Impact Resistance of Armor Composite Made of Kevlar29 and Al$_2$O$_3$ Powder

Aidy Ali, L. H. Abbud, A. R. Abu Talib and F. Mustapha, Selangor, Malaysia

In this study, the impact behavior of a composite material made from Kevlar29 – Al$_2$O$_3$/Epoxy for hard body armor is considered. The present experimental method focused on the behavior of the ballistic limit, energy absorption and final velocity of flat cylindrical and conical projectiles. The results indicated that the maximum ballistic limit at impact velocity is 400 ±7 m/s for an 18 mm target thickness. Experimental results showed that the best ballistic performance was achieved with composite materials made of Kevlar29 – Al$_2$O$_3$/Epoxy. The results concerning the initial and final velocities showed good agreement compared with the Ipson and Recht equation.

Since the impact energy of high velocity objects 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 projectiles is sheared and pushed forward, causing a hole or “plug” slightly larger than the diameter of the projectile [1]. The projectile body armor under impact by using targets from Kevlar 29 and 129 were subjected to projectiles of 7.5 mm diameter hardened steel 1200 with a cylindrical – conical shape and a 9 mm hemispherical nose. Such projectile differences were selected under consideration of different failure mechanisms, including penetration and delamination, where the striking velocity of the projectile in the experiment was between 130 and 250 m/s [2]. Composite laminated plate Kevlar29 /Vinylester [3], the target in the ballistic experimental test, had the dimensions 40 x 40 cm and was firmly clamped on the edges. In addition, a projectile impact velocity at around 400 m/s has been used, depending slightly on the number of plies, and the shear force of the material, as well as other variables.

The experiment was also simulated by using finite difference, in order to study the ballistic impact on composite laminated plates reinforced with fiber. Investigations on a study on the ballistic impact behavior of two-dimensional woven fabric E-glass/epoxy composites were presented as a function of projectile and target parameters [4] and ballistic impact was generally a low-mass high velocity impact caused by a propelled source.

The analytical method presented was based on wave theory. Different damage and energy-absorbing mechanisms during ballistic impact have been identified.

The fiber properties have the major effect on the absorbing energy, due to high velocity impact, and 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 maintained a reasonably high breaking strain [5]. The absorbed energy was found to be a linear relation with the thickness of the composite laminate, ensuring that the weight efficiency of the fiber composite is greater than the metallic targets, like steel. For this important effect of the fiber mechanical properties the fabrication of hybrid composites from multiple types of layered fibers was used.

The technique of interlaminate hybridization was found to enhance delamination under impact loading. Delamination was found to be an effective energy absorber in hybrids. The impact energy absorption capability depends on which side faces the direction of the impact. In general, the non-symmetric 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 10 km/s [6].

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 the projectile velocity increases.

The other important parameter affecting the high velocity impact is the projectile mass. Cantwell and Morton [7] 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 structures. When the kinetic energy of the impacting object is greater than the ballistic range, perforation takes place. Now, the ballistic limit of the velocity will be an additional pa-
Ballistic impact testing involves investigating the normal impact and absorbed energy [17]. An experimental approach to parametric values, considering various projectiles and target plate variations, was studied for parametric values, considering the combination of projectile and target plate configurations. The ballistic limit was increased with a real density [10, 11] and the striking velocity decreased with the number of repeated impacts, while the delamination zone was increased.

Different composite modes were used in the perforation studies, which included ceramic spheres embedded by matrix [10], multi-layered metallic plates [11], pure cloth specimens [12], and woven fiber composites [13]. The fracture cone shape occurred for the ceramic composites, while the 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 [10].

For the perforation of PE fabric, the two kinds of perforation modes, that is, cutting of yarns and pullout of yarns, were observed depending on the textile structure [12]. For woven fiber composites, the ballistic impact increased with the increasing in the thickness of the laminate. Further, the satin weave laminates exhibited higher ballistic limit than the plain weave [13].

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 [13], tensioned Kevlar over wind [14] or added layers of super elastic nitinol [1, 15]. Small amounts of these additives gave a large percentage of the absorbed energy and increased the impact resistance.

On the basis of a series of tests [16] found that multi-layered beams were more effective in resisting perforation than monolithic beams of the same weight under projectile impact. The experiments were studied for parametric values, considering various projectiles and target plate variables, and were carried out to find their effect on the response of the plate and ballistic parameters, such as ballistic limit and absorbed energy [17]. An experimental investigation of the normal impact and perforation of conically-tipped hard-steel cylinders was done on laminated Kevlar-29 / polyester targets. The dynamic tests were executed using both pneumatic and powder guns, mostly with a 12.7 mm barrel diameter [18].

In this study, the tensile strength, impact resistance, and fracture toughness behavior of unidirectional, chopped, and bidirectional fiber reinforced glass and Kevlar/polyester composite increase when the fiber volume fraction increases. Also there were establishing empirical relationships between tensile strength, impact resistance, and fracture toughness values [19]. The study shows that the addition of oxy-fluorinated Kevlar TM fiber into the syndiotactic polystyrene matrix significantly affects the dynamic mechanical properties of the composite by appreciably increasing storage modulus. Oxy-fluorinated fiber incorporation leads to improved tensile strength, elastic modulus, and impact strength [20].

To the authors’ knowledge, there has no study yet being conducted on Kevlar-29 and Al₂O₃ powder/epoxy composite under high velocity impact. This paper reported an experimental for composite materials under a ballistic velocity impact. The aim is to develop manufacture composite material which has high absorbed energy.

**Experimental Setup**

**Test Specimen Preparation.** Test specimens were prepared using panels of the composites materials, Kevlar29 fiber and Al₂O₃ with epoxy resin. Different layers in the fabrication specimens were used. The composite material panel was machined to (100x100 mm) high velocity impact test target dimensions or to the standard (ASTM D 3039/D 3039 M-95a) tensile test specimen dimensions, according to the type of required test and by using quarter bridge strain gages to find the strain for the composite material.

**High Velocity Test.** High velocity tests were carried out using a high velocity testing rig. Basically, the rig consisted of a double–clamped base on which a gun barrel of (10 mm) nominal bore and (300 mm) in length was mounted. In the line of fire for the projectile, the velocity before the target and the residual velocity after the target were measured by high speed cameras that recorded the impact event at 200 000 frames per second with an image size of
512 × 48 pixels per image. The camera recorded the velocity of the bullets before and after the penetration of the target. Hot-shot camera software provided clear images for the horizontal distance, and the time the projectile traveled was calculated by reviewing the video film, as shown in Figure 2. Steel projectiles of 85–87 HRB hardness, 8 mm in diameter weighing 5.2 g were propelled up to 400 m/s velocity using commercial gas gun charges. Various projectile velocities were obtained by manipulating the weight of the gas gun charges. The tested targets were clamped between two steel constraining plates with an 80 mm center aperture and firmly tightened. The striking velocity and the residual mean velocity were estimated and obtained, respectively, by high speed camera.

Results and Discussion

The ballistic limit, or \( V_{50} \), is commonly defined as a 50% probability of penetrating a target at the given impact velocity. The energy absorption, in relation to the impact velocity, was interpreted by the effect of the striking velocity on the amount of kinetic energy that was absorbed by the composite material. Hence, the energy absorbed by the fabric is equal to the residual energy amount subtracted from the total impact energy. In the event when no penetration occurs, it means that the projectile was fully arrested by the kinetic energy of the bullet. Thus, the residual velocity will be equal to zero.

Figures 3 and 4 show photos of the armor composite materials target of woven unidirectional fiber after undergoing the impact of three types of projectiles (flat cylindrical, conical tip) for different thicknesses. Upon impact, the target plate firstly acts as an elastic circular plate clamped at its boundary, which is acted upon by a concentric force that would drive the target plate up to the utmost possible elastic deflection permitted by the elasticity of the material. The last elastic deflection stage marks the onset of the plastic deflection stage, the material under the direction of the moving projectile. As the projectile moves on, it finally exits through the target material, which retains to its final permanently deformed shape. If the ceramic is suffering from a defect it reduces its effectiveness when used in body armor, and fragments and cracks, which leads to significant damage.

Heavy damage in the ceramic panels exposed to munitions leads to not only damage to the area of injury, but rather spreads cracks as well. The spread of cracks over a large part of the surface of the board could lead to injury. The Kevlar fiber classes play an important role in the prevention of cracks and fragmentation of ceramics during the process of penetration and fragmentation, which as a result of this breach, maintains them as well as absorbs the bulk...
of the kinetic energy. Kinetic energy of the supernatural fabric prevents the penetration of the shot. The impact tests that were done for the fabricated specimens will be discussed in this section. The first parameter studied for these tests is the effect of the incident velocity on the resting velocity and the absorbing energy. For this reason, the different thicknesses of woven fiber Kevlar and Al₂O₃/Epoxy composite plate were studied. Increasing the number of layers tended to increase the work done and comparison was also made with the experimental results, where good agreement was obtained as shown in Figure 6.

Figures 7 to 16 show the residual projectile velocity versus the initial velocity for armor composite material targets of different layers in the range of 4, 6, 8, 10 and 30 layers. In both figures, the theoretical curves were obtained by introducing the experimental recorded ballistic limit \( V_b \) into the empirical formula for the Ipsen and Recht [23] equation. The formula is given in Equation (1) and is shown to predict well the residual velocity for the composite targets, and good agreement of the results is obtained. The formula is a power function of the initial velocity and the ballistic limit:

\[
V_r = \sqrt{\frac{V_i^2}{b}} - V_b
\]

with \( V_r \): Final velocity, \( V_i \): Initial velocity and \( V_b \): Ballistic limit.

The experimental ballistic limit velocity, \( V_b \), for various thicknesses is shown in Figure 5 and it gives good correlation in the investigation. In studying woven fiber Kevlar₂₉ + Al₂O₃/Epoxy, the best materials in terms of the stacking sequence were found to be at 30 layers, which indicates that this stacking sequence withstands a higher velocity and with no penetration at the maximum velocity of 400 ± 7 m/s, and therefore absorbs more energy during the impact, as shown in Figures 15 and 16.
Data is expressed as the mean ± 7 m/s. Statistical analysis was performed using Student’s t-test and a confidence level of p = 0.05 was utilized to compare differences within the data sets. Values of p < 0.05 were considered to indicate statistical significance. In this statistical analysis the p value was at 0.2386, which is larger than the confidence level of 0.05. The computed value of t is -1.24, and comparing this value with the critical value at a degree of freedom of 12, according to Student’s t Table, the value is ±1.7823, which is within the acceptance region, And we can accept the null hypothesis.

Conclusions

Based on the results of the experimental work that was carried out in this investigation, the main conclusions that can be drawn are:

1. The increase in target thickness improves the ballistic performance of a target.
2. The number of layers has an increasing effect on the ballistic limit and layers undergo more on target and thus are absorbing much more energy.
3. The thickness of the targets increase the energy absorbed from the impact increase, so the Al₂O₃ powder helps increase the energy absorbed.
4. The results indicate improvement of mechanical properties in the performance of Kevlar 29 and Al$_2$O$_3$ powder/Epoxy for bullet-proof applications.

**References**


12. H. Kasano, K. Abe: Perforation characteristics prediction of multi-layered composite plates subjected to high velocity impact, Proceeding of ICCM-11, Australia (1997), pp. 522-531


**Table 1. Measured mechanical properties for the manufactured composites**

<table>
<thead>
<tr>
<th>Fiber/Matrix/Layers</th>
<th>Tensile Strength ($\sigma_t$ (MPa))</th>
<th>Compression Modulus ($E$ (GPa))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar29 Al$_2$O$_3$ Epoxy 4 layers</td>
<td>175.2</td>
<td>12.1</td>
</tr>
<tr>
<td>Kevlar29 Al$_2$O$_3$ Epoxy 6 layers</td>
<td>145.42</td>
<td>10.3</td>
</tr>
<tr>
<td>Kevlar29 Al$_2$O$_3$ Epoxy 8 layers</td>
<td>125</td>
<td>4.91</td>
</tr>
<tr>
<td>Kevlar29 Al$_2$O$_3$ Epoxy 10 layers</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Abstract**


**The Authors of This Contribution**

You will find the article and additional material by entering the document number MP110312 on our website at www.materialtesting.de.

54 (2012) 3