Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

# Numerical and Experimental Study of Hybrid Composite Body Armor

**Iftikhar A. Saleem**[a], **Mayyadah S. Abed**[b*], **Payman S. Ahmed**[c]

[a,b]Materials Engineering Dept., University of Technology-Iraq, Alsina'a street, 10066 Baghdad, Iraq.
[c]Manufacturing & Industrial Engineering Department, Faculty of Engineering, Koya University, Koya, Kurdistan Region.
*Corresponding author Email: mayyadah.s.abed@uotechnology.edu.iq

## HIGHLIGHTS

- Composite laminate materials were used to produce Body armor by hand layup as ballistic structural armors.
- Simulation is able to assist decrease costs in the creation of armor.
- Silicon Carbide + Ultra high molecular weight polyethylene + Polycarbonate can stop a 9mm FMJ bullet with just a little distortion.
- The ceramic layer absorbs the largest percentage of the overall energy absorbed.

## ARTICLE INFO

**Handling editor:** Jawad K. Oleiwi

**Keywords:**
Hybrid composite; Light armor; Polycarbonate; Aramid fabric; Treated fiber; Numerical simulation.

## ABSTRACT

Kevlar is widely used in ballistic applications to protect against hand pistols, due to its high strength, lightweight, and high impact resistance. Compared to other fabrics, Kevlar is considered a typical material due to its strength properties for bullet-proof vests. This project aims to develop a hybrid composite and investigate its behavior under ballistic impact both experimentally and theoretically. Ceramic/woven fabric reinforced epoxy/polycarbonate multilayered armors were developed. The initial layer of defense against the bullet is silicon carbide (SiC). The intermediate composite is made up of aramid fabric (Kevlar) reinforced epoxy (KEV/EPX). The rear layer was made of polycarbonate (PC). A 9 mm FMJ bullet was fired in 310 m/s, towards samples of 900 cm$^2$. To simulate the ballistic test, Ansys Workbench Explicit Dynamics and Ansys AUTODYN 3D were used. An integrated methodological approach of experimentation and simulation was followed to assess the behavior of samples. Obtained results showed that SiC+ KEV/EPX+ polycarbonate was able to stop the 9mm FMJ bullet and indicated that armor layers perforated without penetration. Back Face Signature BFS was also measured, which is within the allowed limit. The ceramic layer absorbs the largest percentage of the overall energy absorbed, compared to fiber-reinforced epoxy and polycarbonate, which reach 77.8% of the entire energy.

## 1. Introduction

Integral armor systems are one of the most recent advancements in lightweight armor. Multiple-layer armors that are structured from sequenced layers of different materials are shown to be the most effective, rather than Monolithic systems consisting of either steel materials, composite materials, or ceramic materials [1-3]. Based on the danger and weight limits, sandwich systems often incorporate an exterior ceramic layer consisting of silicon carbide (SiC), aluminum nitride ($Al_2N_3$), boron carbide ($B_4C$), or alumina ($Al_2O_3$) [4]. The projectile is blunted and worn down by the ceramic layer. The ceramic layer should be supported by another, more flexible layer that can also capture the projectile's slowing remains while maintaining the system's integrity. Polymer composites could be a possible option, interconnecting layers of ceramic and others to build a lightweight, integrated armor system [5].

Several pieces of research have investigated the ballistic resistance of Kevlar and composites, to determine the properties of materials and efficacy when subjected to impact loads. D. Zhu et. al. studied the ballistic effect by finite element modeling on multi-layer Kevlar 49 fabrics. they develop a model suitable for simulating the actions of ballistic-impacted dry fabrics [6]. F. S. Luz et. al. investigated the ballistic behavior of multilayered armor with jute fabric reinforced epoxy as an intermediate layer. Multilayered armors consist of the ceramic layer in the front face and are followed by Kevlar fabrics used against high-velocity gunfire. The 7.62 calibers ammunition ballistic impact test showed that both the plain epoxy and the jute fabric composite had a reasonably identical Kevlar™ performance and also matched with the NIJ body protection standard [7]. A. Soydan et al. have investigated the ballistic behavior of composite armor experimentally and numerically. In their study several designs and materials have been developed using composite materials for ballistic armor. The results revealed that when subjected to a 9 mm FMJ bullet, only very minimal deformation was seen in the fiber-cement layer (8mm), the Kevlar 29 layer (2.4mm), and the steel 1006 plate (3mm) [8]. Compston et al. observed particular damage types in Fiber Metal Laminates (FMLs) when they were subjected to impact loading, including fiber breakage, composite delamination, matrix cracking,



http://doi.org/10.30684/etj.v39i11.2274
Received 03 July 2021; Accepted 24 August 2021; Available online 25 November 2021
2412-0758/©Publishing rights belongs to University of Technology's Press, Baghdad, Iraq

plastic deformation, debonding between the different layers, and buckling in the metal layers [9]. The major damage processes or patterns for low-velocity collisions are matrix cracking and delamination, according to Heimbs et al., When high-velocity collisions occur, “fiber rupture” happens [10]. Ballistic tests, according to Findik and Camci, can be split into three categories: low-velocity ballistics (Vi 50 m/s; Vi – inlet velocity of the projectile), medium velocity ballistics (50 Vi 1300 m/s), and high-velocity ballistics (Vi > 1300 m/s) [11]. F. Mullaoğlu et.al. studied the dynamic behavior of polycarbonate under projectile impact at various speeds. LS-DYNA is used to investigate the response of a PC plate under impact numerically. The result showed that PC materials have high impact-resistant compare to several materials [12]. Sh. Esfahlani investigated the dynamic failure of Polycarbonate and Polymethyl methacrylate samples at different impact speeds and projectile core density of 30 and 90 degrees inclined and normal impact. Because the samples have the same structure as the models, only half of them were simulated. These two materials were found to be able to deflect the bullet path from its original penetration angle [13].

Overall, developing body armor is highly intriguing. The ballistic resistance of hybrid composite body armor is investigated in this study. According to the NIJ procedure, 0101.06 standard ballistic tests were performed from a distance of 5 meters with a Daewoo pistol and a 9 mm FMJ bullet. The type of damage to the samples tested is evaluated once the ballistic assessment is completed. The findings of this test will be used to create the best composite armor possible.

A principal aim of this research is the fabrication of body armor from hybrid composites and to investigate the ballistic behavior experimentally and theoretically using Ansys R20. The front layer is made of 0.3 cm of ceramic (silicon carbide), the middle layer is made of 6 pre-preg fiber-reinforced polymers (Kevlar reinforced epoxy type Sikafloor-156), and the rear layer is made of 0.4 cm of polycarbonate. This design was based on existing research to offer the needed protection against ballistic as a high-velocity impact while keeping the cost, weight, and thickness to a minimum.

## 2. Experiment Work and Simulation

### 2.1 Materials Used

Yixing Huaheng High-Performance Fiber Textile Co. Ltd, China, provided Aramid 1414 Kevlar 49. The fabric's specifications were given in Table 1. Sika AG. Turkey supplies epoxy resin (Sikafloor-156). Sikafloor-156 is a low viscosity, two-part, solvent-free epoxy resin. A 3:1 weight ratio of resin (A) to hardener (B) was used in the combination. Xiamen Innovacera Advanced Materials Co., Ltd, China provided the silicon carbide (SiC) ceramic plate. Table 2 lists the material specifications.

**Table 1:** The specifications of Kevlar fabric

| Properties | Aramid Kevlar 49 |
|---|---|
| Density (g/cm$^3$) | 1.45 |
| Tensile strength (cN/tex) | 200 |
| Tesile modulus (cN/tex) | 8300 |
| Elongation at break (%) | 2.5 |
| Temperature range (°C) | 204 |
| Decomposition temperature (°C) | 400 |
| 300°C 100 h strength resistance (%) | 60-65 |
| Moisture absorption (%) | 4.5 |
| Wear resistance | General |
| Solvent resistance | Good |
| Acid resistance | Bad |
| Alkali resistance | Good |
| UV resistance | Bad |

**Table 2:** The specifications of Sikafloor, and SiC

| Properties | Sikafloor-156 epoxy resin | Silicon carbide (SiC) |
|---|---|---|
| Flexural strength | ~30 N/mm$^2$ | |
| Compressive strength | ~95 N/mm$^2$ | |
| Shore D hardness | 83 (seven days) | |
| Bulk density | | > 3.12 g/cm$^3$ |
| Bending strength | | > 400 MPa |
| Rockwell hardness | | >93 HRA |
| Thermal conductivity | | 148 W.m$^{-1}$.k$^{-1}$ |
| Elastic modulus | | 415 GPa |
| Fracture toughness | | > 4.5 MPa.m$^{1/2}$ |

### 2.2 Preparation of body armor

One layer of SiC ceramic was applied to the front layer, six separate layers of Kevlar reinforced epoxy was applied to the middle layer, and lastly, one layer of polycarbonate sheet was applied to the rear layer in 30*30 cm$^2$. Body armor was made by hand layup, as illustrated in Figure 1, by adding the hardener to epoxy resin and combining them in a 1: 3 weight ratio.

To evacuate bubbles and remove extra resin, samples are compressed into a 34*34 cm2 glass mold using mechanical pressure and clamps. For 1-2 days, the samples were kept at room temperature. To connect composite layers and ceramic with composite, epoxy resin glue was utilized, while silicon rubber was used to bond composite with polycarbonate. Table 3 depicts the design parameters of the prepared body armor

**Table 3:** The body armor prepared

| Materials used in body armor | No. of layers | Thickness of layer | Total thickness | Total weight |
|---|---|---|---|---|
| SiC | 1 layer | 0.3 cm | 1.07 cm | 1.550 kg |
| Kevlar reinforced epoxy | 6 layers | 0.045*6 cm | | |
| Polycarbonate | 1 layer | 0.4 cm | | |

## 2.3 Simulation

### 2.3.1 Modeling Process

The armor was modeled using numerical simulations using Ansys Workbench version 20.R2; it consists of two sections (3D model) for the projectile and the armor with real dimensions. The model was solved and the results' modeling was obtained using Ansys Explicit Dynamics with AUTODYN. Model elements such as mesh and part-to-part contact conditions were built up after the materials for each component were modeled into Ansys engineering data. Finally, the solver properties such as beginning circumstances, system statics, and dynamic properties, have been established, as well as the intended output.

### 2.3.2 Projectile

The bullet's geometry was split into two halves. The inside component is the core of the bullet, while the outside part is the jacket of the bullet. Steel is used for the core, and cart brass used for the jacket is full metal (FMJ). Steel is assigned to the core, and Cart Brass is assigned to the jacket, according to Ansys' explicit material database. The Ansys Explicit Dynamics mesh modeler was used to build the bullet geometry and 3D mesh. Steel and cart brass have both been represented as explicit materials. Figure 2 depicts the geometry and 3D mesh of the projectile and armor.

### 2.3.3 Ballistic Armor

The body armor is made up of three layers of various materials: ceramic, Kevlar-reinforced epoxy, and polycarbonate. Ansys' explicit material database used for ceramic (SiC) and polycarbonate materials, as well as Ansys material engineering data, had to be used for Kevlar-reinforced epoxy. Figure 3 illustrates a material designer. It was chosen to apply it to this sample's modeling. In Ansys Design Modeler, the armor's shape was represented as solid materials with varying thicknesses for each layer. The samples were 900 $cm^2$ in size in both the x and y directions and their thickness varied as shown in Table 3. A macrohomogeneous model was used to represent the Kevlar-reinforced epoxy layers, assuming that all layers had the same shape and orthotropic mechanical characteristics. They were represented as bilinear isotropic hardening composite materials with linear isotropic elasticity. The mesh of layers was created as a body mesh with high smoothness and default element size using the Ansys Explicit dynamic mesh modeler. This mesh was also used to create additional body armor materials.

### 2.3.4 Analysis Settings

The model was solved using Ansys workbench V20.R2 in Ansys Explicit dynamics using the Ansys AUTODYN 3D solver [14]. The test's beginning condition was reproduced by identifying the initial velocity of the bullet components, which was 307 m/s in the Z direction and the support location was in the X and Y directions. The analysis took $1.2*10^{-4}$ s to complete, with a maximum number of cycles of 9296. The contact state sample layers were simulated, bonded contact was established in the Ansys model simulation parameters between the ceramic layer and the Kevlar-reinforced epoxy layer, as well as between the Kevlar-reinforced epoxy layers with others and the Kevlar-reinforced epoxy layer with the polycarbonate layer. The literature Bonded [15,16] has many information explanations of the AUTODYN 3D code that is used in specific dynamic situations. In a nutshell, the approach uses boundary starting conditions to calculate mass and momentum conservation rules in Eulerian or Lagrangian form. Mechanical parameters and failure reactions of the materials must enter into the code, after which the software will calculate and show the stresses in terms of pressure, volume, and internal energy [17]. Several forms of stress, such as equivalent (von Mises) stress and shear stress, may be addressed by the code. To establish the system's ballistic behavior, the solution output sets compute the overall and deformation that occurs in Z directional of the sample. The mechanical characteristics and failure scenarios were described in the material modeling section. The whole system's residual stress was also displayed using Von Mises stress.

## 2.4 Ballistic test

Personal body armor must be made following international regulations (e. g. National Institute of Justice-0101.06). Depending on guidelines, the primary objective of armor is to prevent projectile penetration. Another essential objective is to prevent damage to interior organs even with non-penetration. The backface signature (BFS) must be smaller than 44 mm [18].

The body armors were put to the test using the National Institute of Justice's 0101.06 standards. According to the National Institute of Justice's 0101.06 Level II-A bullet speed standard, the distance must be 5 meters between handgun and sample, and the speed of a Daewoo handgun firing a 9 mm FMJ bullet was 307 meters per second. The velocity of the bullet was measured using the Ballistic Precision Chronograph placed between the gun and the armor. The sample was supported by a steel frame window with a 30 x 30 $cm^2$ surface area and no back support. An FMJ bullet with a mass of 8 g and a diameter of 9 mm was utilized. The caliper is used to determine the depth of penetration. Figure 4 depicts the experimental setup. Samples were sliced and cross-sectioned after the ballistic assessment to identify the types of damage and Specify damage processes.

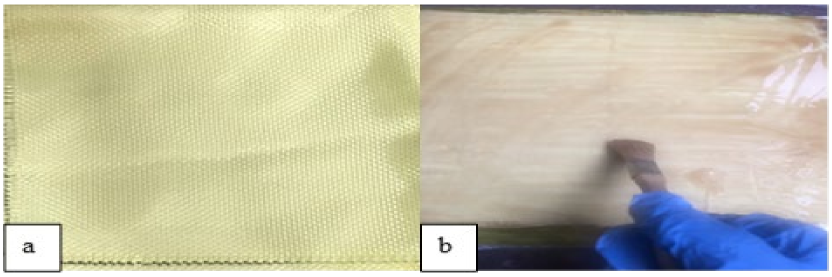


**Figure 1:** (a) fabric (b) hand layup

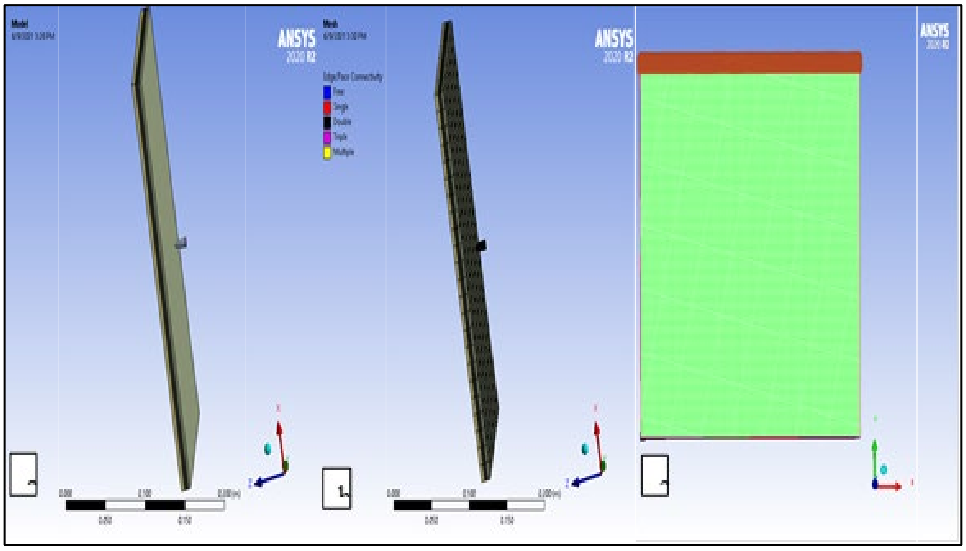


**Figure 2:** (a) Bullet and armor geometry (b) 3D mesh of bullet and armor in explicit dynamic (c) mesh in AUTODYN

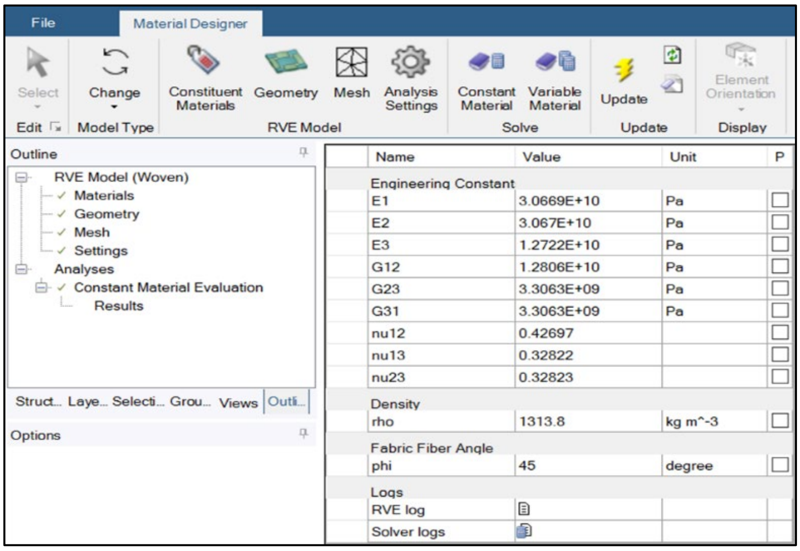


**Figure 3:** Material designer of KEV/EPX

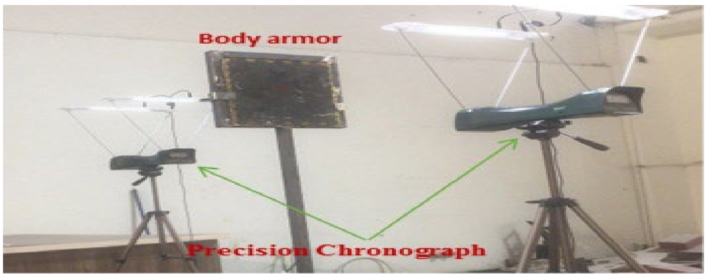


**Figure 4:** Ballistic test

## 3. Results, Discussion, and Simulation Analysis

To save time, experimentation, and production costs, the simulation was completed first, followed by the ballistic test based on the simulation findings. There are several methods for comparing experimental and simulation ballistic test results. Experimental and numerical results can give a clear picture of the damage shape and magnitude. Furthermore, the simulation model can estimate total and directional deformations, as well as residual stress in the bullet and target.

Figure 5 shows the deformation behavior of SiC/KEV/EPX/Polycarbonate under a high-velocity (307 m/s) bullet impact and a comparison between it and simulation, demonstrating the sample's capacity to stop the bullet without penetration. The shock energy of the bullet was spent in ceramic failure, brittle crack of the KEV/EPX layers, delamination, and plastic deformation on both KEV/EPX layers and Polycarbonate sheet that caused cone shape formation on the back face of the layer, also known as backface signature, as shown in the cross-section of the sample shown in Figure 5. The (BFS) was 0.6 cm, which is within the allowed range [18].

The bullet can shatter ceramic and brittle cracks in KEV/EPX layers without penetration, according to the exploded image of the target, although it produces minimal delamination and plastic deformation of polycarbonate.

Through cracking and fracturing, the ceramic layer will absorb the majority of the projectile's kinetic energy. The fiber-reinforced composite will absorb the projectile's remaining kinetic energy through plastic deformation and damage. This layer will also provide support for the cracked ceramic layer [19]. Ballistic efficiency is better when the ceramic face is used as a single plate covering the whole back layer due to the increased lateral restriction of the impact zone. Projectile damage, on the other hand, can affect the entire ceramic plate, but with tiny tiles, it just affects the tiles around it [20]. Tiny ceramic tiles were utilized in this paper. The projectile will erode, distort, and stay inside the KEV/EPX layers. The textiles utilized in this work's body armors are usually woven materials that can trap bullets by forming a network around them. This network transmits the bullet's kinetic energy through the fibers [21].

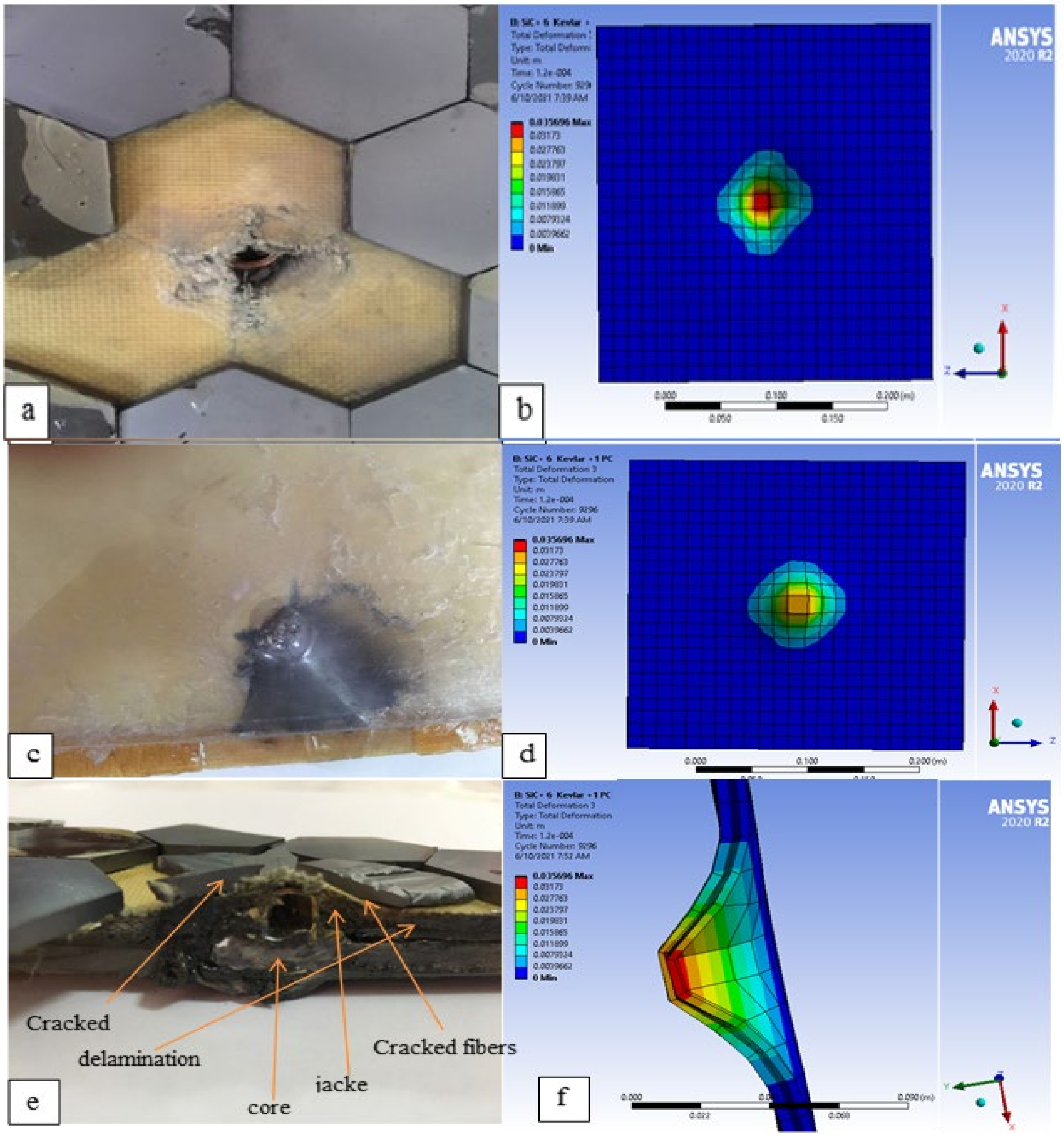


**Figure 5:** Result of body armors (a) front face of experiment test (b) front face of simulation result (c) back face of Experiment test (d) back face of simulation result (e) cross-section of experiment test (g) cross-section Of two bullet (f) cross-section of simulation result

The kinetic energy of bullets (Cart Brass and steel) is 83.4 J, while internal energy absorbed by ceramic, composite, and polycarbonate is 52.98 J seen in Figure 6 using the Ansys AUTODYN 3D solver. The remaining energy of the bullet is absorbed by delamination of layers, deformation of bullet, ceramic cracking, and other types of deformation. The results of the ballistic test and simulation were reported in Table 4. The energy absorbed by the ceramic material is more than that absorbed by fiber-reinforced composites and even polycarbonate which reach 77.8% of the total energy absorbed by body armor, as seen in the figures and table. Velocity - Time curve is shown in Figure 7.

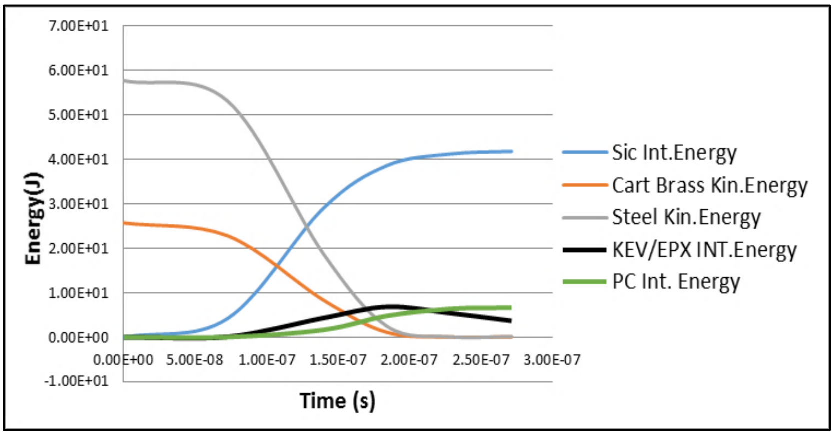


**Figure 6:** Internal and kinetic energy of material used in body armor

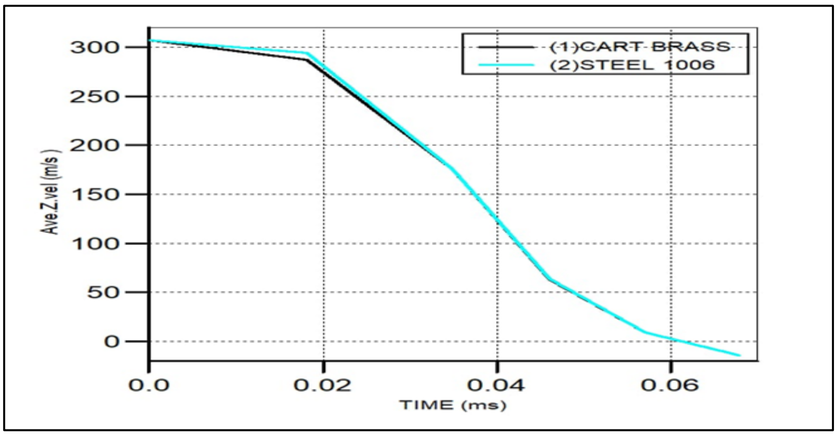


**Figure 7:** Velocity – Time curve of the bullet

**Table 4:** The results of the ballistic test and simulation

| Materials of body armor | Depth of (BFS) | Diameter of (BFS) | Perforation depth through composite | Kinetic Energy of bullet | absorbed energy |
|---|---|---|---|---|---|
| Sic<br>Kevlar reinforced epoxy<br>Polycarbonate | 0.6 cm | 1.6 cm | 0.85 cm | Steel: 57.7 J<br>Cart Brass: 25.7 J<br>Total: 83.4 J | Ceramic layer: 41.2 J<br>Composite layers: 5.41 J<br>Polycarbonate layer:6.37 J<br>Total: 52.98 J |

## 4. Conclusions

Composite laminate materials were used to produce ballistic structural armors from various materials and designs. A 900 $cm^2$ laminate plate sample was made up of three different materials in this investigation. The Ansys simulation program was used to model ceramic, composite laminate constructions with (KEV+EPX) woven fabric, and a polycarbonate layer to determine the armor's technical feasibility. The sample was tested experimentally for verification. According to the findings, SiC/UPE+EPX/PC can stop a 9mm FMJ bullet with just a little distortion. By anticipating ballistic behavior and design constraints, as well as giving important insights throughout the product development process, simulation can assist decrease costs in the creation of armor.

**Acknowledgment**

The authors would like to acknowledge the University of Technology/ Material department Engineering and Manufacturing and Industrial Engineering Department - Faculty of Engineering/ Koya University.

**Author contribution**

All authors contributed equally to this work.

**Funding**

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

**Data availability statement**

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

**Conflicts of interest**

The authors declare that there is no conflict of interest.

## References

**[1]** B. A. Gama, T. A. Bogetti, B. K. Fink, C. Yu, T. D. Claar, H. H. Eifert, J. W. Gillespie, Aluminum foam integral armor: A new dimension in armor design, Compos. Struct., 52 (2001) 381–395. http://dx.doi.org/10.1016/S0263-8223(01)00029-0

**[2]** M. Tanoglu, S. H. McKnight, G. R. Palmese, J. W. Gillespie, Effects of glass-fiber sizings on the strength and energy absorption of the fiber/matrix interphase under high loading rates, Compos. Sci. Technol., 61(2001) 205–220. http://dx.doi.org/10.1016/S0266-3538(00)00195-0

**[3]** U. K. Vaidya, A. Abraham, S. Bhide, Affordable processing of thick section and integral multi-functional composites, Compos. Part .A. Appl. Sci. Manuf., 32 (2001) 1133–1142. http://dx.doi.org/10.1016/S1359-835X(01)00033-1

**[4]** C. Navarro, M. A. Martinez, R. Cortés, V. Sánchez-Gálvez, Some observations on the normal impact on ceramic faced armours backed by composite plates, Int. J. Impact. Eng., 13 (1993) 145–156. http://dx.doi.org/10.1016/0734-743X(93)90113-L

**[5]** P. J. Hogg, Composites for Ballistic Applications, Proc. Compos. Process., (2003) 1–11.

**[6]** D. Zhu, A. Vaidya, B. Mobasher, S. D. Rajan, Finite element modeling of ballistic impact on multi-layer Kevlar 49 fabrics, Compos. Part. B. Eng., 56 (2014) 254–262. http://dx.doi.org/10.1016/j.compositesb.2013.08.051

**[7]** L. H. L. Louro , F. S. Luza , E. P. L. Juniora , S. N. Monteiroa , Ballistic test of multilayered armor with intermediate Epoxy composite reinforced with jute fabric, Mater. Res., 18 (2015) 170–177. https://doi.org/10.1590/1516-1439.358914

**[8]** A. M. Soydan, B. Tunaboylu, A. G. Elsabagh, A. K. Sarı, R. Akdeniz, Simulation and experimental tests of ballistic impact on composite laminate armor, Adv. Mater. Sci. Eng., 2018 (2018) 1–12. http://dx.doi.org/10.1155/2018/4696143

**[9]** P. Compston, W. J. Cantwell, C. Jones, N. Jones, Impact perforation resistance and fracture mechanisms of a thermoplastic based fiber-metal laminate, J. Mater. Sci. Lett., 20 (2001) 597–599. http://dx.doi.org/10.1023/A:1010904930497

**[10]** S. Heimbs, T. Bergmann, D. Schueler, N. Toso-PentecÔte, High velocity impact on preloaded composite plates, Compos. Struct., 111 (2014) 158–168. http://dx.doi.org/10.1016/j.compstruct.2013.12.031

**[11]** E. Camci , F. Findik, Ballistic impact performance of laminated composite structures, Period. Eng. Nat. Sci., 7 (2019) 1329 –1344. http://dx.doi.org/10.21533/PEN.V7I3.700

**[12]** F. Mullaoğlu, F. Usta, H. S. Türkmen, Z. Kazanci, D. Balkan, E. Akay, Deformation behavior of the polycarbonate Plates subjected to impact loading, Procedia. Eng., 167 (2016) 143–150. http://dx.doi.org/10.1016/j.proeng.2016.11.681

**[13]** S. S. Esfahlani, Ballistic performance of Polycarbonate and Polymethyl methacrylate under normal and inclined dynamic impacts, Heliyon, 7(2021) e06856. http://dx.doi.org/10.1016/j.heliyon.2021.e06856

**[14]** C. Y. Tham, V. B. C. Tan, H. P. Lee, Ballistic impact of a KEVLAR helmet: Experiment and simulations, Int. J. Impact. Eng., 35 (2008) 304–318. http://dx.doi.org/10.1016/j.ijimpeng.2007.03.008

**[15]** G. R. Johnson , T. J. Holmquist, An improved computational constitutive model for brittle materials, AIP Conf. Proc., 981 (2008) 981–984. https://doi.org/10.1063/1.46199

**[16]** N. Robertson, C. Hayhurst, G. Fairlie, Numerical simulation of impact and fast transient phenomena using AUTODYN$^{TM}$-2D and 3D, Nucl. Eng. Des., 150 (1994) 235–241. http://dx.doi.org/10.1016/0029-5493(94)90140-6

**[17]** A. A. Ramadhan, A. R. Abu Talib, A. S. Mohd Rafie, R. Zahari, High velocity impact response of Kevlar-29/epoxy and 6061-T6 aluminum laminated panels, Mater. Des., 43 (2013) 307–321. http://dx.doi.org/10.1016/j.matdes.2012.06.034

**[18]** National Institute of Justice, Guide body armor: selection and application guide to ballistic-resistance body armor, Ncj, 247281 (2014).

**[19]** E. Medvedovski, Lightweight ceramic composite armour system, Adv. Appl. Ceram., 105 (2006) 241–245. http://dx.doi.org/10.1179/174367606X113537

**[20]** A. L. Florence, Interaction of projectiles and composite armor Part II, STANFORD Res. INST MENLO Park CA, USA, (1969).

**[21]** J. W. Song , B. L. Les Lee, 8 - Fabrics and composites for ballistic protection of personnel, Lightweight Ballistic Composites .,(2006) 210–239. http://dx.doi.org/10.1533/9781845691554.2.210