Original Article

Performance of natural curaua fiber-reinforced polyester composites under 7.62 mm bullet impact as a stand-alone ballistic armor

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ABSTRACT

A multilayered armor system (MAS) is intended to personal protection against high kinetic energy ammunition. MAS layers are composed of materials such as a front ceramic and a back composite that must show both high impact resistance and low weight, usually conflicting characteristics. Synthetic fiber fabrics, such as Kevlar™ and Dyneema™, are the favorite materials to back the front ceramic, due to their high strength, high modulus and relatively low weight. Recently, composites reinforced with natural fibers have been considered as MAS second layer owing to their good performance associated with other advantages as being cheaper and environmentally friendly. Among the natural fibers, those extracted from the leaves of the Ananas erectifolius plant, known as curaua, stand out due to its exceptional high strength and high modulus. Thus, the objective of the present work is to evaluate the performance of curaua fiber-reinforced polyester composites subjected to ballistic impact of high energy 7.62 mm ammunition. Composites reinforced with 0, 10, 20 and 30 vol.% of curaua fibers were produced and stand-alone tested as armor target to evaluate the absorbed energy. Analysis of variance (Anova) and Tukey’s honest significant difference test (HSD) made it possible to compare the results to Kevlar™ laminates. Among the tested materials, the 30 vol.% fiber composites were found to be the best alternative to Kevlar™.

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1. Introduction

As the technology of guns and ammunition progresses, attention is being paid to the development of new materials that resist to ballistic impacts. High strength materials are necessary, but the search for the best performance should also consider the mobility that the soldiers and the defense systems must have [1–3].

Currently, synthetic fiber fabrics such as aramid (Kevlar™ and Twaron™) as well as ultra-high molecular weight polyethylene (Dyneema™ or Spectra™) are the favorite materials to protect personnel and to provide defensive armor systems against high energy ammunitions, such as 7.62 and 5.56 mm [2–4]. However, aiming to improve performance and considering new economic and environmental issues, several other lightweight materials are being tested [5–16].

In this scenario, natural fiber reinforced composites have demonstrated good ballistic behavior to compose multilayered armor systems (MAS) [10–12]. The fiber extracted from the Amazon plant Ananas erectifolius, called curaua, stand out among the natural fibers due to their high strength and high modulus, low weight and high toughness of their composites [16–19].

Monteiro et al. [19] have already studied the curaua fiber-reinforced polyester composites as part of a MAS. However, the individual energy dissipation of the curaua composites was not investigated. This is important for the contribution of each material to the MAS model of energy absorption. Several methods can be used to evaluate the ballistic behavior of a material [19–21]. In the present work a comparison has been made between polyester composites reinforced with up to 30 vol.% of curaua fibers, neat polyester and aramid fabric laminate. This was conducted by using the value of the projectile’s kinetic energy absorbed by the target. This technique allows a fast individual evaluation of the materials that compose the MAS. Thus, the objective of the present work is to evaluate the individual performance of these materials when subjected to ballistic impact with 7.62 mm ammunition. The reason for the stand-alone ballistic tests is to determine how each investigated material would behave without the front ceramic. This might permit more complete understanding of the energy dissipation mechanisms that were first studied for Kevlar™ [4].

2. Experimental methods

Table 1 shows the materials tested in the present work and their designations. Besides the polyester composites reinforced with curaua fibers, neat polyester resin and aramid fabric laminates (Kevlar™) were evaluated for comparison.

The curaua fibers were supplied by the Pematec Triangel firm, Brazil, in the form of bundles. The isophthalic polyester resin and hardener (methyl ethyl ketone), fabricated by Dow Chemical, were supplied by the Resinpoxy firm, Brazil. For the composite preparation, the curaua fibers were 150 mm cut in length and dried at 60 °C for 24 h. The fibers were carefully positioned in layers, inside a steel mold, keeping the fiber alignment along the mold’s length. The layers were intercalated with polyester–1% hardener mixture. A pressure of 3 MPa was applied and the composite plate cured at room temperature for 24 h. The final composite plates were rectangular in shape with 120 mm × 150 mm × 10 mm dimensions.

The aramid fabric was a model S745 with areal density of 460 g/m², acquired from LFJ Blindagens (Conquex) firm, Brazil. It was provided as 8 layer panels (model MENEOKV08) impregnated with neoprene rubber. In each 16 layer samples, 2 panels were joined together using polyurethane based glue, resulting in a laminate with approximately 10 mm in thickness, same as the neat polyester and curaua composite plates.

The materials were subjected to ballistic impact at the Army Assessment Center (CAEx), in the Marambaia Peninsula, Rio de Janeiro. The shooting device was a model B290 HPI (High Pressure Instrumentation), which consists of a gun barrel with laser sight (Fig. 1(a)). For the velocity measurements, it has been employed a model SL-520P Weibel Doppler radar provided with a Windopp software to process the radar raw data. The ammunition was a commercial 7.62 mm M1, weighting 9.7 g. The target (Fig. 1(b)) was positioned 15 m from the gun barrel, and the shooting performed with the bullet following a trajectory perpendicular to the target, as schematic shown in Fig. 1(c).

The projectile’s velocity was measured immediately before (v_i) and after (v_f) the impact. The kinetic energy variation of the projectile was related to the energy absorbed by the target (E_abs) and used for comparison between the materials. It can be calculated by Eq. (1).

$$E_{\text{abs}} = \frac{m(v_i^2 - v_f^2)}{2}$$

where $m$ = mass of the bullet.

Nine tests were made for each material target. The lowest and the highest values of absorbed energy for each material were discarded. The values were then statistically treated using the analysis of variance (Anova). The mean values were then compared using Tukey’s test, also called honestly significant difference (HSD), and calculated by Eq. (2) [22].

$$HSD = q\sqrt{\frac{\text{EMS}}{r}}$$

where $q$ = HSD constant tabulated for 5% significance; EMS = error mean square of the Anova; $r$ = number of repetitions for each treatment ($r = 7$).
3. Results and discussion

Fig. 2 presents a typical Doppler radar reflected raw data, Fig. 2(a), and its corresponding Windopp fitted radial velocity curve, Fig. 2(b). The projectile with decreasing velocity, vertical scale in Fig. 2(b), exits the gun barrel with 879 m/s and hits the target at \(v_1 = 867 \text{ m/s}\). Projectile penetration through the target is associated with a vertical (radar blind) straight line at about 0.018 s form the shooting onset. As shown in Fig. 2(b), the projectile emerges from the target (bottom of vertical line) with a residual velocity \(v_2 = 745 \text{ m/s}\). Thereafter, a single decreasing curve indicates that projectile is intact with continuously decreasing velocity. The values of \(v_1\) and \(v_2\), measured in every test, allowed the calculation of the absorbed energy by means of Eq. (1).

Table 2 shows the projectile’s absorbed energy by the different targets. Considering primarily just the mean values, it might be observed that the type of material influences the absorbed energy. However, the confirmation still needs an additional statistical treatment (Anova and HSD).

Table 3 shows the analysis of variance of the data. In this table it is presented parameters such as degrees of freedom (DF), sum of squares (SS), mean squares (MS), the Snedecor \(F\) and \(F_c\), calculated and critical, respectively, and the p-value. It is important to mention that before the Anova, it has been performed a Shapiro–Wilk test, and it was found that all data follows normal distributions.

Comparing the \(F\) value with the tabulated \((F_c = 2.69)\), the hypothesis that the mean values are the same can be rejected with 95% confidence, since \(F > F_c\). In other words, it was statistically proved that the material of the target, indeed, influenced the projectile’s absorbed energy.

After the Anova, it is possible to compare the mean values using the HSD test. The value of \(q\) for 5 treatments and 30 degrees of freedom for the error is 4.1. Thus, the HSD was calculated by Eq. (2) as 57.5. Table 4 shows the comparison between the mean values using the HSD test. In bold are highlighted the differences between mean values larger than the HSD.

Analyzing Tables 2 and 4, it can be verified that the material P-0%C was the one that absorbed the highest energy value.
This can be attributed to its fragile characteristic that dissipates energy by creation of fracture surfaces, as it happens in ceramics spalling mechanism [4].

On the other hand, HSD test confirmed that the composites (P-10%C, P-20%C and P-30%C) had an inferior result (lower energy absorption) when compared to the neat polyester resin (P-0%C). This is probably due to the change of the fracture mechanisms, starting from a fragile material turning to a tougher one, with more complex fracture features, involving matrix cracking and fibers failure as well as fiber pullout and delamination, among other mechanisms [10].

Fig. 3 shows the general aspect of the samples after the ballistic tests. The neat polyester, P-0%C, was totally fragmented, as can be observed in Fig. 3(a). Despite its higher energy absorption, the fragmentation is a practical problem when the material is subjected to multiple impacts. Among the composites, the P-30%C was the one with the best aspect, and absorbed the same amount of energy than the Kevlar™ laminate. Although P-30%C absorbed less energy than P-0%C, the fact that P-30%C kept its integrity after the impact is of great importance to integrate a MAS against 7.62 mm ammunition, especially as second layer, backing the ceramic tile [11-15].
Table 2 – Projectile’s absorbed energy due to ballistic impact.

<table>
<thead>
<tr>
<th>Material</th>
<th>P-0%C</th>
<th>P-10%C</th>
<th>P-20%C</th>
<th>P-30%C</th>
<th>Aramid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbed energy [J]</td>
<td>225</td>
<td>120</td>
<td>127</td>
<td>152</td>
<td>194</td>
</tr>
<tr>
<td>230</td>
<td>150</td>
<td>147</td>
<td>186</td>
<td>201</td>
<td></td>
</tr>
<tr>
<td>260</td>
<td>156</td>
<td>156</td>
<td>194</td>
<td>221</td>
<td></td>
</tr>
<tr>
<td>267</td>
<td>190</td>
<td>163</td>
<td>197</td>
<td>226</td>
<td></td>
</tr>
<tr>
<td>268</td>
<td>224</td>
<td>164</td>
<td>200</td>
<td>228</td>
<td></td>
</tr>
<tr>
<td>292</td>
<td>290</td>
<td>186</td>
<td>218</td>
<td>229</td>
<td></td>
</tr>
<tr>
<td>295</td>
<td>293</td>
<td>199</td>
<td>230</td>
<td>239</td>
<td></td>
</tr>
<tr>
<td>Mean energy [J]</td>
<td>262 ± 27</td>
<td>203 ± 69</td>
<td>163 ± 24</td>
<td>197 ± 25</td>
<td>220 ± 17</td>
</tr>
</tbody>
</table>

Table 3 – Analysis of variance (Anova) of the data.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Fc</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatments</td>
<td>4</td>
<td>36,893</td>
<td>9223</td>
<td>6.6917</td>
<td>2.69</td>
<td>0.0006</td>
</tr>
<tr>
<td>Error</td>
<td>30</td>
<td>41,349</td>
<td>1378</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>34</td>
<td>78,242</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In comparison with P-20%C, the higher absorbed energy was not significant, and both were not fragmented. However, the higher the amount of curaua fibers, the cheaper becomes the composite and there is a slight increase in the absorbed energy. Therefore, the P-30%C is always more advantageous as MAS second layer.

Table 4 – Honest significant difference (HSD) analysis.

<table>
<thead>
<tr>
<th>Material</th>
<th>P-0%C</th>
<th>P-10%C</th>
<th>P-20%C</th>
<th>P-30%C</th>
<th>Aramid</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-0%C</td>
<td>0</td>
<td>59</td>
<td>99</td>
<td>65</td>
<td>42</td>
</tr>
<tr>
<td>P-10%C</td>
<td>59</td>
<td>0</td>
<td>40</td>
<td>6</td>
<td>17</td>
</tr>
<tr>
<td>P-20%C</td>
<td>99</td>
<td>40</td>
<td>0</td>
<td>34</td>
<td>57</td>
</tr>
<tr>
<td>P-30%C</td>
<td>65</td>
<td>6</td>
<td>34</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td>Aramid</td>
<td>42</td>
<td>17</td>
<td>57</td>
<td>23</td>
<td>0</td>
</tr>
</tbody>
</table>

4. Conclusions

- Different materials, including a neat polyester resin, an aramid fabric laminate and composites reinforced with 10, 20 and 30 vol.% of curaua fibers were individually tested by the ballistic impact with 7.62 mm bullets.

- The neat polyester resin showed the highest energy absorption. However, its fragmentation characteristic makes it unsuitable for multi-hit applications.

- Despite that, the 30 vol.% curaua fiber composite showed an interesting group of characteristics for multi-hit applications, such as high energy absorption and good cohesion after the impact.

- Composites reinforced with curaua fibers are potentially able to replace synthetic fiber fabrics as second layer in multilayered armor systems (MAS) for personal protection. In addition to the good performance, the curaua fiber composites are light, cheaper and environmentally friendly.

Fig. 3 – Samples subjected to ballistic impact: (a) P-0%C; (b) P-10%C; (c) P-20%C; (d) P-30%C.
Conflicts of interest

The authors declare no conflicts of interest.

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