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Effects of Hybrid Arrangement and Location of the Stronger Layer on the Impact Resistance of Composite Plate Target

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Abstract

In this paper, response of hybrid woven fabric (E-Glass, Kevlar)/polyester composite laminates subjected to high velocity impact loading is discussed. E-Glass plain weaves with on layer of 3-end satin Kevlar were used to manufacture the laminate using toughened commercial polyester resin system with a curing infusion molding process. For fabrication of laminates, a 3-location of Kevlar lamia was used to reinforce the E-Glass, which are front, back and in the center of the composite. Laminates used in the study were made of 4, 6 and 10 layers of Glass in addition of one Kevlar layer.

Four laminates of each type were subjected to high velocity impact loading at different velocity to determine the ballistic limit using the developed impact tester with computerized chronograph not only measure the incident and resting velocity but also measure the approximate perforation time.

Results of the study indicate that the damage was well contained within the Kevlar lamina. However, ballistic limit was higher for the composite has the Kevlar layer in the back of the target, while it was lower for the case when the Kevlar layer in the front location. Ballistic limit increased with the increase in the thickness of the laminate. Further, satin weave laminates exhibited higher ballistic limits in most of the cases.

الخلاصـــــــة

في هذا البحث، تم مناقشة استجابة المواد المركبة الهجينية من الألياف الزجاجية والكفلر والمعرضة لأحمال صدمة بسرعة عالية. تم تصنيع عينات من طبقات نسيجية للألياف الزجاجية والكفلر والمشبعة ببيئة البولستر. تم التصنيع بإضافة طبقة واحد للكفلر وبمواقع مختلفة أمام، وسط وخلف الهدف، ولعدد طبقات ألياف زجاجية مختلفة (4، 6و 10طبقات).

تم فحص العينات في جهاز سرعة عالية صُنع لهذا الغرض وتم حساب الحدود البالستية لكل نوع من المواد المركبة المصنعة.

وجد إن طبقة الكفر تمتص اكبر كمية من الطاقة وان الحدود البالستية تكون أعلى عندما تكون طبقة الكفر في خلف الهدف واقل مايمكن عندما تكون طبقة الكفر أمام الهدف. إن الحد البالستي يزداد مع زيادة السمك وانه يزداد بالنسبة للنسيج الخشن والنسيج ذو القفزات خلال النسج.

1. Impact Testing

Since the high velocity impact energy is dissipated over a smaller region, an additional damage mechanism is presented at high velocities known as the shear plug. Due to the stresses created at the point of impact, the material around the perimeter of the projectile is sheared and pushed foreword causing a hole or "plug", slightly larger than the diameter of the projectile [1].

The fiber properties have the major effect for absorbing energy due to high velocity impact; the experimental results indicated that the rate of energy absorption of the panel increases drastically with the fiber modulus, but the very high modulus material tends to exhibit poor impact resistance due to its low working strain. Aramid fiber seems to exhibit the best combination of high modulus while steel maintaining reasonable high breaking strain [1]. While the absorbed energy was found to be a linear relation with the thickness of the composite laminate insuring that the weight efficiency of the fiber composite is greater than the metallic target like steel [2]. For this important effect of the fiber mechanical properties and the fabrication of hybrid composites from multi types of layered fibers was used [2]. The technique of interlaminate hybridization was found to enhance delamination under impact loading. Delamination was found to be an effective energy absorbing in hybrids. The impact energy absorption capability depends on which side face the impact direction. In general, the unsymmetric hybrids have better impact properties than their alternating sequence counterparts. In most cases, failure in these materials involved perforation, delamination and some tearing of the more brittle layers in conjunction with deflection of the tougher layers, provided the tougher side faced the impact direction. When the more rigid side was struck first, this stiff layer was perforated with a lesser degree of plastic deformation.

There were works on the hypervelocity impact reaching to 10km/s [3]. The perforation hole size increases as the projectile mass increases but was not proportional to the projectile size. The results show that the hole size decreases and the gauge pressure increases as projectile velocity increases.

The other important parameter affecting the high velocity impact is the projectile masses; Cantwell and Morton [4] studied this effect experimentally for low and high velocity impact. They found that varying the mass of the impinging projectile has a significant effect on the initiation and development of damage in composite structure.

When the kinetic energy of impactor is greater than ballistic range, the perforation takes place. Now the ballistic limit of velocity will be the additional parameters added to the parameters study in the high velocity impact. Ballistic velocity is the impact velocity that gives the ability for full penetration without remaining energy. The energy required achieving target perforation and ballistic limit remaining invariant of specimen geometry [5,6]. To avoid the perforation especially for the designing of personal body armor, aramid or spectra fiber composite was used, for this application the repeated impact was used to know the striking velocity [7]. The ballistic limit was increased with a real density [7,8] and the striking velocity decreased with the number of repeated impact, while the delamination zone was increases.

Different composite modes were used in the perforation studies which included ceramic spheres embedded by matrix [8], multi-layered metallic plates [9], and pure cloth specimen [10], and woven fiber composites [11]. The fracture cone occurred for the ceramic composites while cone radius varied according to the sphere radius and energy dissipation was through the breaking up of the ceramic spheres and failure of the backing composite by shearing, fiber cutting and extensive delamination [8].

Kasano and Abe [9] derived a new analytical model for production of the perforation characteristics of unbounded multi-layered composite plates based on the conservation of momentum. Their model was based on the plugging the target through the impact, the plugs will fly in velocities less than the resting velocity of the projectile but values depend on their masses (thickness of the plug's layer). The model gave good agreements with the tests of impact perforation of multilayered aluminum targets.

For the perforation of PE fabric, the two kinds of perforation modes, that is, cutting of yarns and pullout of yarns are observed depending on the textile structure [10]. While for woven fiber composite, the ballistic impact was increased with increasing the thickness of the laminate, further the satin wave laminates exhibited higher ballistic limit than the plain weave [11].

The additions of the higher modulus additives to the composite were studied. These additions were in the cases of cord Kevlar thread by stitching machine [11], tensioned Kevlar over wind [12] or added layers of super elastic nitnol [1,13]. Small amount of these additives gave large percentage of the absorbed energy and increased the impact resistance.

The study of the woven fabric reinforced composites gave the important issues through the few recent years because the high developments of the roving techniques and the good mechanical properties of the woven fiber in the addition to the easier fabrications for these types of composites and their structures [14]. The target may be a two-dimensional weave [10,18], and the three-dimensional weave [19,20]. The behavior for the weave was assumed to be isotropic [15,16], and in the other as an orthotropic [18]. The tests were showed that the woven composites must be assumed orthotropic to give the closer agreement to the tests [20]. It was found that the delamination area-taking place through the impact had a circular shape, while it has an elliptical shape in unidirectional fiber composite. Other parameters were found to be effective on the ballistic response in the addition of the area of delamination, which are the isotropy of the ballistic response; determine measuring the Feret Ratio or the Circular Shape Factor. Feret Ratio is the ratio of the minor to major Feret diameter, which is a basic measurement of region elongation. The Feret Ratio approaches one for an isotropic region or fine plain weave composite and goes to 0 for strongly elongated one (for unidirectional composite, which has, very high ratio of longitudinal to lateral modulus). The circular shape factor is a measurement of the circle based on the region area and perimeter. It is one for perfect circle and as the perimeter grows faster than the area for any other shape, it goes to 0 as the region get less circular [18].

The major damage modes of impacted 3-dimensional woven composite were found to be indentation, matrix failure and fiber breakage with axial and braider fiber yarn pullout, while the delamination does not occur [19,20].

There is a large amount of works dealing with the impact applications on composite structure, as an example; impacting a model section of aircraft structure [21,22], personal body armors [23-26], concrete and building structure [27], and the impact on the thorax [28]…etc.

The famous ballistic testing was the National Institute of Justice (NIJ) standards (MIL-STD-662E, NIJ Standard) [13] as shown in **Fig.(1)**.

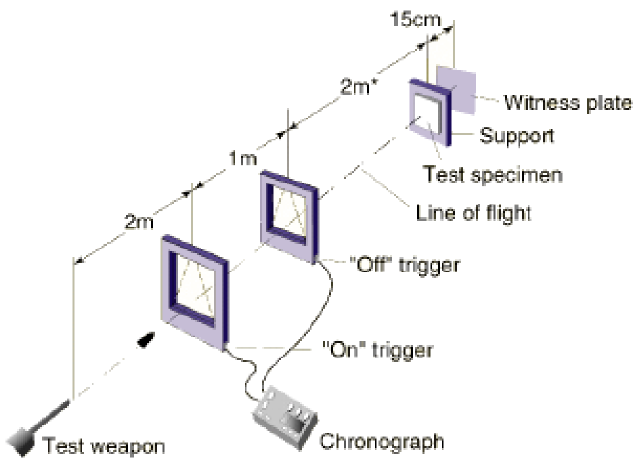


Figure (1) Ballistic testing {National Institute of Justice (NIJ) standards} [13]

These standards are widely used by government agencies and armor manufacturers for product acceptance testing. The energy absorption values for various hybrid configurations can be obtained using these standards. Due to the exploratory nature of the ballistic research, these test standards were chosen because they enable the user to gain an understanding of the aspects of how to improve the ballistic impact resistance of various systems without requiring a large amount of costly test samples. Also, these standards test for the maximum degree of damage a particular projectile can incur. Testing according to these standards does, however, have their limitations. Because they are based on a limited amount of data points, it is difficult to acquire results with a good statistical significance. Also, the standards lack a method for obtaining dynamic information that may help explain the impact event. Damage characterization is limited to energy absorption values and post impact inspection [13].

For tests with fully penetration (perforation), a second chronograph was used after the target to measure the resting velocity and evaluating the observed energy that was equal to the difference between the incidents and resting kinetic energies [29].

The new development through the building ballistic test of this work was the design and builds a computerized chronograph not only measure the after and before impact velocities but also to measure the approximate penetration time using simplest method, specially, that the techniques use to measure the penetration time were vary complex and expansive, in addition of that this techniques was covered with securities due to their military applications, and pointed to their with a fuzzy view through the searches. The ballistic testing rig used in this work is shown schematically in **Fig.(2)**.

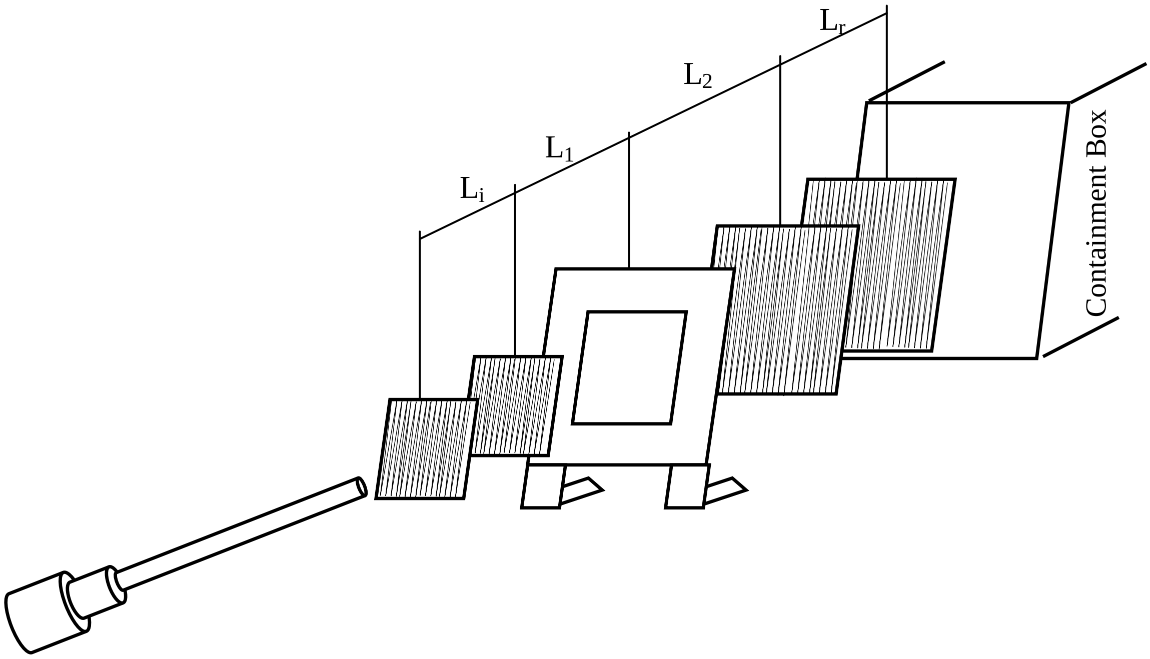


Figure (2) Schematic representation of the ballistic rig

Basically the rig consisted of 3*0.3m rigid frame constructed from 2*(1/8)” L beams to inshore the rigidity as shown in **Fig.(3)**. two rigid clamped were welded to the front of the frame on which a gun barrel (7.85 mm), nominal bore and 750mm length was mounted. The composite chronograph was fixed behind the gun and the target holder was welded in location between the second and the third screen of the chronograph.

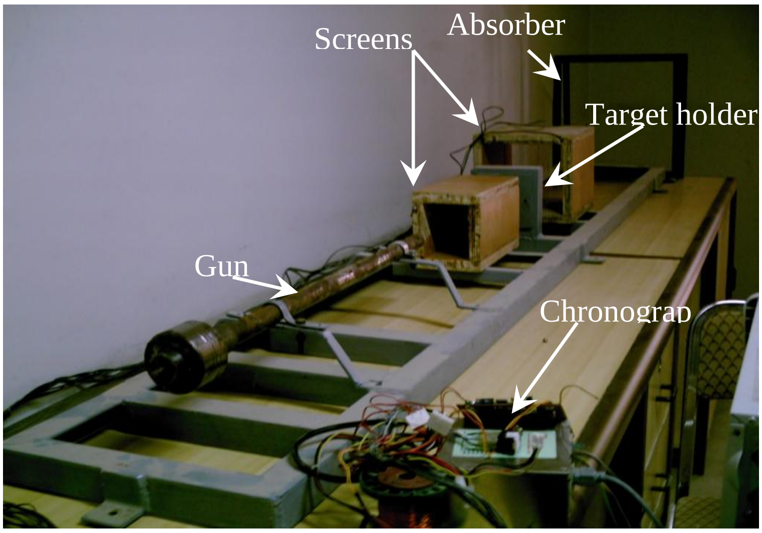


Figure (3) Photographic view of the presented impact rig

1-1 The Launching Gun

The Launching Gun used for tests was constructed and for this perpuse. Briefly, the basic design feature are, a smoothbore gun barrel of 7.85mm nominal internal diameter and 750mm length giving L/D ratio of approximate 95.5. The smooth bore enable the use of the gun to propel rigid projectile of any head shape. Moreover, the cartridge housing situated at the end of the gun was constructed so as to accommodate many kinds of powder gun cartridge. This capability enable accelerating the projectile to velocity rang from (60m/s to 900m/s), Finally, the materials and dimensions were chosen so as withstand internal pressure as high as 3000bars resulting from detonation of the powder gun charge.

(a) The gun barrel: A long cylinder made of special treated alloy steel with 27mm outer diameter and 7.85mm bore, one of the barrels end was threaded internally to be fastened to the envelope housing.

(b) The cartage envelope: a steel cylinder of 27mm outside diameter and 55mm length, the inside configuration was machined so as to envelop the two types of cartridge used in this work

(c) The envelope housing: A hollow steel structure with an internal thread at one end through which it is fastened to the gun barrel. The other end is specially designed to be securely joining to the breach while the inside bore holds the cartridge envelope.

(d) The breech: made to be joined to the envelope housing at one end and to carry the firing pin at the other.

(e) The firing pin: with conical head configuration suited for the capsule initiated cartridges.

The gun is mounted on two clamps and firmly secured by bolts and nuts. The lower parts of these clamps are welded to a steel structure that is fixed to the test rigs base.

1-2 Experimental Setup

The test specimens were rigidly clamped between two steel frames. Bolts at the corners and mid-sections of the steel frame were tightened to insure a rigid mount on all four edges of the test specimen. A 10 mm of material was clamped around the perimeter of the test specimens. These two steel frames were attached to a support structure. The test specimen was perpendicular to the line of flight of the bullet at the point of impact.

2. Results

The impact tests are done for the fabricated specimens as shown and discussed in this section. The first parameter studied for these tests is the effect of incident velocity on the resting velocity, penetration time and the absorbing energy. For this reason the 10-layers plain woven E-Glass reinforces polyester composite plate 4mm thickness and 100*100 mm squared. The clamping reduces the dimensions to 80*80mm. The results for these tests are shown in **Fig.(4)**. The results of the test shown in **Fig.(4)** are show that the resting velocity increased as the incident velocity increases because the resting energy is not absorbed and increases with the incident velocity. The penetration time measured decreased as the incident velocity increases due to high velocity with constant thickness giving the shortest time. The absorbed energy increases as the incident velocity increases due to increase in the deflection, delamination and fragmentation. These results are similar to the analytical results.

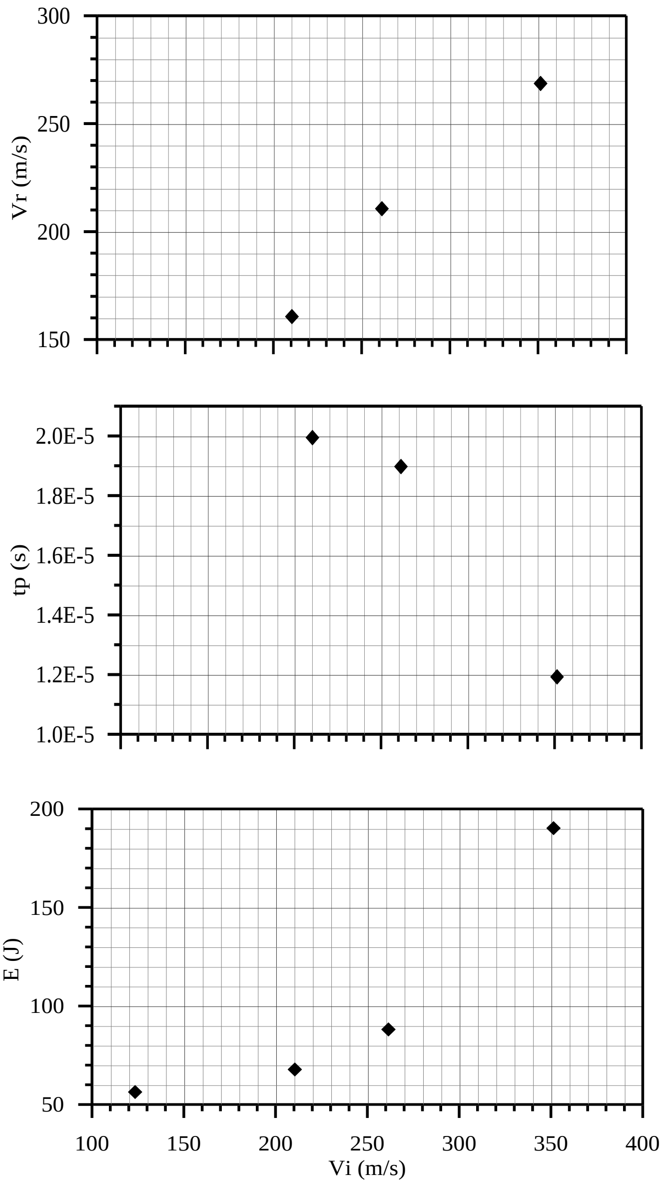


Figure (4) The impact experimental results of the 10-layers p1gp (h=3.9mm), impacted by 60o, 7.5 g steel projectile for various incident velocities

The projectiles cone angles used in the test was 60, 90, 180^o. The effect of these angles on the resting velocity, penetration time and absorbing energy for the 10 layer woven E-Glass fiber reinforced polyester are shown in **Fig.(5)** for Vi~350m/s.

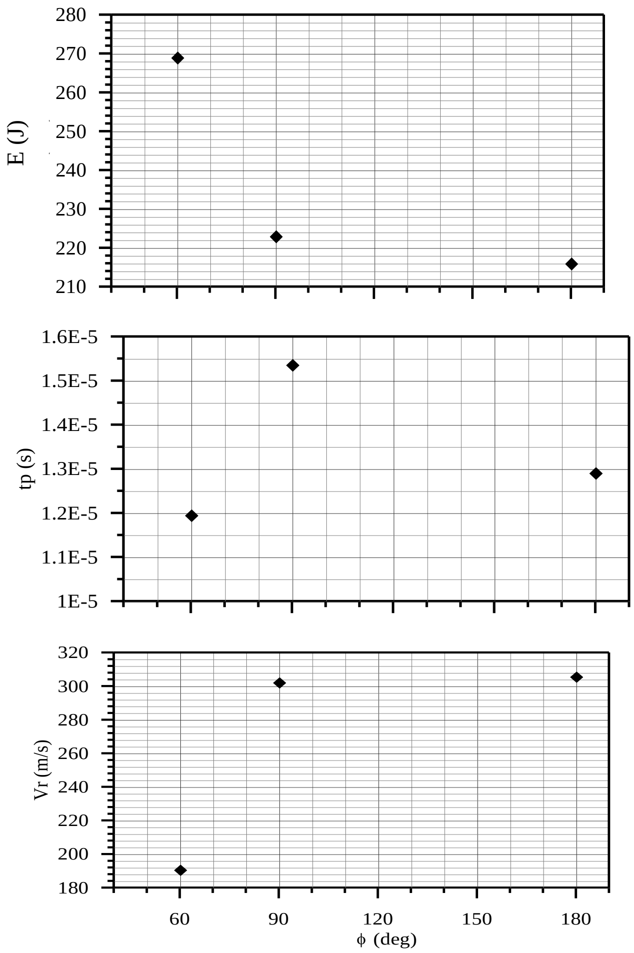
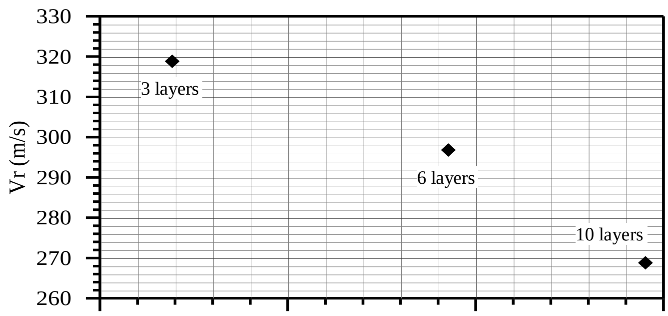


Figure (5) The Impact experimental results of the 10-layers p1gp (h=3.9mm), impacted by 7.5 g (Vi~353m/s) steel projectile with various nose angles

It has been shown that as the cone angle increases the remaining velocity decreases due to increasing the absorbed energy.

The resting velocity, penetration time and absorbing energy are plotted versus the thickness of the fabricated plate in **Fig.(6)**. The resting velocity was decreased as the thickness increases due to increasing the stiffness of the plate then the absorbing energy will be increases. For the same time the penetration time increased with thickness.



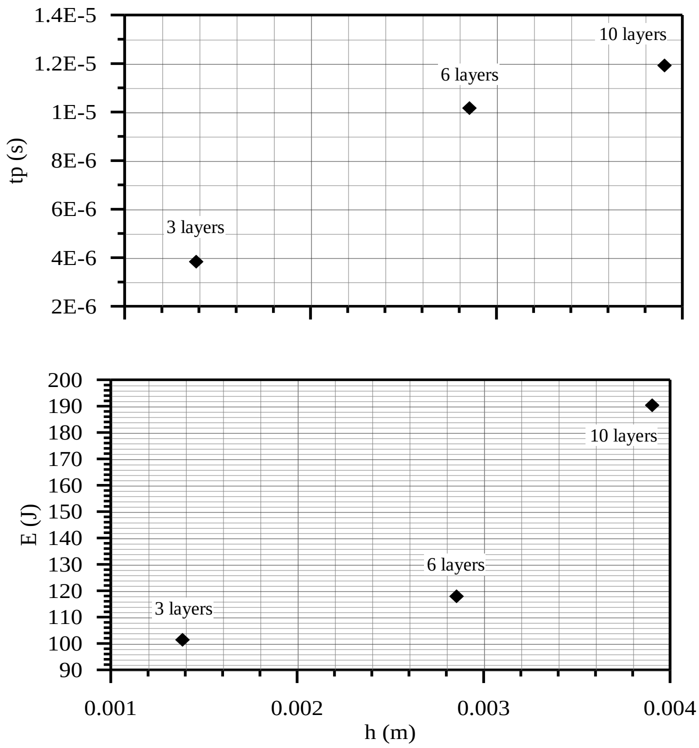


Figure (6) The Impact experimental results of p1gp, impacted by 7.5 g (Vi~353m/s) steel projectile with various thickness (No of layers)

Impact tests were done for glass-reinforced polyester for different weave styles. The results for these tests are shown in **Fig.(7)**. It shows that the 5-end satin (5esgp) and small mass per unit area plain weave (p2gp) composites have the largest amount of absorbing energy. This is because the higher number of layers for these weaves gives large amount of delamination area and then the delamination energy, in addition to that, the satin weave has higher modulus than the plain weave.

Although the random fibers composite has a high modulus compared to other glass fiber styles used in this work, it has a lower amount of absorbing energy and higher value of resting velocity. This is due to there style behavior of discontinuous fibers and lower amount of delamination area due to lower bonding force between the fibers and the matrix in this type of fiber style. The high mass per unit area plain weave (p1gp) composites has a higher resting velocity and minimum absorbing energy due to its small amount of delamination layers and the low modulus and the ultimate stress.

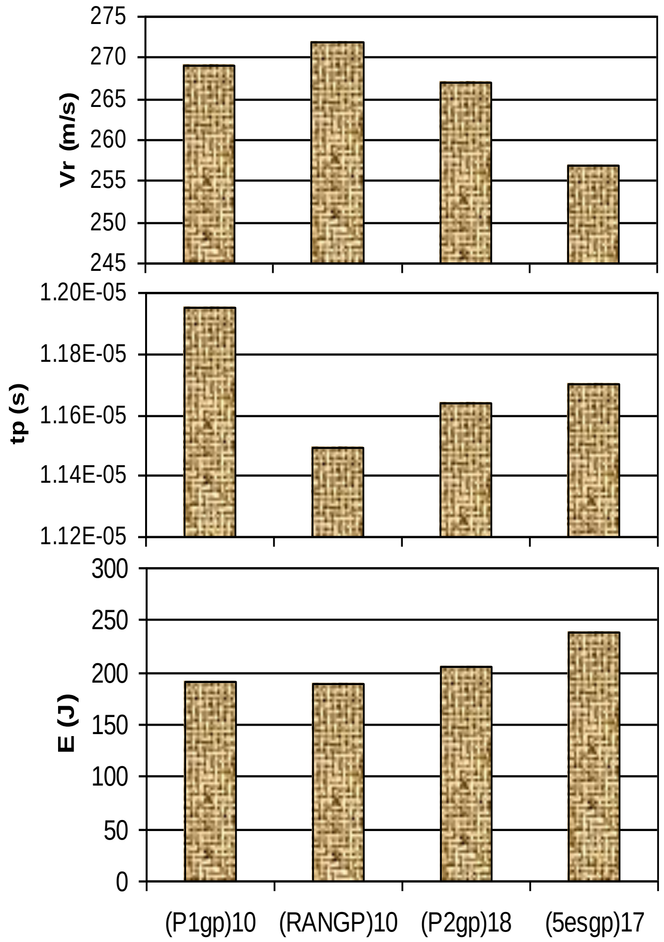


Figure (7) The Impact experimental results of the (h~4mm), impacted by 60o, 7.5 g and (Vi~350) projectile for various weave style of glass reinforced polyester

The comparisons of the fiber materials used for the impact are shown in **Fig.(8)**. It shows that the Kevlar fiber composite has the higher absorbing energy and penetration time and lower resting velocity. The Kevlar composite has the higher modulus and ultimate stresses and because of that it absorbs the higher amount of kinetic energy. The carbon fiber composite has been the second in the absorbing kinetic energy. In fact the resistively of high temperature for the carbon fibers composite give its benefit to use the carbon fiber composite for the application that need high temperature and impact as in the combustion chamber and the spacecraft nose but with thermal resistive matrix as ceramic. Again the satin weave has the better receptivity to impact and absorbing energy than the plain weave carbon fiber.

The E-glass fiber composite has the lower absorbing energy than the other type of fiber composite material. But because the economic price of the glass fibers and the easy availability of these type of fiber, hoping to improve the impact properties for glass fiber composites, which was investigated by adding layer of strong fiber composite, which is Kevlar fiber composite.

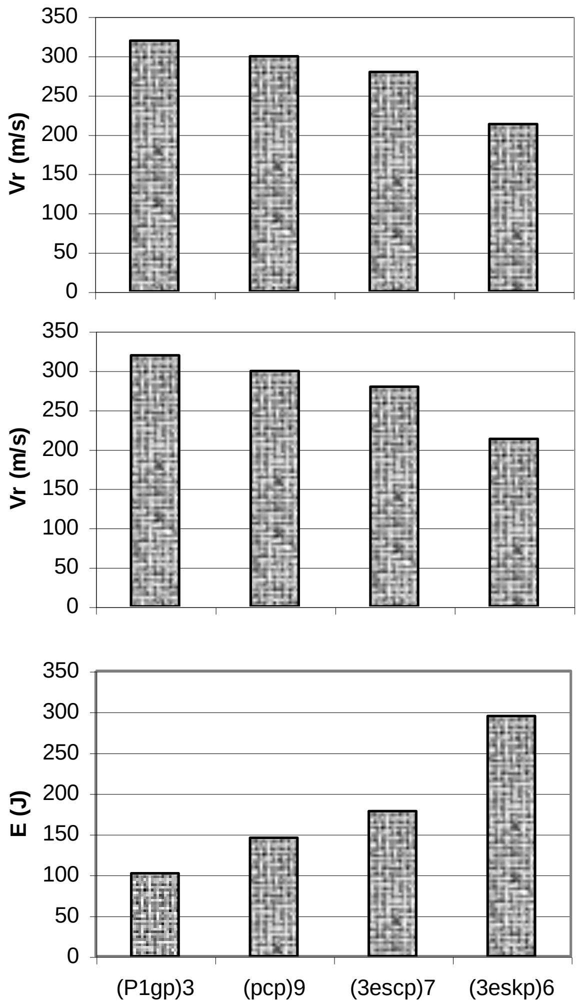


Figure (8) The Impact experimental results of the (h~1.4mm), impacted by 60o, 7.5 g and (Vi~350) projectile for various composite materials)

The addition Kevlar layer in 10 layers plain glass fiber composite was used for different location of the Kevlar fiber which are front, center and back relative to the impact surface. The resting velocity and approximate penetration time were measured and the absorbing energy was evaluated. These results are plotted against the incident velocity as in **Fig.(9)**. It shows that the composite has the higher absorbing energy and penetration time with lower resting velocity when the Kevlar layer was in the rear location. The reason of these results is the deformation shape for the rear of the plate due to impact, which is higher than that for the entrance of the plate impact.

The entrance of the impact projectile to the plate target forms a small hole equal in diameter to that of the projectile. The rear plane of the target has a large deformation and strain energy absorbing the kinetic energy. The location of the stiffened Kevlar layer in the rear of the plate absorbs more kinetic energy because of its high modulus will give it high stiffness.

The results in **Fig.(9)** shows that as the incident velocity increases the resting velocity and absorbing energy increases and the penetration time decreases. The rate of absorbing energy for the composite rear Kevlar layer has increased as the incident velocity increased due to increasing the deformation in the backside as the incident velocity increases.

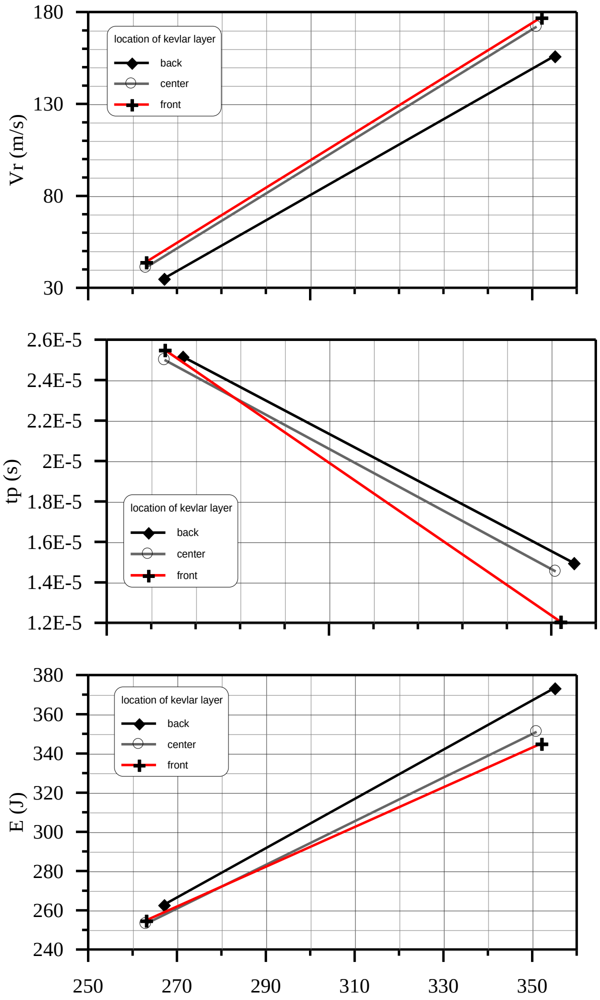


Figure (9) The Impact experimental results of verses incident velocity for hybrid composites of 10layers plain E-Glass with different location of Kevlar layer (fiber reinforced polyester composite)

The comparisons of the Kevlar location for same incident velocity are shown in **Fig.(10)**. The higher absorbing energy for the composite with rear Kevlar layer is shown clearly due to the same reasons discussed for **Fig.(9)**. Then the best location of the stiffened layer is shown to be in the backside relative to the impact direction.

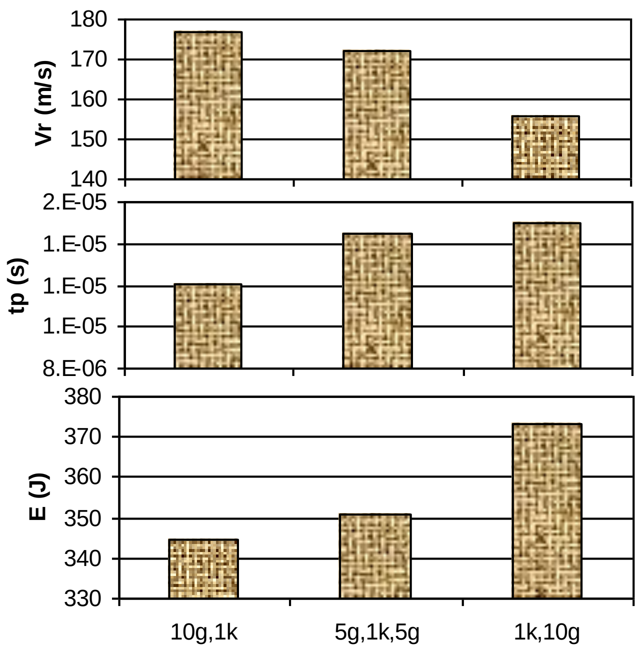


Figure (10) The Impact experimental results verses location of Kevlar layer for hybrid composites of 10layers plain E-Glass with different location of Kevlar layer (fiber reinforced polyester composite) for Vi~350m/s

3. Conclusions

The main conclusions of that can be drawn are:

1. The carbon fibers reinforced composites have a higher energy absorbed due to impact than that of the E-Glass reinforced composites and lower than that of the Kevlar reinforced composites theoretically and experimentally.
2. In general, as the incident velocity increases the energy absorbed due to impact increases.
3. The absorbing energy due to impact is found to be higher for composite materials that have the higher mechanical properties.
4. In hybrid composite materials, the best location for the stiffened layer to absorb the higher energy was the back location relative to the entrance of the impactor.

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