holder was used to fix the composite armed vertically and perpendicular to the shooting bullet. This setup was used to examine the ballistic performance of each layer separately and the final composite as well. The results from the individual layer were used to select the optimum material location, thickness, and sequence in the panel structure. The elastic properties of the chosen material are listed in Table 1.

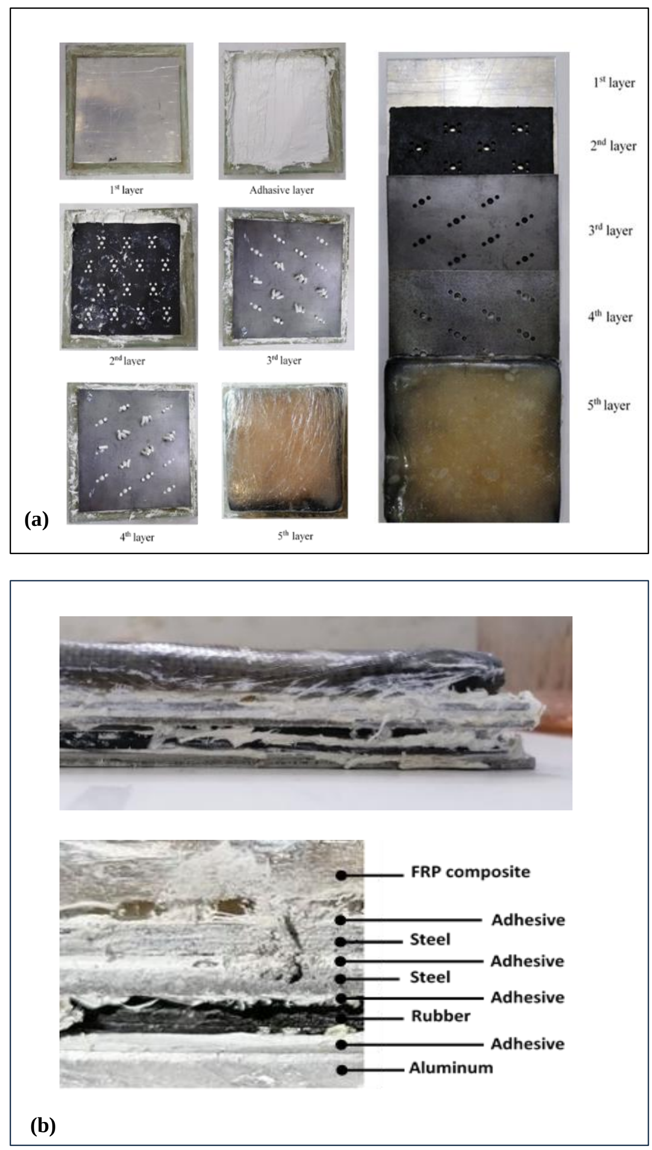
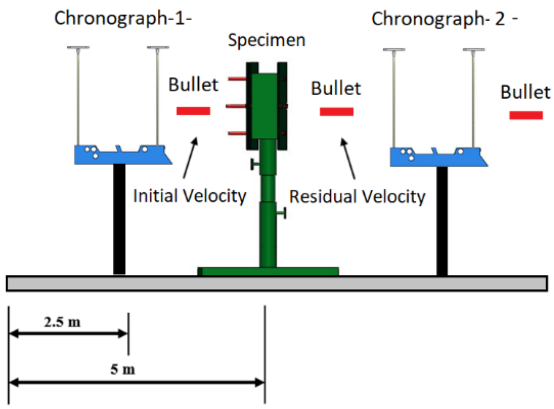


Figure 3. Actual specimen layers preparation, (a) The composite layers of Aluminium, Steel, Rubber, and FRP, (b) The specimen after assembling with the schematic to show the sequence of the layers



(a)

(b)

Figure 4. The experimental setup, (a) Schematic of the full setup that includes the speed sensors, chronograph 1 and 2, and the specimen holder located at 5m from the shooting point, (b) Photograph of the real lab setup located in Baghdad, Iraq.

Table 1. Mechanical properties of each layer of the panel

Property	**Al. 6065**	**Steel 1080**	**Rubber**	**Composite**
Density (Kg/m^3)	2780	7724	1132	1031
Young's modulus (GPa)	72.3	203	0.081	16.1
Shear modulus (GPa)	26.1	77.6	0.031	1.43

Several types of standards are used to fabricate specimens, such as E8/E8M, D638, and D412 for metals, FRP composite, and rubber materials, respectively [23]. In this work, the FRP composite was fabricated using the hand-lay-up technique; indeed, ballistic fiber type UHMWPE with matrix material was used via mixing with a hardener with weights of about 25 % to 75 %, respectively.

2.3. Experimental data recording

The energy absorption can be found depending on the ballistics test of monolithic plates of each panel layer; this study selected aluminum as the first layer and the second layer as the rubber material. The third and fourth layers were steel, and the last layer of armor facing the shooting bullets was the UHMWPE/ Epoxy composite material. The arrangement of layers in the panel depends on the layer function. Thus, the selection of material and arrangement of layers in the armor structure plays a significant role in the ballistic performance of armor [26]. Five layers were selected to manufacture this structure, and aluminum material was used based on the amount of energy that can be absorbed from the projectile; hence, this layer was used in the back of the structure to prevent any kind of residual energy. The rubber plate was employed in this structure after the aluminum plate to reduce the effect of the shockwave of impact; on the other hand, the two steel monolithic plates in this design were utilized to absorb the largest amount of kinetic energy of the projectile. Finally, the front layer of this armor was fabricated from UHMWPE/ epoxy composite material, and this layer attempts to distort the projectile. The bullet that was used to test the composite armor was made from two materials - lead and brass, and their properties are listed in Table 2. Thus, Lead and Brass were used for the core and jacket, respectively.

Table 2. Properties of bullet used

Part	**Material**	**Density (Kg/m^3)**	**Modulus of elasticity (GPa)**	**Yield strength (MPa)**	**Poisson ratio**
Core	Lead	11270	17	8	0.4
Jacket	Brass	8520	115	206	0.31

3. Results and discussions

Three types of results are presented in this section- kinetic energy absorbed by each layer individually, the energy of plastic deformation of each individual layer, and the resistance of composite armed to the high-speed impact of the bullet. The **9 mm** bullet was shot from a **5 m** distance to the composite layers. The bullet speed before and after the impact was measured. In all these tests, the bullet's mass was assumed constant; thus, the linear elastic kinetic energy equation, Eq. 1, was used to determine the kinetic energy absorbed, **ΔE**, of each plate or layer of armor [26].

$$\Delta E = \frac{1}{2}\left(v_i^2 - v_r^2\right) \quad (1)$$

Where, v_i and v_r represent the initial and residual Velocity of the bullet, respectively.

The energy of each layer was examined, and the energy absorbed from the bullet was calculated and listed in Table 3. The Coefficient of Projectile geometry (λ) was calculated from Eq.2, where m_p is the mass of the projectile and m_{pl} is the mass of the Plug, and in this context, a 9 mm bullet approximately has a hemispherical nose shape. Thus the value of $(\lambda_{\text{hemispherical}})$ is between 0.779 and 1. This Coefficient was used to find the ballistic Velocity of the bullet (V_{bl}) from Eq.3, where k is a fitting constant with $K \approx 2$, [26]. Moreover, the kinetic Energy Loss (KEL) was determined using Eq. 4 [27]. The results are listed in Table 3.

$$\lambda = \frac{m_p}{m_{pl}+m_p} \quad (2)$$

$$V_{bl} = \left[\left(V_i^K - \left(\frac{V_r}{\lambda}\right)^k\right)\right]^{\frac{1}{k}} \quad (3)$$

$$KEL = 1 - \frac{v_r^2}{v_i^2} \quad (4)$$

As listed in Table. 3, the steel plate can absorb energy more than the aluminium and composite materials. Thus, one layer of steel plate can absorb an amount equal to aluminium and composite together. Thus, the final multilayer composite heave armed should be able to absorb energy up to 680 J. The real deformed specimens are shown in Fig.5.

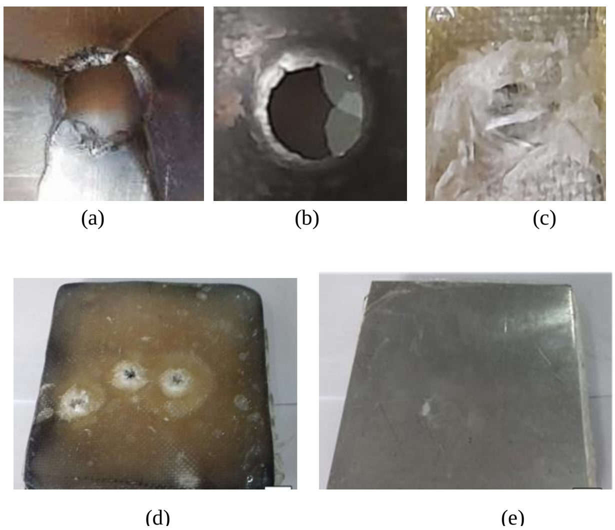


Figure 5. Actual investigated plates and composite armor where (a) Aluminum plate, (b) Steel plate, (c) Composite layer, (d) Front face of composite armor, and (e) Back side of composite armed specimen

The ballistic impact on the aluminum plate presents a similar behavior of quasi-brittle material with high residual Velocity compared to steel monolithic plates. Furthermore, aluminum shows large plastic deformation, and the cracks start from four corners. Also, aluminum under a high loading rate shows brittle behavior, and that might be because the high heat effect zone forms the contact area, Fig.5a. The steel plate offers low residual Velocity, which means increased energy absorption besides the deformation of this material was ductile behavior as well as pealing failure. The failure of the FRP composite includes resin and fiber failure, Fig.5b. The composite materials, Fig.5c, show different failure mechanisms than aluminum and steel. The combined failure was palling and cracking with shear and crazing failure mechanisms. Figures 5a, b, and c relate to the aluminium plate, steel plate, and composite layers, respectively.

Table 3. Ballistic Velocity, Energy absorption, and kinetic energy loss ratio of the armed layer under bullet impact of 8G

Type of plate	Initial Velocity (m/s)	Residual Velocity (m/s)	Ballistic Velocity (m/s)	Energy Absorption (KJ)	kinetic Energy Loss (%)
Aluminium plate	367	328	86	108.420	20
Steel plate	361	232	230	305.176	59
FRP composite	361	252	-	267.268	51

The ballistic test refers to the ability of armor to resist high energy of impact. Figure 5d and e show the two sides of the proposed multilayer heave armed panel after the ballistic test. Most of the impact energy and heat energy is absorbed by composite materials as shown in Fig. 5d. The aluminium side adds extra support to the distortion of the impact loading wave without any plastic deformation, Fig. 5e. In general, the proposed heave-armed worked well even with high impact loading wave and reducing the weight by mesh holes doesn't affect the protection performance of the structure.

4. Conclusion

A new multi-layered composite of heavy armor was proposed and investigated experimentally under high-impact load. Different approaches to reducing the total weight and increasing the strength of the composite layers were presented. This structure consists of five main layers made of different materials, such as aluminum, steel, and FRP composite. The layers stacked together offer the best energy absorption and less deformation. The results indicate significant improvement in ballistic performance with reasonably reduced mass and excellent bonding strength between the layers. In addition, the ballistic test results showed that the holes' size is most critical, contributes to reducing the mass, and does not affect the panel's ability to resist projectiles. Moreover, linking these layers via the holes in the panels allows the adhesive materials to penetrate through all layers. Reducing the mass and increasing the bonding between the layers in the structure of the panel while maintaining the ability of the system to resist the ballistic impact is provided by the new armor. These results can be used in the manufacturing of protective armor for personal, vehicles and buildings that necessiate protection with a low mass armor structure. The study also recommends using the finite element techniques like Abaqus explicit or LS-Dyna software to perform extensive stress analysis between the layers and testing under different bullet speeds.

Author's contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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