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Suggesting a New Model of Armors Utilizing Composite Plates Enhanced with Nanographene

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Abstract

The current focus in armor development is on the creation of lightweight, thin, and cost-effective solutions. This study explores innovative techniques by incorporating nanomaterials into composite plates, combined with fiber pre-stressing methods during the polymer matrix curing process. Woven Kevlar fibers experienced a pre-stress of 2 MPa in two dimensions while being cured with an epoxy resin containing varying ratios of Nanographene (0.5, 1, and 2 wt.%). Results demonstrated that the optimal combination for enhanced mechanical properties, particularly impact strength, occurred with a 2 wt.% nanographene ratio and 2 MPa fiber pre-stressing. However, exceeding a 2 wt.% nanographene ratio led to nanoparticle agglomeration within the resin, negating their positive effects. The proposed armor model successfully passed ballistic testing and comprises four layers of composite plates, each layer consisting of epoxy resin with 2 wt.% nanographene, Kevlar fibers pre-stressed at 2 MPa, and a 3mm thickness. These layers are interspersed with additional 1mm layers of Kevlar fiber. This innovative approach offers a promising advancement in armor design, achieving a balance between low density, reduced thickness, and cost-effectiveness.

1. Introduction

Composite materials with a high strength/density ratio, such as polymers reinforced with glass, aramid, and carbon fibers, have increased usage in applications that require high-performance materials and offer potential improvements in production methods in unique fields such as spacecraft, aviation, sports equipment, and defense applications [1, 2]. The properties of durability, strength, and shock resistance make aramid fibers (Kevlar fibers) suitable for reinforcing composite plates in applications that demand ballistic resistance, such as armor production, shield plates, and other anti-ballistic applications. Researchers have explored techniques to enhance the impact strength of composites and reduce the risk of failure under high-velocity impact loads. These techniques include surface treatments of Kevlar fibers before the resin molding process or other methods [3, 4].

A study by A. Ramadhan et al. [5] investigated the response of composite plates to high-speed impacts using a nitrogen gas gun. The high-velocity impact test was simulated using the ANSYS Autodyne V.12 code, showing good convergence between practical and numerical values (with a maximum divergence of 3.6%). Gonçalves da Silva et al. [6] utilized the ANSYS Autodyn code to simulate an experimental test with a STANG-2920 projectile on plastic laminates reinforced with Kevlar fibers. The results demonstrated good agreement between experimental and numerical findings. Santos da Luz et al. [7] tested multi-layered Armor, consisting of a ceramic front layer followed by Kevlar fiber, against high-velocity bullets. They also replaced Kevlar fiber with jute fiber of the same size and epoxy resin, showing the superior performance of jute fibers in energy dissipation compared to Kevlar fiber at a lower cost. Iftekhar et al. [8] produced composite plates and studied their behaviour under ballistic effects through practical and numerical analysis. The results showed that composite plates composed of SiC+UPE/EPX+Al-alloy and SiC+KEV/EPX+Al-alloy effectively resisted 9 mm bullets, penetrating multiple layers of Armor without complete penetration. There was good agreement between experimental and numerical results. Santos da Luz et al. [9] developed new types of armor materials using pineapple leaf fibers, aiming to achieve sustainability and cost reduction compared to traditional fibers like aramid. These results met the standards of the National Institute of Justice (NIJ) for ballistic protection against firearms. Mora et al. [10] prepared armor composite plates using polybenzoxazine/urethane (poly (BA-a/PU)), multi-wall carbon nanotubes, and aramid fibers as reinforcing elements, demonstrating their high ability to withstand penetration by a 7.62 mm projectile traveling at a velocity of 847 m/s. Iftekhar et al. [11] conducted a numerical and experimental study on hybrid composite plate armor. The numerical model was built using ANSYS Workbench of AUTODYN 3D, while the experimental hybrid composite consisted of ceramic/woven reinforcement with multiple layers of epoxy, Kevlar fiber, and silicon carbide (SiC). The results indicated that the ceramic layer absorbed the most energy (approximately 77% of the kinetic energy). Jesuarockiam et al. [12] reviewed advanced graphene-based composite materials used in armor applications, highlighting the enhancement of impact resistance by incorporating graphene due to its ability to absorb kinetic energy from bullets. Zunior et al. [13] recommended combining high-strength 3D woven aramid fiber fabric with vinyl ester resin to produce panels incorporating graphene nanoplatelets (0.1, 0.2, and 0.3 wt.%). The impact, tensile, and flexure strength were evaluated along with dynamic-mechanical analysis by DMA and Hopkinson split bar tests. The findings demonstrated superior performance for the composite containing 0.1% graphene nanoplatelets. F. Bragaa et al. [14] investigated the effect of the thickness of Kevlar fabric layers on their ability to prevent penetration by a 7.62 mm bullet, revealing that 96 layers with a thickness of 50 mm provided adequate protection against penetration.

The present work suggests a new model for solid Armor made from epoxy, Kevlar fiber, and different weight percentages of Nanographene platelets as (0.5,1, and 2 wt.%) to find a suitable value of graphene that produce a new model of Armor. The suggested new model is characterized by low density, small thickness, low cost, and high performance in protecting the human body from the harmful effects of bullets.

2. Methods and Materials

2.1. Materials

The composite plate for armor application contains:

A- Epoxy Resin: Epoxy resin from a commercial brand (Renksan-Renfloor HT 2000) is used as a base material. The epoxy resin was composite with a hardener in a ratio of 2:1, offering desirable properties such as low viscosity, transparent colour, and mechanical properties. Table (1) presents the epoxy properties.

Table (1): Epoxy Properties.

Property	Density [kg/m³]	Viscosity [Poise] at 35 ° C	Compressive Strength [MPa]	Fracture Toughness [MPa-m½]	Tensile Strength [MPa]	Bending Strength [MPa]	Modulus of elasticity [GPa]
Epoxy	1040	1.1	69	0.56	26	62	2.75

B- Kevlar fabric: The fabric of Kevlar produced by MB Company Fiberglass in England is woven in directions 0°, 90° at a woven thickness of 1mm.

Table (2): Kevlar fibers properties.

Type	Density [kg/m³]	Tensile strength [GPa]	Young's Modulus [GPa]	Ductility [%]	Melting Temp. [°C]
Kevlar	1390	4.4	121	3.65	490

C- Nanographene Platelets: The nanographene platelets used in this study were supplied by Skyspring Nanomaterials, a company based in the USA. These platelets have a Nano size with a thickness ranging from 6 to 8nm as and a purity of 99%. The properties of Nanographene are summarized in Table (3).

Table (3): Nanographene Properties.

Type	Density [kg/m³]	Tensile strength [GPa]	Young Modulus [GPa]	Specific Surface Area [m^2/g]	Melting Temp. [°C]
Graphene	2310	128	990	115-145	3550

2.2. Preparation of Mold

Figure (1) shows the Hands layout method employed to fabricate composite plates with dimensions of 200 × 200 × 3 mm. The plates were produced using a steel mold and an acrylic cover. To minimize the shearing effect on the fibers and achieve an isotropic composite plate, a pre-stress of 2 MPa was applied to the Kevlar fabric in two directions. This pre-stress was accomplished by applying dead loads. After the curing process (solidification of resin matrix with Kevlar fibers after adding the hardener), the plates are put under compression, further enhancing its strength against tensile and impact loads. The effect of fiber pre-stress is shown in Figure (2), which demonstrates that the pre-stress aligns the fibers in a straight state and imparts greater stiffness to the fiber due to compressive stress in the matrix after curing [15].

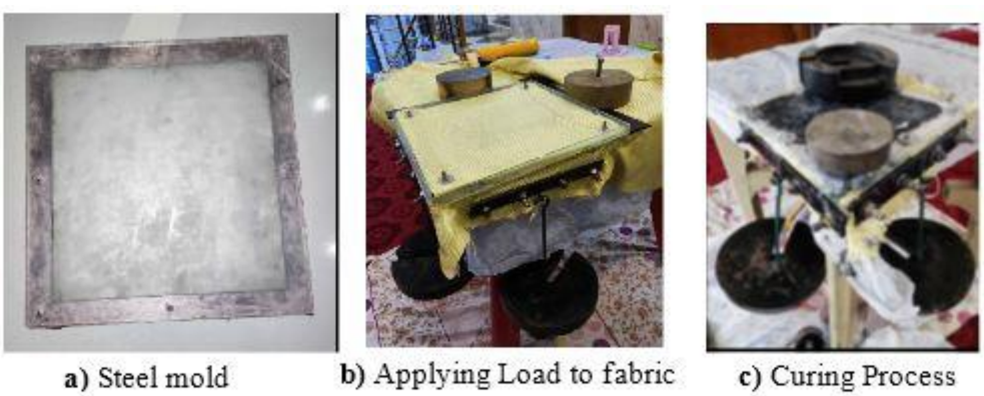


Figure (1): The process of hand layout of the plate of composite.

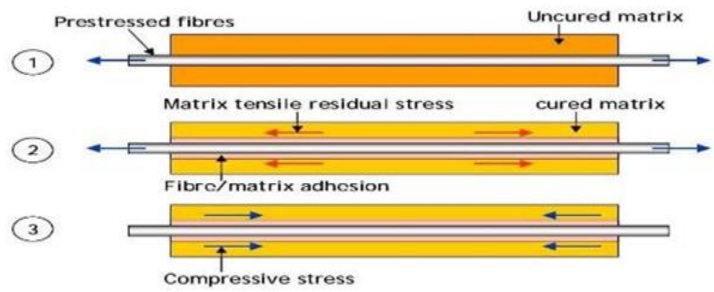
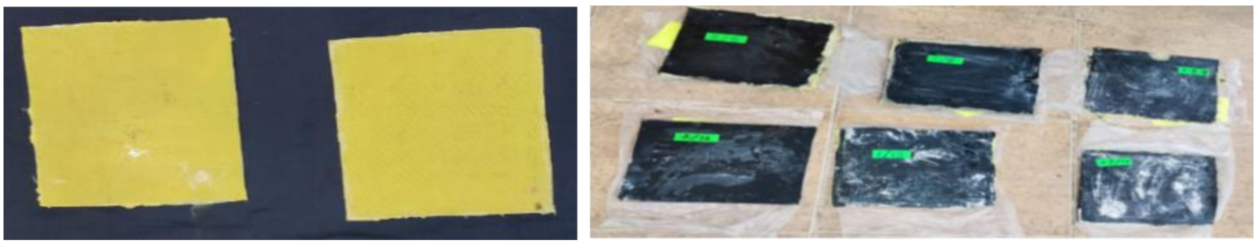


Figure (2): Effect of fiber pre-stressing [15].

Figure (3) shows types of composite plates that are produced by hand layout process without Nanographene and with different values of Nanographene.



(a) **(b)**

Figure (3): a) Plate of Composite without Nanographene, **b)** Plate of Composite with Nanographene.

3. Testing of Composite Samples

The composite material samples were tested according to a standard specification as follows:

3.1. Impact Testing

The samples for impact testing were prepared according to the ISO-180 standard [16], with dimensions (10 × 80 × 3 mm) as shown in Figure (4 a, b, & c), where the impact test samples with and without Nanographene are presented. The impact test was performed using the impact tester device shown in Figure (5) for composite materials in the labs of the Polymers Department at Babylon University

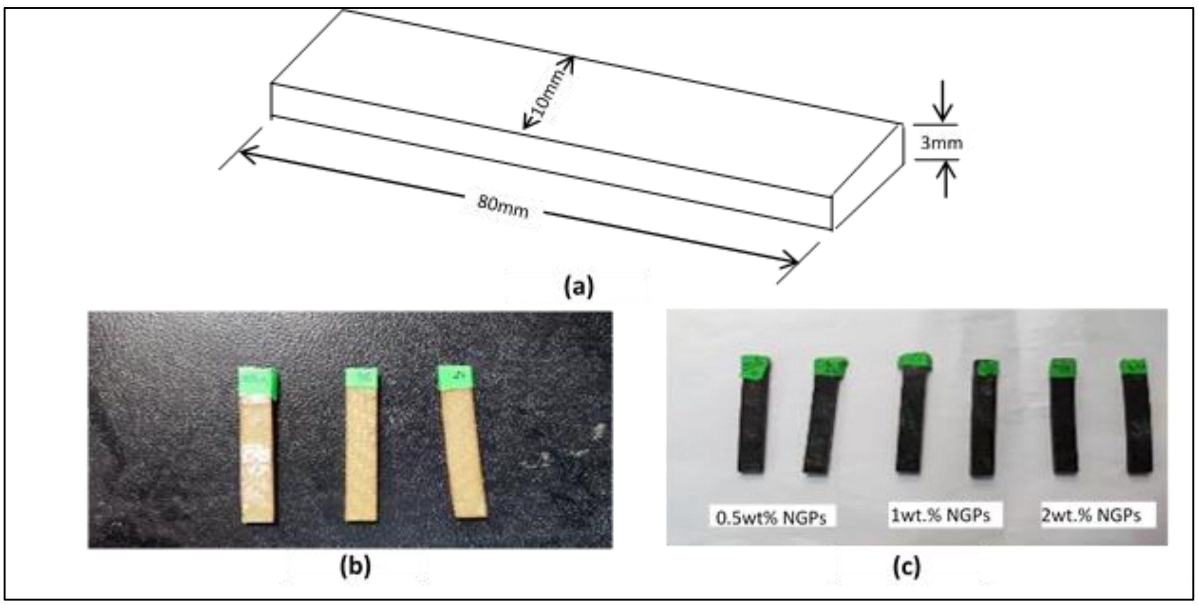


Figure (4): (a) Dimensions of impact test specimen according to ISO-180 standard [16], **(b)** Samples without Nanographene before the test, and **(c)** Samples with Nanographene before the test.

Figure **(5):** Impact tester.

3.2. The Bullet Test

A lightweight, high-performance ballistic material is utilized in armor technology, which involves combining one or more high-performance ballistic materials to counter various types of ballistic threats or meet specific requirements.One of the crucial tests conducted to assess the effectivness of armor material against projectile impacts is the Bullet test. This test is done according with the standard of the National Institute of Justice (NIJ) with the specification of MIL-662E, NIJ Standard 0108.01 [17].

To measure the velocity of the projectile, speed sensors are placed in front of the target. The bullet is fired from the depicted firearm type and passes through the speed sensor, which calculates its velocity just before impact with the target. The first speed sensor is located 2 meters away from the gun, followed by another 2-meter distance to reach the second sensor. The target is positioned 2 meters beyond the second sensor. Therefore, the total distance between the gun and the target is 6 meters. The bullet used in the test has a mass of 8 grams, a semicircular head, and a diameter of 9mm. Its velocity ranges between 350 and 400 m/s. The objective of this test is to assess the effectiveness of the composite plates, used as Armor, in protecting against bullets and preventing penetration.

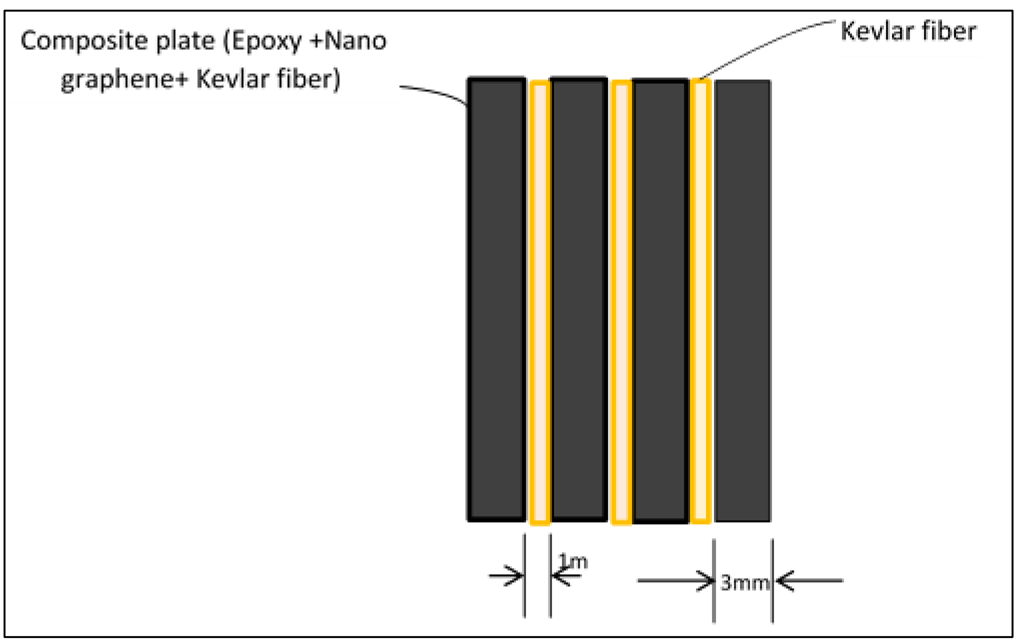


Figure (6): Layers of Armor.

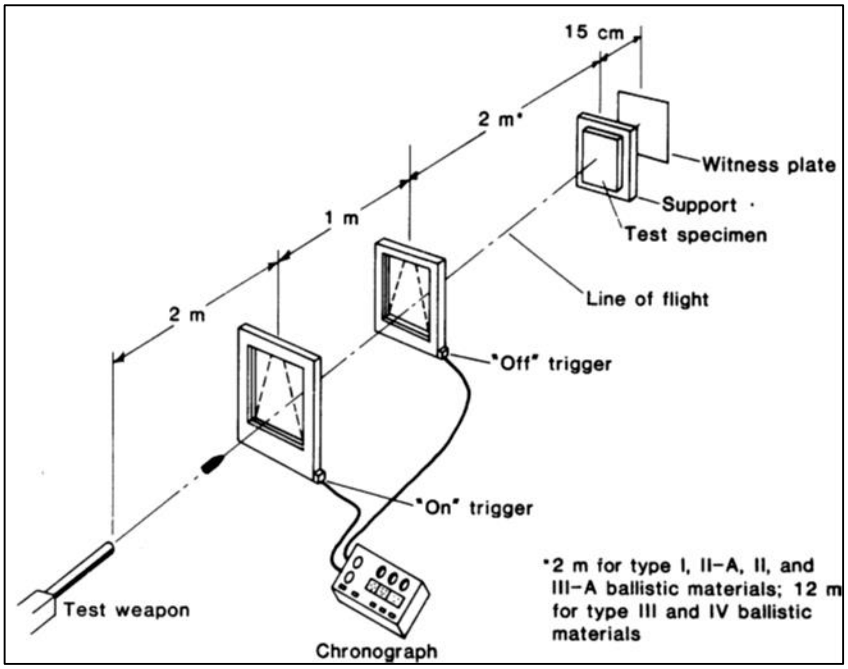


Figure (7): Bullet test system [17].

4. The Results and Discussion

4.1. Impact Test Results

Figure (8) shows the impact strength of the tested sample with fibers pre-stressed value of 2 MPa at different ratios of Nanographene. These results showed an increase in the impact strength for composite samples with an increase in the nanographene platelet ratio. The impact strength was 73kN/m for 2 wt.% nanographene sample with fiber pre-stressing of 2 MPa. The impact strength value for the samples without fiber pre-stress and no nanographene is 37.5kN/m. Figure (9) shows the ratio of improvement for impact resistance of composite plate that is reaching 92% for the 2 MPa fiber pre-stressed samples with 2% Nanographene. The effect of the presence of Nanographene on improving impact resistance is attributed to the high impact resistance property of Nanographene platelets and their ability to absorb the shock load, as well as to the effects of fibers pre-stressing.

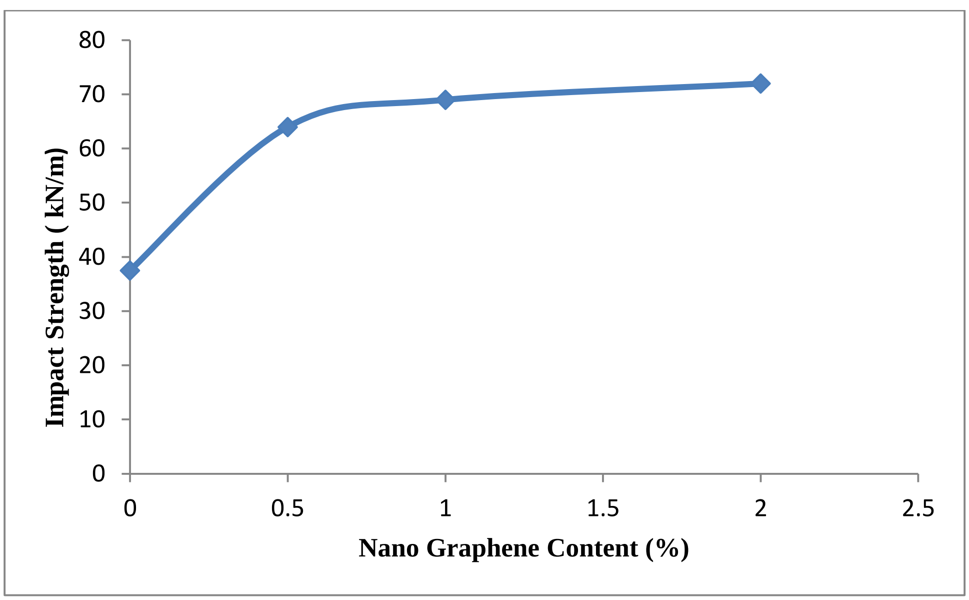


Figure (8): The impact strength of tested sample.

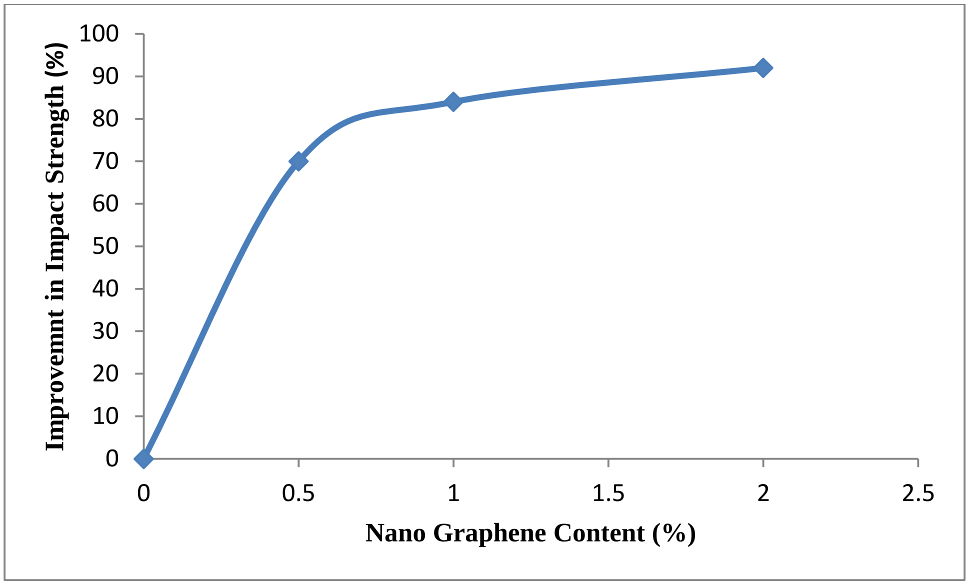


Figure (9): The improvement in Impact Strength.

4.2. Bullet Test Results

Table (4) shows the bullet test results for samples made of four layers of composite plates (Kevlar fibers with epoxy and nanographene platelets) with additional Kevlar layers. The results of testing with a 9 mm bullet of weight (8.1g) at high velocity (360–400 m/s) showed that the samples that were not subject to fiber pre-stressing and did not contain Nanographene would be easily penetrated, fractured, and fragmented, as shown in Figure (10). The samples that are subjected to pre-stress (2 MPa) without Nanographene are shown in Figure (11); samples with fiber pre-stress (2 MPa) and different ratios of Nanographene (0.5, 1, and 2 wt.%) also failed with varying values of permeation of the bullets through the clay target that can be seen in Figures (12, 13, & 14). Only the sample of 2 MPa pre-stress with 2wt.% Nanographene that succeeds in the test will be stopped at the 3rd layer (thickness 12mm) of Armor and won't pass through it, despite its high speed (395m/s) and high kinetic energy, as shown in Figure (14). These results can explain the fibers pre-stressing effects and the existence of Nanographene in enhancing the ability of Armor from composite materials to reduce the harmful effects of projectiles on the body due to the high impact properties of Nanographene, as well as the influence of pre-stressing for fibers in increasing the material's strength and stiffness. The suggested new model is characterized by low density, small thickness, and low cost compared with models of armors in [11, 12, 13, 14].

Table (4): Bullet Test Results.

No.	**Sample**	**Bullet Velocity(m/s) Mass of Bullet = (8.1gr)**	**Kinetic Energy (K.E = $\frac{1}{2}m * v^2$) J**	**Bullet Penetration**	**Result for Test**
1	Without pre-stress Without Nano graphene	362	1061	More than 25 mm	Failure Fig. (10)
2	With pre-stress 2MPa Without Nano graphene	365	1079	More than 25 mm	Failure Fig. (11)
3	With pre-stress 2MPa With 0.5wt.% Nano graphene	367	1090	More than 22 mm	Failure Fig. (12)
4	With pre-stress 2MPa With 1wt.% Nano graphene	367	1090	More than 20 mm	Failure Fig. (13)
5	With pre-stress 2MPa With 2wt.% Nano graphene	395	1263	12 mm	Succeed Fig. (14)

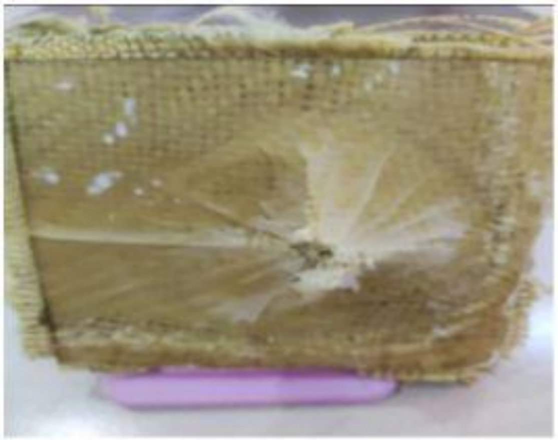


Figure (10): Tested sample of Bullet Test without pre-stressing fibers and without Nanographene.

Figure (11): Tested sample of Bullet Test with pre-stressing fibers of 2MPa without Nanographene.

Figure (12): Tested sample of Bullet Test with pre-stressing fibers of 2MPa and 0.5wt.% Nanographene.

Figure (13): Tested samples of Bullet Test with 2MPa pre-stressing fiber and 1wt.% Nanographene.

Figure (14): Tested sample of Bullet test with 2MPa pre-stressing fiber and 2wt.% Nanographene.

5. Conclusions

The proposed model of Armor suggests the use of multi-layered composite plates composed of epoxy, Kevlar fiber (pre-stressed at 2 MPa), and 2 wt.% nanographene platelets (NGPs). This model offers several advantages over traditional Armor types, including low density, cost-effectiveness, reduced thickness, and superior performance. The multi-layered structure incorporates layers of Kevlar between the composite plates. This design also makes it possible for the Armor to successfully absorb the bullet penetration beyond a distance of 12mm preventing the bullets from penetrating through the full Armor thickness of 15mm. The impact strength of the composite plates is significantly enhanced by the inclusion of 2 wt.% NGPs and the application of 2 MPa fiber pre-stress. The incorporation of NGPs contributes to a remarkable 92% increase in impact strength. NGPs have unique characteristics, especially in the containment of energy from high-velocity bullets and absorption of shock. Additionally, the fiber pre-stress guarantees that the cured composite plate will be compressed thus increase the stiffness of the Armor and avoiding fragmentation in the case of bullets penetration. This feature assists in reducing the negative impact as a result of bullets. The Armor module for multi-layered composite plates with the inclusion of NGPs and fiber pre-stress is more beneficial in aspects such as impact strength, energy dissipation, and bullet-proof characteristics. Furthermore, it comes with assets like, low density, lower cost and reduced thickness as compared to other Armor types.

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Conflict of Interest

The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

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