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Role of pre-stressing on anti-penetration properties for Kevlar/Epoxy composite plates

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ABSTRACT

Bulletproof vest capability improvement is considered an important issue, especially for vests made from composite materials. Composite materials consisting of Kevlar 29/Epoxy at different volume fractions of 30, 40, and 60% were made to produce the test samples used in this work. These samples consisted of two plates; the plates were gathered within a frame, making a gap of 10 mm between them. Two sets of test samples were used. The first set consisted of two plates in their normal state (set A). In contrast, the second set (set B) was exposed to bending load generating pre-bending stress in the plates before the ballistic test. A 9 mm handgun was used to shoot the bullets. Chronographs were used to detect the projectiles' speed before and after hitting the samples. The samples were labeled according to the fiber volume fraction (A_{30} *,* A_{40} *,* A_{60} *,* B_{30} *,* B_{40} *, and* B_{60}*). Each sample was exposed to three successive shots. The results showed that B30 decreases the final velocity of the projectile by 45% compared to set* A_{30} *when the plates were loaded with 120 MPa stress. Increasing the stress value in sample B30 from 50 MPa to 120 MPa causes an increase in the sample's absorbed energy value of about 47%, 22%, and 1% for first, second, and third shots, respectively. A similar pattern of results has been obtained for other volume fractions.*

Keywords: composite materials, ballistic test, bulletproof vests, Kevlar, Epoxy

1. INTRODUCTION

Bulletproof vests were developed to safeguard the wearer's vital organs from injury caused by firearm projectiles. Armor vests have evolved over 25 centuries from their earliest designs made of animal hides, linen, woven coconut palm fiber, and linked rings or wires of iron, steel, or brass [1]. Since the plastic revolution of the 1940s, vests have become limitedly available. Vests of that era were constructed of ballistic nylon and reinforced with steel plates, fiberglass, ceramic, boron, titanium, and the most effective ceramic-fiberglass composites. Kevlar, a liquid polymer that can be spun into aramid fiber and woven into cloth, was invented in 1965. Until the 1970s, ballistic nylon was the standard fabric for bulletproof vests. Nowadays, polyethylene fiber (used initially for sailcloths) is used to create a nonwoven material lighter and stronger than traditional Kevlar and is used in bulletproof vests [2]. Science advancements have facilitated the use of composite materials in the military industry. Composite materials containing various fibers, such as carbon

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fiber, boron fiber, fiberglass, and walnut fiber, have been used in the armor due to their lightweight, flexibility, and high resistance to penetration. Recently, bulletproof vests have been made from PARA-ARAMID fibers such as polyethylene, spectra, Twaron, and Kevlar due to their numerous advantages of being lightweight, flexible, durable, and having a high tensile strength [3]. Kevlar is a material composed of a series of carbon rings that have a strength five times that of steel due to the strong bonding between their atoms. As a result, it is used in bulletproof vests. Kevlar is one of the greatest inventions of people working on the distracting strength of trauma to the shot and smoothly absorbs the high kinetic energy, limiting the danger that reaches the body and saving the wearer's life. The disadvantages of Kevlar, such as its high cost, susceptibility to ultraviolet rays, and humidity, have compelled us to develop alternative materials that increase efficiency, resist sunlight, and are less expensive.

Numerous research disciplines have been conducted on the topic of bulletproof vest enhancement. Several of them examined the type of reinforcement materials used, such as industrial or natural materials, and their arrangement; others examined the effect of additives on the ballistic properties of vests, and a few others examined the effect of changes in the crystalline structure of vest materials.

Using a simple-dimensional model, D.P. Goncalves et al. [4] analyzed the projectile's impact with ceramic/metal armor. They examined the ceramic's internal structure and the effect of grain size on ballistic performance. They concluded that increasing the grain size of the ceramic will increased the efficiency of the armor. Other articles discussed ways to enhance the ballistic properties of composite materials by using additives [5–12]. The remainder of the research in the area of ballistic property enhancement is concerned with the structure of the composite material armor, such as the number of layers, the types of materials arranged within the layers, and the fiber direction and orientation numerically, experimentally, or both [13–22].

Kurji and Ameen [23] employed Kevlar 29/Epoxy plates having three different volume fractions of 30, 40, and 60%. Two composite plates were gathered by a frame, keeping a gap between them. Depending on the gap condition, three different types of samples were used. The first type included an open gap, the second featured a pressured gap, and the third featured a vacuumed gap. The pressure gauge indicated a value of 35 kPa. 9mm bullets were used to test the samples. It was concluded that when the sample is compressed to 35 KPa, 39 percent of the speed decrease is achieved from the 30% V_f. This number increased to 42% for the 40% V_f sample and around 46% for the 60% V_f sample.

The identical approach as Kurji and Ameen [23] was employed in this work, except that pre-stressed samples of Kevlar29/Epoxy composite plates were used in place of compressed and vacuumed samples.

2. MATERIALS AND METHOD

The experimental work consists of preparing the test samples by casting Kevlar29/Epoxy plates with 21 cm length, square-shaped. Figures 1 and 2 show the Kevlar mat and Epoxy container respectively and Table 1 presents the materials properties. The composite plates were fixed on the steel frame (shown in Figure 3) which is designed for this purpose; the frame combines two plates with 10mm in between. The way of fastening the plates to the frame generates elastic stress stored as potential energy in the plates (pre-stressing).

Ballistic test applied by using a 9 mm hand gun shooting the bullets toward the test samples three times on each sample recording the brojectile speed before and after penetration using velocity measurement device (chronograph) shown in Figure 4.

Figure 1. Kevlar29 mat

Figure 2. Epoxy

Table 1. The mechanical properties of the materials used in this work [19]

Materials	Density (Kg/m^3)	Young's Modulus (GPa)
Kevlar	**1180**	**36**
Epoxy	**1100**	**1.06**

Figure 3. The steel frame

Figure 4. Chronograph and the test sample in the steel frame

The bullet net mass was 8 gm, and the initial velocity was 350 m/s. Three different fiber volume fractions were used as the testing samples: 30, 40, and 60%. These volume fractions were suggested by Kurji and Ameen [23] and the results of this work are to be compared with their results. There were two sets of samples used, the first set is (A), where the samples are made up of two parallel adjacent symmetric composite plates fixed to the steel frame. The samples were labeled (A_{30}, A_{40}, and A_{60}) for volume fractions of 30%, 40%, and 60%, respectively. The second set is (B), where the samples are two parallel adjacent symmetrical composite plates fastened to a unique steel frame designed to produce a bending load on the plates when fastened and generate bending stress. Bending stress is regarded as pre-stress in plates. These samples were labeled (B_{30}, B_{40}, and B_{60}) for volume fractions of 30%, 40%, and 60%, respectively. A range of stress values was used to test the effect of this parameter on the absorbed energy from the projectile. Figure 5 depicts the pre-stressed sample.

Figure 5. Pre-stressed sample

The ballistic test was performed following the HOSDB Body Armor Standards [24]. Three shots were fired from 5-meter distance in quick succession on each sample. Each projectile's final velocity (after sample penetration) was measured. Figure 6 shows the testing action.

Figure 6. Testing action

3. RESULTS AND DISCUSSION

The average values of the final velocity for the samples of the set (A) are shown in Table 2. In set (A), there is no difference in the results of the three shots on each sample, i.e., the final speeds of the first, second, and third bullets were nearly similar. The test results on set (B) are shown in Table 3. The results of set (B) clarifies the effect of pre-stressing the plates on the ballistic properties of the samples, which is not similar to the set (A). For the first shot, the final velocity in the samples for set (B) decreases from 45 to 51% compared to set (A).

Table 2. The final velocity of the projectile (set A)

Sample	**Final bullet's Velocity (m/s)**		
	First shot	**Second shot**	**Third shot**
A_{30}	**261**	**263**	**266**
A_{40}	**249**	**250**	**252**
A_{60}	**225**	**226**	**226**

Table 3. The final velocity of the projectile (set B)

Sample	**Final bullet's Velocity (m/s)**		
	First shot	**Second shot**	**Third shot**
B_{30}	**150.8**	**218.5**	**262**
B_{40}	**131.4**	**205.5**	**251**
B_{60}	**109.5**	**192.4**	**227**

Figure 8 presents the effect of the pre-stress value of the sample on absorbed energy from three successive shots on sample B30. Figures 9 and 10 present the effect of pre-stress values in the samples (B_{40} & B_{60}).

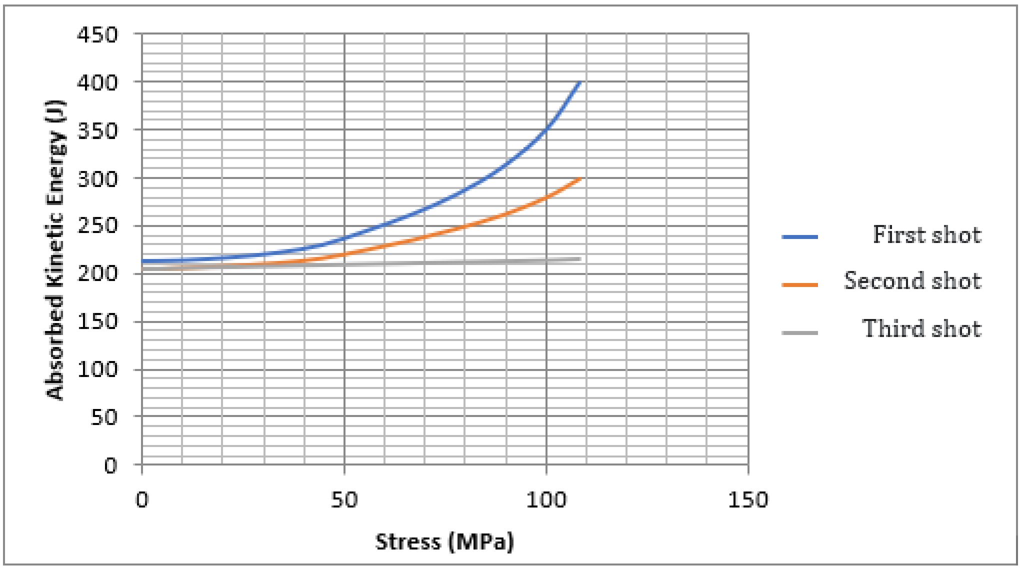

Figure 8. The effect of pre-stress value on the amount of absorbed energy in B$_{30}$

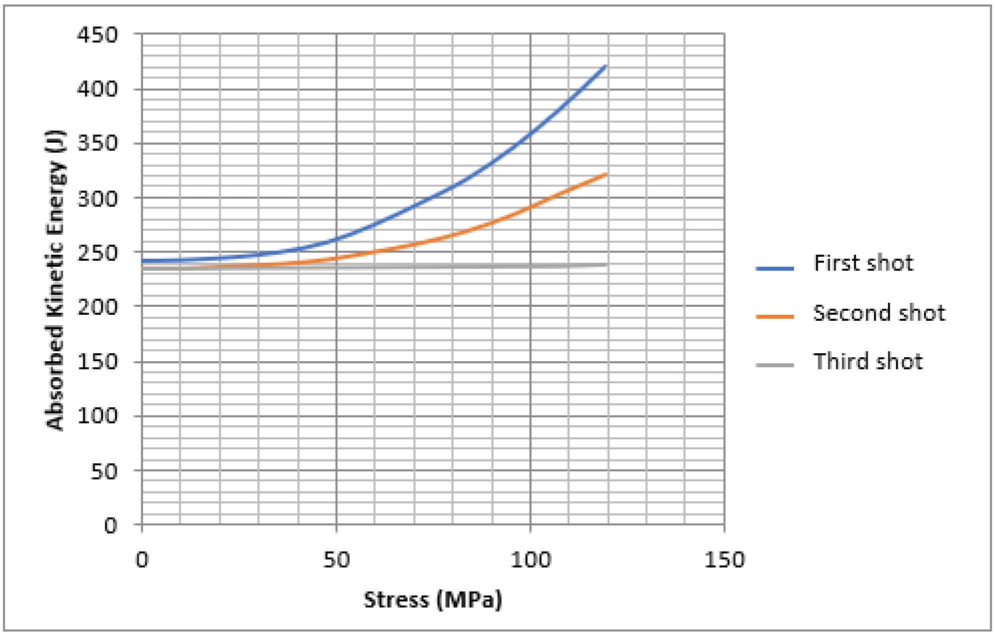

Figure 9. The effect of pre-stress value on the amount of absorbed energy in B$_{40}$

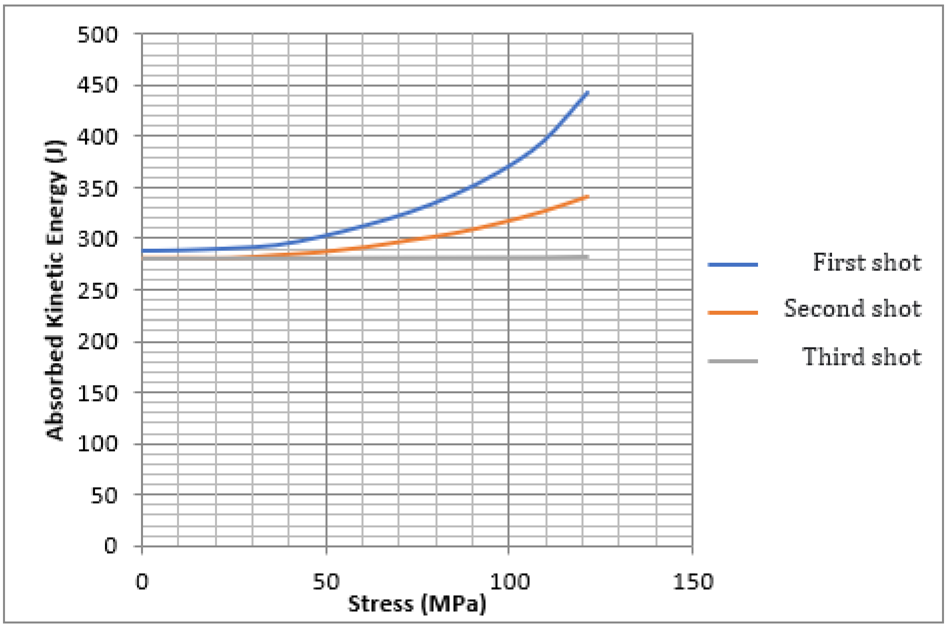

Figure 10. The effect of pre-stress value on the amount of absorbed energy in B_{60}

The pre-stress process generates latent (potential) energy in the sample and this energy (also known as elastic strain energy) begins to release when the sample is exposed to the projectile. The role of this energy as an additional resistance to the model against penetration and the process of releasing this energy may be repeated when exposed to the second shot because of the presence of a remaining part that has not yet been released (residual stress). The effect of this energy becomes more evident when the model is exposed to the third shot, where the model shows less resistance and the penetration occurs by absorbing relatively a small part of the projectile's kinetic energy.

The 120MPa pre-stressed sample B_{30} absorbed energy from the projectile by 84% more than sample $A_{30.}$ This percentage clears the advantage of this mechanism. Increasing the pre-stress value in the sample B_{30} from 50 MPa to 120 MPa increases the value of the absorbed energy by the sample B_{30} by about 47% for the first shot and 22% for the second shot, and 1% for the third shot. In sample B_{40}, the increase in absorbed energy was 62% within the range of (50-120 MPa), and for $B_{60,}$ the increase was 47%.

4. CONCLUSION

The conclusion is that the fiber volume fraction of the Kevlar/Epoxy plate has a noticeable effect on the value of the absorbed energy due to the impact test. In addition, when the Kevlar/Epoxy plates were pre-stressed, another amount of absorbed energy was gained, which improved the ballistic properties of FRP vests. The final results correspond in terms of approach to those of the previous research [23], but the difference is to get better performance in this work in terms of the model's resistance to penetration and endurance of more than one shot.

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