Original Article

Ballistic performance of multilayered armor with intermediate polyester composite reinforced with fique natural fabric and fibers

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A B S T R A C T

Multilayered Armor Systems (MASs) with a front ceramic followed by synthetic fabric are currently used against high velocity ammunition. In these armors, the front layer, which shatters the ceramic and spalls the bullet, is followed by an intermediate layer, usually plies of synthetic aramid fabric (Kevlar®). In the present work, the intermediate Kevlar® layer was replaced by an equal thickness layer of two configuration of fique fibers, as fabric or aligned fibers. Both fique fabric and aligned fibers in amounts of 10, 20 and 30 vol% were used to reinforced polyester matrix composite. Ballistic impact tests against high velocity 7.62 caliber ammunition revealed that the plain polyester as well as the fique fabric and aligned fiber composites have a relatively similar shock impedance performance as that of the Kevlar®. Indentation around 16–20 mm in witness clay for MASs with fique fabric and aligned fique fiber polyester composites as second layer, were better than that of 23 mm for Kevlar®. These values attended the US National Institute Justice standard, which requires a maximum of 44 mm for body protection. The energy dissipation mechanisms related to the contribution of fique fabric and fibers composites were analyzed in terms of distinct failure modes, visually supported by scanning electron microscopy. These were found to be the same mechanisms recently disclosed for aramid fabric and other natural fibers composites.

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1. Introduction

Ballistic protection of personnel, equipment and vehicles is now of surging importance due to armed urban conflicts and regional wars involving increasing firepower. The use of high velocity, impact and power (VIP) ammunition, such as Class III [1], 7.62 × 51 mm, constitutes a major personal threat. In this case, single layer shielding, such as those made of synthetic aramid fabric plain (Kevlar®) laminates would require a heavier and large thickness (>50 mm), which interferes with the user’s mobility. For protection, the multilayer armor system (MAS), normally composed of three different materials, is a
Table 1 – Depth of indentation as a NIJ standard ballistic performance of front ceramic multilayered armor systems (MAS) with natural fabric and fiber polymer composites. Same thickness of Kevlar® laminate for comparison.

<table>
<thead>
<tr>
<th>MAS natural fabric or fiber polymer composite</th>
<th>Depth of indentation* (mm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 vol% fique fabric/polyester</td>
<td>15 ± 3</td>
<td>[15]</td>
</tr>
<tr>
<td>30 vol% jute fabric/polyester</td>
<td>17 ± 2</td>
<td>[16]</td>
</tr>
<tr>
<td>30 vol% non-woven mat/polyester</td>
<td>24 ± 7</td>
<td>[17]</td>
</tr>
<tr>
<td>30 vol% sisal fiber/polyester</td>
<td>22 ± 3</td>
<td>[18]</td>
</tr>
<tr>
<td>30 vol% curaua non-woven fabric/epoxy</td>
<td>28 ± 3</td>
<td>[19]</td>
</tr>
<tr>
<td>30 vol% aligned mallow fiber/epoxy</td>
<td>22 ± 1</td>
<td>[20]</td>
</tr>
<tr>
<td>30 vol% curaua fiber/polyester</td>
<td>22 ± 2</td>
<td>[21]</td>
</tr>
<tr>
<td>30 vol% curaua 90° cross-grid fiber/polyester</td>
<td>18 ± 3</td>
<td>[21]</td>
</tr>
<tr>
<td>30 vol% ramie fabric/epoxy</td>
<td>17 ± 1</td>
<td>[22]</td>
</tr>
<tr>
<td>30 vol% sugarcane bagasse fiber/epoxy</td>
<td>21 ± 1</td>
<td>[23]</td>
</tr>
<tr>
<td>Kevlar® laminate</td>
<td>23 ± 3</td>
<td>[15]</td>
</tr>
</tbody>
</table>

* NIJ backface signature [1].

As an ongoing research based on a previous one [15], the objective of this work was to perform an in-depth evaluation of the ballistic performance of 10, 20 and 30 vol.% fique fabric and aligned fiber reinforced polymer composites as a MAS second layer subjected to VIP ballistic impact. It was also investigated for the first time the impedance matching of the impact wave propagation in the MAS and the energy dissipation mechanisms of these composite associated with failure modes supported by scanning electron microscopy analysis.

2. Experimental procedure

The MAS investigated in the present work was composed of a front hexagon-shaped (30 mm in edge and 10 mm in thickness) Al₂O₃-4%Nb₂O₅ ceramic tile. A rectangular 120 × 150 mm plate with 10 mm of thickness was used as second layer composed of polyester composites reinforced with configuration of fique fiber. A back layer of 5052 H34 aluminum alloy, supplied by Metalpak Metais, Brazil, also as rectangular 120 × 150 mm plate with 5 mm of thickness, finished the MAS. The layers were bonded together using a polyurethane adhesive.

The composite matrix, an orthotropical polyester resin hardened with 0.5 wt.% of methyl ethyl ketone, was supplied by the Resinpoxy, Brazil. The fique fabric and fiber, as shown in Fig. 1, were supplied by one of the co-authors (HACL) from Colombia. Both fique fabric and aligned fiber composite plates were prepared by compression molding, at room temperature (25°C), in the amounts of 10, 20 and 30 vol.%. After adding the resin with hardener, the mixture was kept under a pressure of 5 MPa for 24 h.

Ballistic tests were performed with NATO 7.62 × 51 mm military VIP ammunition, following the NIJ procedures [1]. The experimental test arrangement is schematically shown in Fig. 2a and a typical MAS mounted for the test in Fig. 2b. The shooting device was a model B290 gun barrel with laser sight (Fig. 2c), produced by HPI - High Pressure Instrumentation, available at the Brazilian Army Assessment Center (CAEx), located in the city of Rio de Janeiro, Brazil.

The bullet velocity was measured by both optical barriers and a model SL-520P Weibel Doppler radar. The velocity was kept in the standard 847 ± 9 m/s range. An indentation was imprinted by the armor in the clay witness after the impact. The standard specifies that the mean indentation be no deeper than 1.73 inch (44 mm) [1]. Fig. 2d depicts the measurement procedure of the indentation by means of a laser sensor.

Impedance matching of the impact wave propagation in the MAS front ceramic and reflection at the backing plate was evaluated to compare the efficiency of the fique composites. According to Meyers [29], the pressure generated in the interface between layers during shock can be calculated by the following equation:

\[
P = \rho_0 U_s U_p = ZY_p
\]

Where \( \rho_0 \) is the density of the material; \( U_s \) is the shock wave velocity and \( U_p \) is the particle velocity. The product \( Z = \rho_0 U_s \) in Eq. (1) is known as shock impedance of the material. In the present work, the value of \( Z \) was calculated by the impedance matching technique applied to the
ceramic/second layer interface. This method basically finds the solution to the conservation equations (mass, momentum and energy) together with the equation of state of the material [25].

Six samples of each group were tested and the data were statistically treated by the Weibull analysis, which gave information about the indentation distribution of probability. The Weibull’s density of probability function is given by Eq. (2).

\[ F(x) = 1 - \exp \left( -\left( \frac{x}{\theta} \right)^{\beta} \right) \]  

where \( x \) is the value assumed by the random variable; \( \theta \) is the scale parameter and \( \beta \) is the shape parameter, also known as Weibull modulus.

In order to identify the failure modes of the MAS, a microscopic evaluation of the fragments was carried out by scanning electron microscopy in a FEI Quanta FEG 250 equipment, using secondary electrons and 20 kV.

3. Results and discussion

Fig. 2 shows aspect of MAS targets with reinforced polyester composite with 10, 20 and 30% with aligned fique fibers and fique fabric after the projectile impact. As noted in these figures, MASs with polyester composite reinforced with fique did not exhibit perforation of the projectile. The armor systems absorbed its impact energy and prevent penetration beyond the limit of 44 mm required by the standard [1]. In all cases,
there was a complete destruction of the ceramic material. As for the composite plates, Fig. 2 also shows that those with aligned fique fibers, Fig. 2(a) to (c), were almost totally broken. By contrast, composite plates with fique fabric, Fig. 2(d) to (f), remained cracks, as in 2(f). At least three failure modes would be associated with the results in Fig. 2. First, the rupture of the polyester matrix, which appears to be the main mechanism in the case of aligned fique fibers composites. Second, delamination between fabric and polyester causing macro cracks as in Fig. 2(f). A third mode might be the individual rupture of fique fibers including those in the fabric. In any case, new surface areas are created in either the polyester or the fiber fracture surfaces as well as due to decohesion between them. Creation of new ruptured surface areas is an efficient way of absorbing the energy imposed by an applied stress or shock wave pressure [25–27].

In terms of the penetration in the clay witness, Table 2 shows the values obtained for the indentation depth associated with the different MAS ballistic tested. In this Table it should be noticed the relatively small, 16–20 mm, indentation values for all fique fabric and aligned fiber polyester composites. These values are better than the 23 mm found for Kevlar® with same 10 mm thickness as MAS second layer [29].

Table 2 – Average depth of indentation in the clay witness backing different multilayered armors.

<table>
<thead>
<tr>
<th>Fique fiber</th>
<th>Intermediate material layer</th>
<th>Average depth of indentation (mm)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aligned</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fabric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 vol.%</td>
<td>17 ± 2</td>
<td>PW*</td>
<td></td>
</tr>
<tr>
<td>20 vol.%</td>
<td>16 ± 1</td>
<td>PW*</td>
<td></td>
</tr>
<tr>
<td>10 vol.%</td>
<td>17 ± 3</td>
<td>PW*</td>
<td></td>
</tr>
<tr>
<td>20 vol.%</td>
<td>20 ± 2</td>
<td>PW*</td>
<td></td>
</tr>
<tr>
<td>10 vol.%</td>
<td>17 ± 3</td>
<td>[13]</td>
<td></td>
</tr>
<tr>
<td>Aramid fibers laminate</td>
<td>23 ± 3</td>
<td>[15]</td>
<td></td>
</tr>
</tbody>
</table>

* Present Work.

Table 3 – Weibull parameters for ballistic tests with MAS having different second layers.

<table>
<thead>
<tr>
<th>Fique fiber</th>
<th>Intermediate material layer</th>
<th>Weibull modulus (β)</th>
<th>Scale parameter (Δ) (Indentation depth mm)</th>
<th>Correlation coefficient (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aligned</td>
<td></td>
<td>17.23</td>
<td>17.46</td>
<td>0.99</td>
</tr>
<tr>
<td>Fabric</td>
<td></td>
<td>19.72</td>
<td>17.05</td>
<td>0.82</td>
</tr>
<tr>
<td>30 vol.%</td>
<td>6.66</td>
<td>18.31</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>20 vol.%</td>
<td>5.26</td>
<td>18.99</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>10 vol.%</td>
<td>9.84</td>
<td>20.84</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 – Calculated parameters of the impedance matching analysis (Eq. 1).

<table>
<thead>
<tr>
<th>Second layer at Al₂O₃ ceramic interface</th>
<th>Uᵢ (m/s)</th>
<th>P (GPa)</th>
<th>Uₛ (m/s)</th>
<th>Z (10⁶kg/m² s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester-30 vol.% fique fiber</td>
<td>754</td>
<td>1.5</td>
<td>2210</td>
<td>2.4</td>
</tr>
<tr>
<td>Polyester-20 vol.% fique fiber</td>
<td>749</td>
<td>1.7</td>
<td>2092</td>
<td>2.3</td>
</tr>
<tr>
<td>Polyester-10 vol.% fique fiber</td>
<td>750</td>
<td>1.7</td>
<td>2047</td>
<td>2.2</td>
</tr>
<tr>
<td>Neat polyester resin</td>
<td>771</td>
<td>1.5</td>
<td>1987</td>
<td>2.0</td>
</tr>
</tbody>
</table>

In other words, the variability of depth of indentation values within the groups was purely statistical. Indeed, the distribution of probabilities follows a Weibull distribution with high accuracy.

The impedance matching analysis are shown in Table 4 for MAS’s with neat polyester resin as well as both fique fabric and aligned fiber composites in the second layer. These shock wave impedance values are expected since the lower the impedance (Z) of the second layer, the smaller the indentation in the clay witness. However, as the results in Table 4 are very close to each other, the trauma protection provided by the second layer might not be so sensitive to its shock impedance. However, the NIJ requires multiple shots in the last stages of ballistic approval. As shown in Fig. 3, both the neat polyester resin and fique aligned-fiber composites did not keep their integrity after the shot. Thereby, polyester composites reinforced with fique fabric are best suited for MAS second layer in ballistic armor for body protection.

Fig. 4 illustrates by SEM a micrograph of the fracture aspects typical of a 30 vol% fique fabric polyester composite as MAS second layer. The microscopic aspect in this figure is associated with the macro failure modes of rupture of the composite plate shown in Fig. 3. Indeed, the delamination crack observed in Fig. 3f indicates one of the main mechanisms of impact energy dissipation by creating relatively large rupture surface areas. From this figure, one may infer that the energy dissipation mechanism is mainly associated with the ability of collecting the fragments from both the projectile and the front ceramic layer. Indeed, previous works revealed that this is accomplished by mechanical incrustation, as well as...
4. Conclusions

Multilayered armor systems (MAS) using 10, 20 and 30 vol.% of fique fabric and aligned fiber reinforced polyester composites were for the first time found equally efficient for ballistic protection against 7.62 mm caliber ammunition, based on the NIJ 0101.06 criteria related to the depth of indentation in the clay witness (single-hit protection).

Among all the aligned fique fiber reinforced polyester composites studied in the present work, that with 30 vol.% presented the best results, in terms of trauma prevention, indentation depth lower than 44 mm and physical integrity after the impact. However, only the fique fabric composites were able to keep their integrity after the ballistic impact and, therefore, could provide protection against multi-hit shooting. Shock wave impedance analysis indicate similar values for plain polyester and fique fiber polyester composites, corroborating the corresponding indentation values.

The fracture of both fique fabric and fique fiber composites identified the mechanisms of energy absorption associated with different failure modes and related to the microscopic capture of ceramic and projectile fragments resulting from the projectile impact against the MAS.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

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