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Research Article

Ballistic impact response of hybrid composite plates

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ABSTRACT

The behaviors exhibited by materials used in military and civilian daily applications in response to ballistic impacts constitute an important field of study. These behaviors have been investigated experimentally on composite plates with different configurations. For this purpose, Para-Aramid (Kevlar)/epoxy and Para-Aramid (Kevlar)/Glass hybrid composite plates with two different configurations were produced. Specimens obtained from these plates were subjected to tests at velocities corresponding to armor levels IIIA, IIA, and II. As a result of the tests, the effects of the velocities on the target specimens were compared. At the same time, the deformations on the plates were also examined. The study, conducted at three different velocities, yielded positive results from the Para-Aramid (Kevlar)/epoxy composite in the level IIA test, while negative results were obtained from the two hybrid plates. In the levels II and IIIA velocity tests, deformations were observed in the composite plates. Matrix cracks and fiber breakages were detected in the deformations obtained.

1. INTRODUCTION

Materials are exposed to different loading conditions in their areas of use. These loading types are factors that affect the life, use, and safety of the material. Impact loading in the ballistic field is one of the most important conditions under which materials will be affected. In this sense, the resistance of the material used against impact and puncture is an important parameter to seek.

The use of composite materials in ballistics is becoming widespread. The analysis of ballistic impact response and failure mechanisms in layered composites is complex. Since some variable parameters, such as composite composition, fibers, and volume, are affected, the level of complexity increases with the impact velocity. For this reason, a good understanding of the properties of composite materials is required for structural materials [1]. Again, the use of polymer matrix composites and hybrid composites is among the techniques used to increase the protection capabilities of composite materials in the ballistic field. It is critical to comprehend how hybrid composites behave when subjected to ballistic impact loads. Factors affecting this loading response include fiber and matrix type, plate thickness, arranging sequence, geometry, and boundary conditions. Ballistic impact response additionally depends on the dimensions, form, and kinetic energy of the projectile [2].

Experimental [3-13,15] and numerical [14] studies have been conducted on the use of composite materials in ballistics. Signetti et al. [3] developed an analytical model and conducted extensive experimental ballistic tests to investigate the ballistic behavior of multi-layer composite protective armor subjected to high-velocity impacts of projectiles with random incidence angles, form, dimensions, and friction characteristics. They concluded that graduated multi-layer configurations provide higher toughness as the projectile enters the layers with decreasing fracture strength. Kędzierski et al. [4] performed experimental and numerical investigations of the strength of ten fabrics made from high-strength fibers. They investigated materials in a variety of sizes, such as multiaxial fabrics, unidirectional plates, and plain woven fabrics. They found that the normalized results obtained experimental and numerical revealed that most of the fabrics analyzed provided similar levels of protection, but the best strength was provided by multidirectional fabrics and the least strength was provided by plain woven fabrics. Deliktaş et al. [5] developed a numerical model for predicting ballistic impact performance. They estimated parameters influencing the ballistic performance of composite materials using the model. They found that projectiles with different geometries and the orientation of the plate had significant effects on the ballistic results. Tarım et al. [6] experimentally examined the ballistic impact performances of some polymer composites. In one experimental group, they produced glass fiber prepregs with 6, 12, 18, 22, 28, and 36 layers. In the second group, they bonded the Al layer on both sides of 6, 12, 18, 22, 28, and 36-layer glass fibers. In ballistics tests, they found that thinner composite plates had higher flexibility than thicker ones. Furthermore, they discovered that while perforation did not occur in the 28th and 36th layers of the composite plate, full perforations occurred in the 18th and 22nd levels. Choudhury et al. [7] examined the effect of temperature changes on the mechanical properties of glass fiber reinforced polymer (GFRP) composites and their capacity to halt projectiles during ballistic impact. They indicated that plain woven GFRP was affected by cylindrical projectiles at four different temperatures. Zhikharev et al. [8] experimentally and numerically investigated the ballistic impact response of 2 mm-thick composite plates subjected to a uniaxial tension preload. They determined that the ballistic limit is decreased by the single axial tension preload. Naik and Shrirao [9] compared the ballistic impact behavior of E-glass/epoxy and T300 carbon/epoxy composites. They reported that the ballistic limit of E-glass/epoxy was higher than T300 carbon/epoxy for the same ballistic impact conditions. Reddy et al. [10] used a mild steel core projectile to study the ballistic performance of an E-glass/phenolic composite as a function of plate thickness and projectile impact velocity. They observed a non-linear connection between plate thickness and energy absorbing. Ansari et al. [11] investigated the [0°/90°] ballistic performance of glass fiber-reinforced polymer (GFRP) composites against 19 mm diameter steel nose cone projectiles. They also reproduced ballistic tests by performing three-dimensional finite element simulations. They determined that as the aspect ratio of the composite target increased, so did its ballistic performance, with the effect of the aspect ratio being more obvious in thicker targets. Jenq et al. [12] investigated the ballistic limit of flat woven glass/epoxy composite plates struck by a hard projectile weighing 14.9 g and having a 5 mm tip radius. They investigated the progressive failure modes of the targets. They performed quasi-static penetration tests to characterize the penetration process. They indicated that the rhombic delamination of impact-failure specimens was greater than that of quasi-statically penetrated specimens. Liu et al. [13] conducted impact tests using a 14.5 mm ballistic gun with a cylindrical projectile to examined the ballistic resistance of polyurea-coated carbon fiber-reinforced plastic (CFRP) composites. They found that as the initial velocity of impact increased, the deformation of the projectiles increased. Sorrentino et al. [14] evaluated an analytical model to determine both the performance of composite armor made of Kevlar 29 fabrics impregnated with thermosetting resin and the ballistic limit velocity. In their studies, they concluded that the ballistic test results showed that the technological process was appropriate and that the materials used to produce the armor provided good ballistic performances, showing ballistic limits about 8% higher than predicted by the analytical model. Naik et al [15] presented a review of the latest technology in the field of ballistics for kevlar composites. Research on Kevlar fiber-reinforced composites has been conducted, focusing on structural properties and characterization, development, applications in various engineering and related sectors, ballistic post-impact degradation mechanisms, and methods used in analysis.

In the literature, hybrid composites [16-26] made by combining many composite materials, such as Kevlar, glass, and carbon, have been studied. In an effort to increase ballistic impact strength, Peng et al. [16] investigated hybrid layered constructions made by combining compressed wood, Dyneema, ceramics, and Kevlar. They stated to have given the information needed to verify computer models that would help with further conceptual designs on hybrid ballistic panels and the development of lightweight composite armor. The high-velocity projectile impact failure of a hybrid composite consisting of carbon, glass, and Kevlar composites was numerically investigated by Karthick et al. [17]. They stated that carbon fiber composites are not as strong as Kevlar in terms of impact strength, but that by hybridizing carbon composites with Kevlar and glass, the impact strength and ballistic limit velocity can be raised. Yanen et al. [18] experimentally investigated the usability of layered hybrid composites in individual armor materials. They conducted ballistic tests of Glass Fiber/Aramid Fiber/Carbon Fiber layered composite plates with different fiber-reinforcement angles, different layer numbers, and different thicknesses. In their study, they stated that the ballistic resistance of fabrics with twill weaving structures is better. Bitlisli et al. [19] found that in composite armor materials for armored vehicles, ultra-high molecular weight polyethylene (UHMWPE), Aramid, Carbon, Hybrid and Glass Fiber types used as reinforcement materials, and PE film layers without using any resin as matrix material were placed layer by layer and then combined under pressure and temperature effects under press to form a layered structure. They fired shots in accordance with NIJ standards used in ballistic applications. In their study, they determined that the most suitable process as a production method is the thinnest and lightest of the bulletproof plates. Alarçin [20] used a hydraulic press to compress UHMPW-PE and carbon fiber materials in various layers at a specific pressure and temperature to create hybrid composite plates. He determined that by adding 1 layer, 3 layers, and 6 layers of carbon fiber prepreg to 25 layers of UHMPW-PE composite, the ballistic strength enhanced by 8.06%, 14.6%, and 22.6%. Sah et al. [21] conducted research to perform a numerical analysis of the ballistic effect on different hybrid composite combinations. They used different stackings of Kevlar 3D, Basalt 3D, and Hybrid-3D layers (combination of Kevlar 3D and Basalt 3D fabric layers). In the six hybrid composite panels they modeled (K3B3, B3K3, B3H3, H3B3, K3H3, and H3K3), they used a 9 mm full metal jacket (FMJ) projectile with an impact velocity range of 240 m/s to 350 m/s. They concluded that the B3K3 panel performed the best among all panels (K3B3, B3K3, B3H3, H3B3, K3H3, H3K3) with a ballistic limit of 332 m/s, while H3B3 performed badly with a ballistic limit of 251 m/s. Reddy et al. [22] studied the development of hybrid composite plates for armor applications to take advantage of the advantages of carbon and E-glass fibers. For this purpose, they produced three hybrid composite plates based on carbon and E-glass with epoxy resin matrix in weight ratios of 75:25, 50:50, and 25:75 and carbon and E-glass composites for comparison. They used a 7.62 mm mild steel projectile in their study. In terms of energy absorption, they discovered that composite plates with a 50:50 (CE 50-50) carbon to E-glass ratio performed best. Using hydrocode simulations, Kumar et al. [23] examined the influence of hybridization in hybrid composite armor under ballistic impact. They stated that hybridization improves the relative ballistic performance of hybrid composite armor. They determined that the hybrid layer's stacking sequence had an impact on ballistic performance metrics like energy absorption, residual velocity, and ballistic limit. Yavaş et al. [24] investigated the effects of ply number on the ballistic performance of Kevlar49/UHMWPEHB26 (ultra-high molecular weight polyethylene) layered hybrid composite. They conducted ballistic tests according to NIJ Standard-0101.04 level III standards. They stated that as the total number of plies in the composite specimens decreased, the impact depth increased. Randjbaran et al. [25] experimentally investigated the influences of stacking order on the ballistic energy absorption of hybrid composites obtained with the use of glass, carbon, and kevlar woven fabrics. They calculated the velocity and absorbed energy. According to the authors, glass and carbon combined in the middle layers provide more efficiency. Yahaya et al. [26] used two distinct procedures to create woven kenaf-Kevlar hybrid composites, altering the woven kenaf content between 5.40 and 14.99 by volume. The hybrid composites were subjected to ballistic measurement experiments using fragment simulated projectiles at varying impact and residual velocities. In comparison to other hybrid composites, they discovered that the hybrid composites exhibited better ballistic performance.

In this study, the ballistic test performances of hybrid composites formed by the sequence Para-Aramid (Kevlar), which has a good strength property [27], with glass fiber-reinforced layers were experimentally investigated. Glass fiber reinforced fabrics were positioned in the middle levels of the study, while Para-Aramid (Kevlar) fabric was used in the upper and lower layers. In this sense, plates produced by three different groups were subjected to the test. Ballistic tests were performed on three different plates at three different velocities. The results obtained were evaluated and discussed.

2. MATERIAL AND METHOD

2.1. Preparation of composite plates

In this study, three different composite plates were produced. (Figure 1) All three productions were carried out in 11 layers. Hybrid composite production was carried out, with glass fiber reinforced fabric in the single-layer and 3-layer intermediate layers, and Para-Aramid 100 % (Kevlar) (it is abbreviated as K) in the lower and upper layers. In this sense, in the first group, kevlar/epoxy production was carried out. It was produced using 3Kevlar/1Glass/3Kevlar/1Glass/3Kevlar (3K/1G/3K/1G/3K) in Group II and 4Kevlar/3Glass/4Kevlar (4K/3G/4K) in Group III. Geometric drawings of these are given in Figure 1.

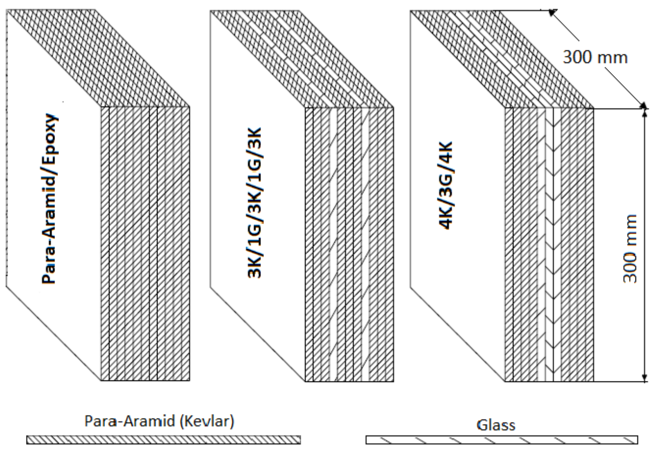

Figure 1. Demonstration of the sequence of layers

All three plates were produced in 500 mm x 500 mm dimensions using the hand lay-up method. Production was carried out at Fibermak Engineering Machinery Mold Composite San. Tic. Ltd. (İzmir/Turkey). The Para-Aramid 100 % (Kevlar) fabric used in the study was obtained from Kipaş Holding Company (Kahramanmaraş/Turkey). The fabric is woven and warp & weft type 3140 DTEX Flament with a Kevlar 100% structure. This Kevlar fabric is 0.4 mm thick, and 1 m^2 is 396.43 gr. F-RES 21-type epoxy resin (Fibermak, Turkey) with a density of 1.15 gr/cm^3 was used at 60%. F-HARD 22 type (Fibermak, Turkey) with a density of 1 g/cm^3 and 40% by volume was used as a hardener. Glass fiber-reinforced twill fabrics (Fibermak/Turkey) at 390 g/m^2 were used in the production of hybrid composites.

First of all, the 101 cm wide Kevlar fabric was prepared by cutting it in 11 layers with dimensions of 500 mm x 500 mm (Figure 2 a). Epoxy resin was applied to each fabric layer by hand lay-up method (Figure 2b). Then, after the gelation period of the fabrics, the semi-finished fabrics were stacked on top of each other, wrapped with fireproof film, and placed in the hydraulic hot press (Figure 2c). First, the fabrics were exposed to a pressure of 10 bars. After then, the temperature was increased to 125 °C from room temperature. For an hour, the plate was maintained in these conditions. The plates were allowed to reach room temperature when the heating element was shut off. The plates with 3K/1G/3K/1G/3K (Figure 2 d,e) in Group II and 4K/3G/4K (Figure 2f) in Group III were obtained by going through the same production steps.

The 11-layer and 4.5 mm thick Kevlar/epoxy composite plate in Group I (Figure 2h) and the plates in the other groups were cut with the help of a CNC machine in the dimensions of 300 mm x 300 mm (Figure 2g), which are the target plate dimensions for the experimental processes (Figure 2h).

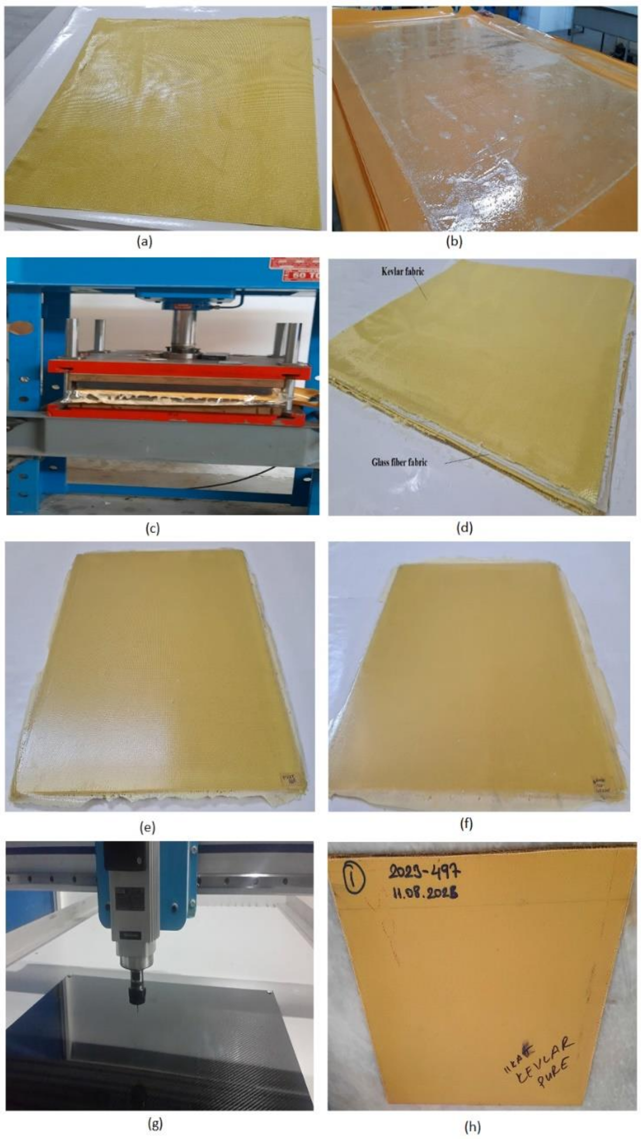

Figure 2. Production of composite plates

2.2. Ballistic Tests

In the Afyon 8th Main Maintenance Factory Directorate, ballistic impact tests were performed. NIJ Standard-0101.04 (The National Institute of Justice Standard) was used for the test setup. The properties of the 11-layer target plates are given in Table 1.

Before the test, the target plates were numbered according to with the standard (Figure 3a, b, c) in order to see the impact failure of the projectile impact on the target plates and the effect of boundary limits. They were then fixed to the setup for firing (Figure 3d). A schematic representation of the ballistic test setup according to NIJ Standard-0101.04 [28] is shown in Figure 3e.

A ballistic impact test apparatus operated by a stepped gas gun was used in the experimental study. A full metal jacket projectile (FMJ RN) was hit at the target specimen. According to 9×19 mm MP-5, FMJs are made in accordance with their definition by MKE (Mechanical and Chemical Industry). The masses, types, and velocities of the FMJ RN projectiles used in the experimental study were selected in accordance with the standard [28] and are indicated in Table 2. In addition, FMJ projectiles used for three different velocities in the study were fired at the target plate from a distance of 5 m. The tests were conducted at a temperature of 21.9 °C and a relative humidity of 48.0%.

The ballistic test starts with the firing of the projectile at a certain velocity, and when the projectile creates a hole in the target specimen, it is considered to have caused perforation and deformation. If the projectile does not create a hole in the target specimen, partial penetration is considered.

TABLE I. TARGET PLATE PROPERTİES

	Description	Weight (g)	Thickness (mm)
I.Group	Kevlar/epoxy	520.5	4.5
II.Group	3K/1G/3K/1G/3K	531.2	4.5
III.Group	4K/3G/4K	518.0	4.5

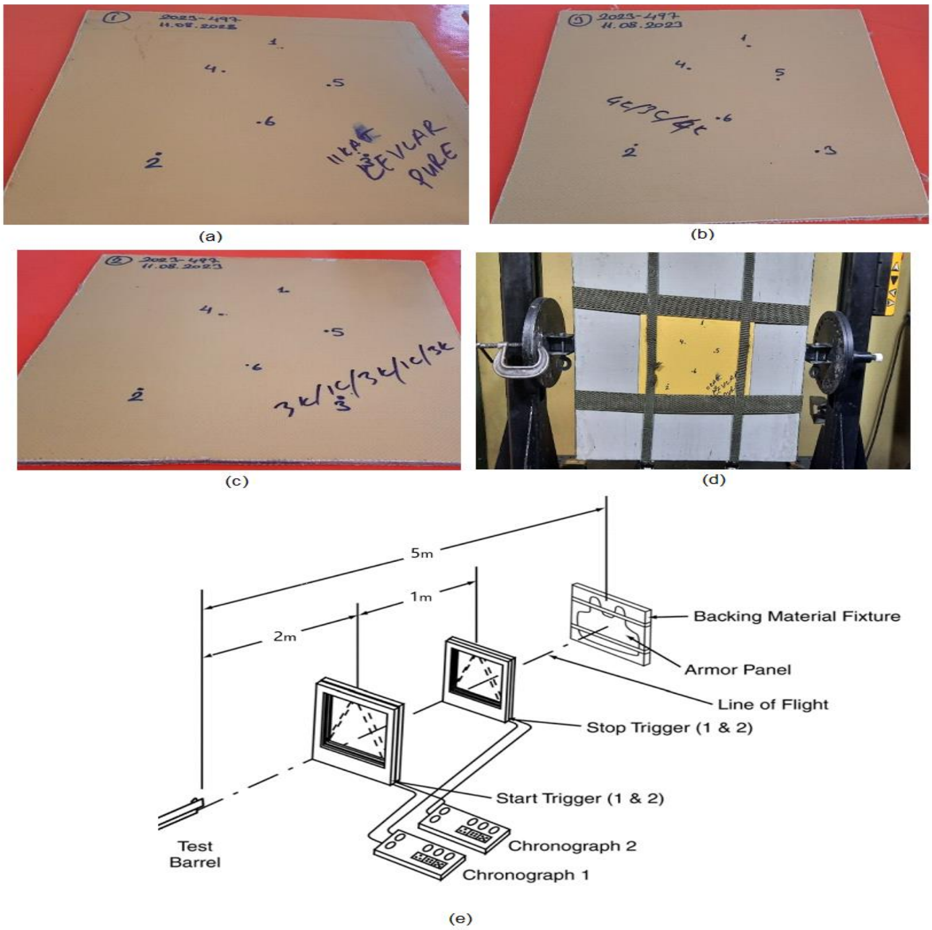

Figure 3. Ballistic testing procedures

TABLE II. EXPERIMENTAL TEST PARAMETERS

Armor-Type	Projectile-Type	Projectile-Weight	Projectile-Velocity
IIIA	9 mm FMJ RN	8.2 gr	436 ± 9.1 m/s
II	9 mm FMJ RN	8.0 gr	367 ± 9.1 m/s
IIA	9 mm FMJ RN	8.0 gr	341 ± 9.1 m/s

The aim of ballistic tests is to prevent or minimize this effect on the materials used. For this purpose, tests were carried out in three groups. In Group I, Kevlar with epoxy resin; in Group II, 3K/1G/3K/1G/3K; and in Group III, target composite plates with a 4K/3G/4K array were subjected to ballistic tests. The tests were conducted at the velocities specified in levels IIIA, IIA, and II (Table 2). These speeds are chosen according to whether the target plate is perforated or not. First, the target was shot at the velocity in level IIIA, then at the velocity in level II, and then at the velocity in level IIA, according to the result obtained. Since the high velocity impact was realized, the failure of the target plate was evaluated.

3. RESULT AND DISCUSSION

3.1. Ballistic results of hybrid composites

Kevlar/Epoxy, 3K/1G/3K/1G/3K, and 4K/3G/4K target composite plates were examined after the test. During the tests, the failure was analyzed to see if the target was completely perforated from behind. Group I; the average velocity values were realized in the range of 431 m/s in the shots fired at the IIIA level in the Kevlar/epoxy composite plate and perforation occurred in the plate (Figure 4). Then the shooting at level II was started. The shots here were fired at an average range of 362 m/s. Perforation was also detected as a result of these shots. The last shot was fired with a speed of IIA level. This firing rate was realized at an average speed of 344 m/s. As a result of the test, it was determined that no perforation occurred in the target plate. It was determined that the depth of depression was 12.11 mm. According to NIJ Standard-0101.04, the depth of depression should be a maximum of 44 mm. Therefore, it was determined that the result obtained in the test performed at level IIA velocity was appropriate according to the standard value.

In group II, the plate with the 3K/1G/3K/1G/1G/3K sequence was first tested at the velocity at level IIIA. In the measurements made, an average velocity of 434 m/s was realized. As a result of the test, it was determined that perforation occurred. Perforation was also obtained in the shots fired at level II, and tests were started at velocity level IIA. It was determined that the measured velocity range in this test was 344 m/s. As a result of this test, perforation occurred in the plate (Figure 5).

The composite plate with the 4K/3G/4K sequence in group III was subjected to tests at the velocities of all three levels. It was determined that the shooting velocities at level IIIA were 434 m/s, level II was 363 m/s, and level IIA was 348 m/s. In these test results, perforation occurred in the plate (Figure 6). The results of the tests are given in Table 3.

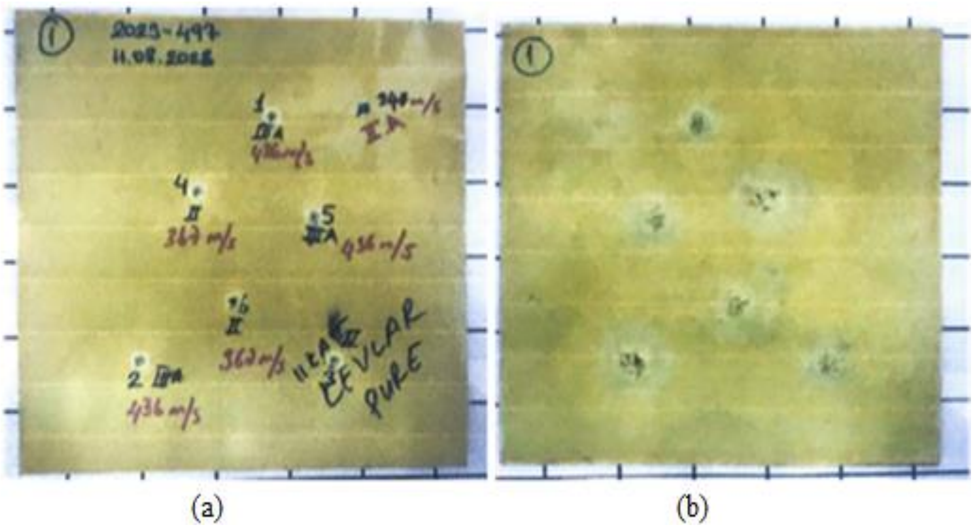

Figure 4. Shotted by projectiles Kevlar/epoxy plate a) Front side b) Back side

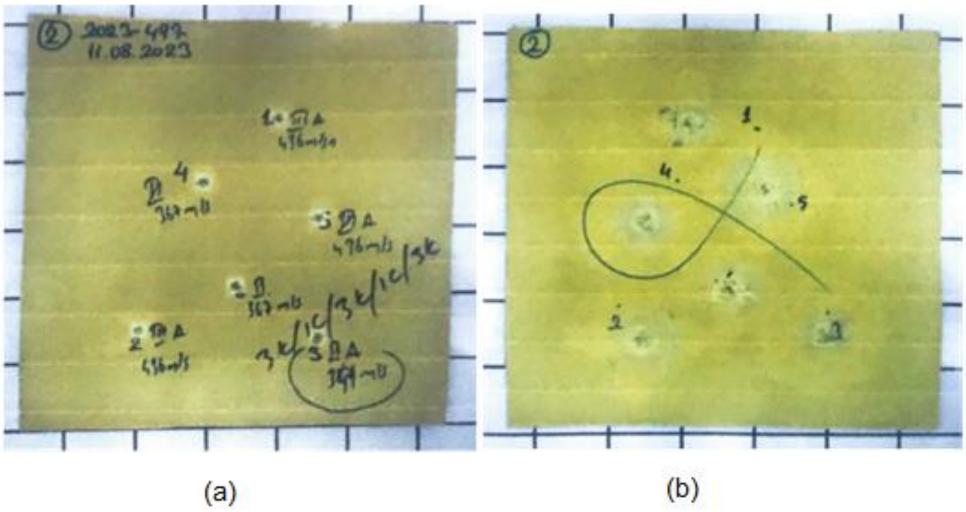

Figure 5. Shotted by projectiles 3K/1G/3K/1G/1G/3K plate a) Front side b) Back side

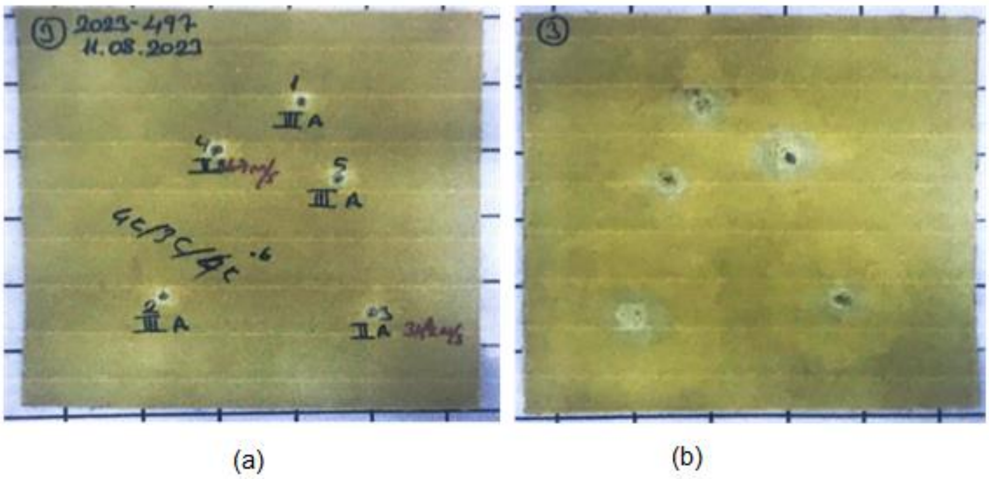

Figure 6. Shotted by projectiles 4K/3G/4K plate a) Front side b) Back side

TABLE II. BALLISTIC TEST RESULTS OF HYBRID COMPOSITES

Plate	Level of Velocity	Failure	Deflection
Kevlar/epoxy	IIIA	Perforated	-
	II	Perforated	-
	IIA	Not Perforated	12.11 mm
3K/1G/3K/1G/3K	IIIA	Perforated	-
	II	Perforated	-
	IIA	Perforated	-
4K/3G/4K	IIIA	Perforated	-
	II	Perforated	-
	IIA	Perforated	-

3.2. Failure Modes

Apart from the level IIA test on the Kevlar/epoxy plate, perforation occurred in the plates as a result of tests performed at other velocities and levels. During ballistic impact, the energy transfer from the fired projectile to the target depends on the density, tensile strength, hardness, toughness, fracture strength, strain-strength relationship, and fracture toughness of Kevlar/epoxy [29]. In this study, it was determined that fiber-matrix failure, matrix cracking, and fiber breakages occurred during ballistic impact as a result of shots at all three levels. At the same time, delamination occurred because of the shear stress occurring between the layers [29].

In this study, ballistic resistance was observed by examining the failure areas on the back side of the target plates according to the shooting levels. After the shots at IIIA and IIA level, it was observed that the affected failure area (matrix cracking) of the hybrid composite plate with 3K/1G/3K/3K/1G/3K sequence was less than the affected area of the other hybrid plate. However, it was observed that the fiber fractures in the hybrid plate with 3K/1G/3K/1G/3K sequence were more noticeable than the fiber fractures in the other hybrid plate. In the Kevlar/epoxy plate, it was observed that the failure areas (fiber fracture + matrix cracks) affected after the shots were more. Therefore, this is thought to be due to the location and thickness of the glass/epoxy layers in the hybrid sequence. It is observed that there are matrix cracks around the point where the projectile hit when examining the Kevlar/epoxy plate, which was not penetrated at IIA level (Figure 7b). In all three plates, due to post-impact stress wave propagation [17], it was found that the failure areas affected on the back surface were more than the failure areas on the front surface. Some results of the plates are given as examples in Figures 7-9.

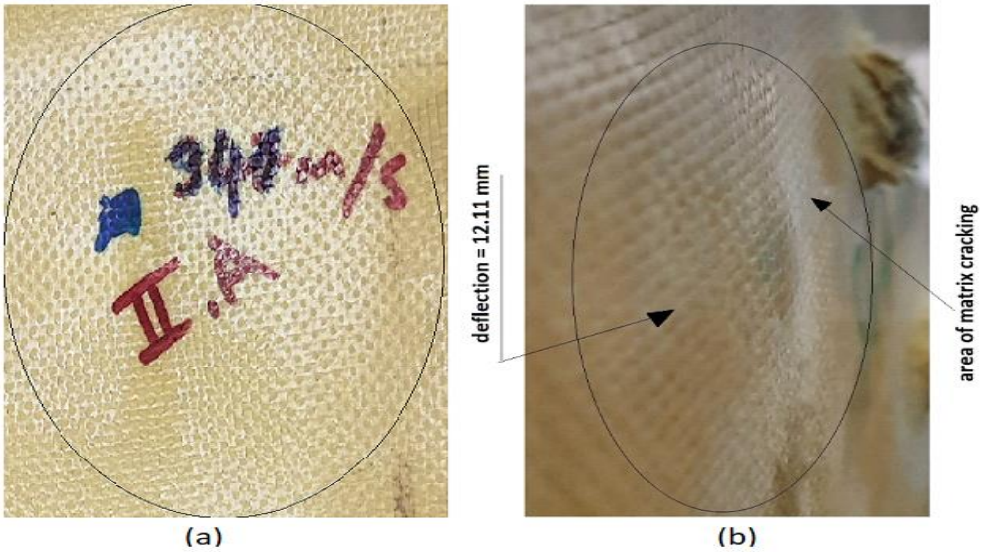

Figure 7. IIA level failure image of Kevlar/epoxy plate a) Front side b) Back side

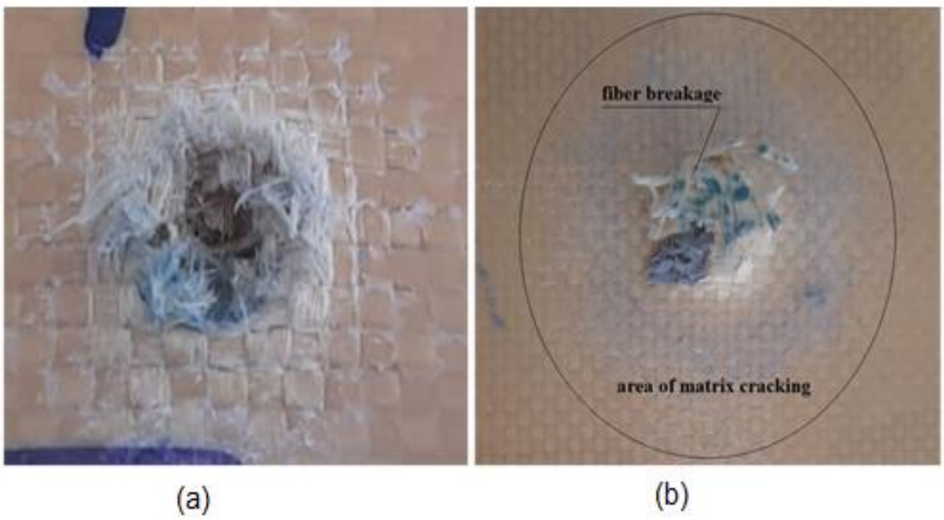

Figure 8. IIIA level failure image of 4K/3G/4K sequence plate a) Front side b) Back side

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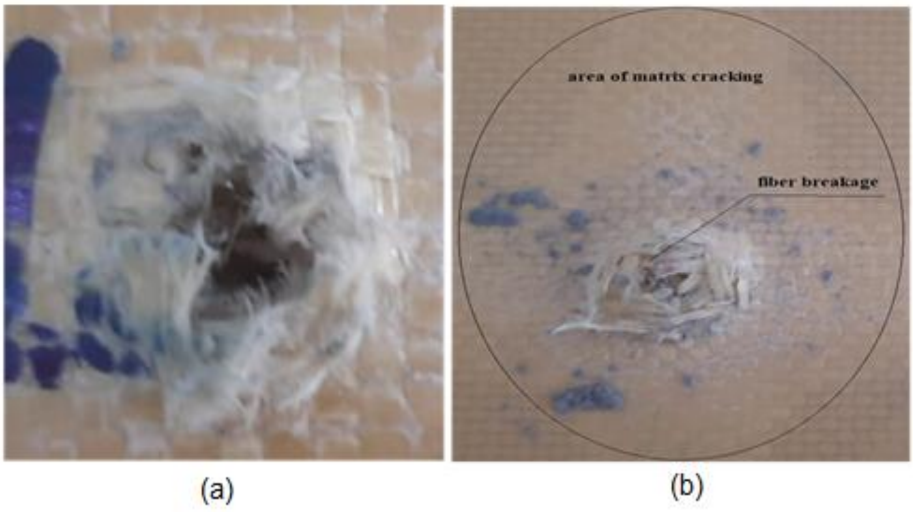

Figure 9. IIIA level failure image of 3K/1G/3K/1G/3K sequence plate a) Front face b) Back face

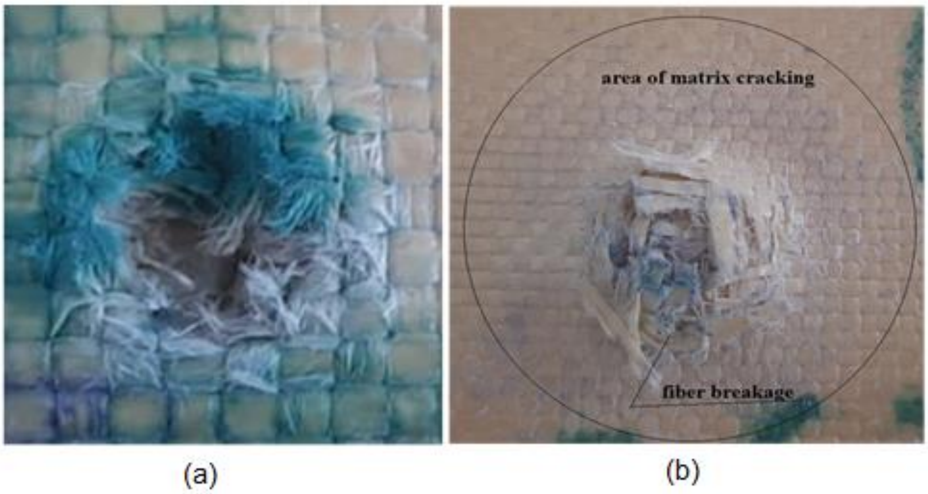

Figure 10. IIIA level failure image of Kevlar/epoxy plate a) front side b) back side

4. CONCLUSION

In this study, 11-layer composite plates were produced, in which Kevlar layers were placed in the lower and upper layers and glass fiber reinforced layers were placed in the intermediate layers. All production was carried out using the hand lay-up method. Ballistic tests were carried out on the produced Kevlar/epoxy, 3K/1G/3K/1G/3K, and 4K/3G/4K hybrid composite plates. Tests were carried out at three different levels with FMJ RN 9x19 mm-diameter projectiles on all three plates. After the test, the ballistic behavior of the plates was determined. The results obtained in the study are briefly stated below:

- The Kevlar/epoxy composite plates were not perforated in the shot made at the IIA level.
- Perforation occurred on all three plates in the shots made at levels IIIA and II.
- Matrix cracks and fiber breakages occurred in all perforated plates.

This work can be improved by changing the number of Glass and Kevlar layers used, their arrangement, and the types of fabric used. We believe these findings will further research in this area.

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