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Evaluation of the Projectile's loss of Energy in Polyester Composite Reinforced with Fique Fiber and Fabric

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Firearms threat has always been a matter of personal concern, especially to soldiers in armed conflicts as well as police officers and civilians involved with public security. A multilayered armor system (MAS) is intended to personal protection against high kinetic energy ammunition, such as that used in rifles. MAS layers are normally composed of a front ceramic followed by a layer that must show both high impact resistance and low weight. Usually, synthetic fiber fabrics, such as aramid in Kevlar® and ultra-high molecular weight polyethylene (UHMWP) in Dyneema® are commonly used as the second layer. Currently, composites reinforced with natural fibers are also being considered as second MAS layer due to their good performance associated with the advantages of being cheaper and environmentally friendly. The fique is a relatively unknown natural fiber extracted from leaves of a plant native of South American Andes. In the present work, fique fibers and fique fabrics incorporated in polyester composite plates with volume fraction of 10, 20 and 30% were ballistic tested. The calculated projectile loss of energy indicated a relatively large energy dissipation by the composite. The tested specimens were statistically treated by the Weibull analysis and were examined by scanning electron microscopy.

Keywords: *natural fiber, composite fique fiber, fabric, ballistic test, absorbed energy.*

1. Introduction

The use of high velocity, impact and power (VIP) ammunition, as the Class III 7.62 x 51 mm (7.62 mm for short) used in rifles, is today associated with increasing threat in urban conflicts, regional wars and terrorism actions. A high-strength material, such as steel is an important ballistic protection for military construction, equipment and vehicles. However, for the best personal performance, one should also consider lightweight and fast mobility in defense systems[1-4].

Single layered armor vests demand a relatively greater thickness, which is the case of those made only of steel or Kevlar®. This interferes with the user's mobility. For protection against VIP Class III ammunition, the multilayer armor system (MAS) with a hard, brittle front material such as a ceramic is an effective solution[5-8]. Traditionally, laminates of aramid fabric such as Kevlar® and UHMWP Dyneema®[9-10] are commercial materials used as the MAS second layer. Another third layer of MAS, commonly a ductile metal sheet, may be added to further reduce the energy carried by the bullet impact shock wave[11].

Aiming to reduce costs and considering new sustainability issues, several other lightweight natural materials are being tested[11-15]. In this scenario, natural fiber reinforced composites have demonstrated good ballistic behavior to compose the second layer of MASs[12-16]. In previous works, fique fibers extracted from the Colombian plant *Furcraea andina* were found to have suitable properties[17-19] and to be a promising reinforcement element for polymer composites[20]. A brief description of these fibers mechanical properties and morphological characteristics is presented in Table 1, together with corresponding ones of the aramid fiber, which is used in Kevlar® laminates[21]. In this table, it is worth noticing the much higher strength and stiffness of the aramid as compared with the fique fiber. However, as further discussed, for a MAS second layer most natural fiber or natural fabric composites might perform in a comparable way to Kevlar®.

The individual energy dissipation of the fique composites has not been investigated so far. This is important to evaluate the role of each material to the MAS model of energy absorption and might contribute to develop improved armor

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Table 1. Mechanical properties of the fique fibers[19,20] and aramid fiber[21].

Fiber	Tensile Strength (MPa)	Young's Modulus (GPa)	Strain at Break (%)	Average Fiber Diameter (μm)
Fique (natural)	237 ± 51	8.01 ± 1.47	6.07 ± 0.69	160
Aramid (synthetic)	1380	76	1.8	15

vests. Some methods with different materials can be used to evaluate the ballistic behavior of a material[22-25]. One method is the ballistic limit (V50) of composite laminates associated with the minimum kinetic energy required for total penetration[23]. Another method is based on the energy absorption by the stand-alone composite upon ballistic impact[24-26]. Both the projectile impact velocity, Vi, and the outcome residual velocity, Vr, allows the evaluation of the absorbed energy. It is therefore proposed an investigation on the ballistic absorbed energy of polyester composites reinforced with up to 30 vol% of both fique fiber and fabric, as well as a comparison with aramid fabric laminate. This is conducted by using the value of the projectile's kinetic energy absorbed by the target in stand-alone tests. This technique allows a fast-individual evaluation of the materials that compose the MAS. It is important to mention that the ballistic absorbed energy of the MAS second layer was primarily found to be associated with the capture of fragments from the shattered ceramic after the projectile front impact[27]. In fact, the strength and stiffness of the fiber in the MAS second layer is of secondary relevance for this purpose. Recently, a detailed view of the mechanisms responsible for dissipating the remaining energy, after the front ceramic impact, by a curaua (natural fiber) polymer composite as second layer was presented[28]. These mechanisms were indicated as: (i) capture of fragments; (ii) fibrils (composing e fibers) separation; (iii) fiber pullout from the polymer matrix; (iv) composite delamination; (v) fiber breaking; and (vi) matrix rupture. Some of these mechanisms - (ii); (iii) and (vi) - would not occur in the case of Kevlar® as MAS second layer, which justifies the comparable ballistic performance of a natural fiber composite. Thus, the objective of the present work is to evaluate the individual performance of both polyester composites, reinforced with fique fiber and fabric, when subjected to ballistic impact with VIP 7.62 mm ammunition. The reason for the stand-alone ballistic tests is to determine how each investigated material would behave without the MAS front layer. This might permit a comprehensive understanding of the energy dissipation mechanisms by each fique (fiber and fabric) polyester composite in comparison with Kevlar®[25].

2. Experimental Procedure

The fique fabric was purchased in Bogota, Colombia, by one of the co-authors (HACL) of this work. Both the isophtalic polyester resin and corresponding hardener (methyl ethyl ketone), fabricated by Dow Chemical, were supplied by the Resinpoxy firm, Brazil. For the composite preparation, the fique fiber was cut 150 mm in length while the fique fabric was cut in pieces of 120x150 mm. Both fibers and fabrics were first dried at 60°C for 24h and then carefully positioned in layers, inside a steel mold. The layers were intercalated with polyester-1% hardener mixture. A pressure of 5 MPa was applied and the composite plate cured at room temperature (~25°C) for 24h. The final composite plates were rectangular with 120x150x10 mm dimensions.

The plates, positioned as targets, were subjected to ballistic impact at the Brazilian 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. 1a). For the projectile velocity measurements, it was employed a model SL-520P Weibel Doppler radar provided with a Windopp software to process the radar raw data. The VIP ammunition was a commercial 7.62 mm M1, weighting 9.7 g. The target (Fig. 1b) was positioned 15 m from the gun barrel, and the shooting performed with the projectile following a trajectory perpendicular to the target, as schematically shown in Fig. 1(c).

The projectile's velocity was measured immediately before (V_i) the impact and after (V_r) perforating and leaving the target. The kinetic energy variation of the projectile was related to the energy absorbed by the target (E_{abs}) and used for a comparison between the investigated materials.

$$E_{abs} = m(V_i^2 - V_r^2)/2 \quad (1)$$

where: m = mass of the bullet.

A relevant virtual parameter is the projectile limit velocity (V_L), defined as the minimum velocity still able to perforate the target. The V_L value may be estimated by considering its associated energy as the absorbed by the target, E_{abs} in Eq. 1. Thus

$$E_{abs} = mV_L^2/2 \quad (2)$$

Seven samples of each group were tested and the data were statistically treated by the Weibull analysis, which provided information on the limit velocity distribution[24]. The Weibull's density of probability function is given by Eq. 3.

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\theta}\right)^{\beta}\right] \quad (3)$$

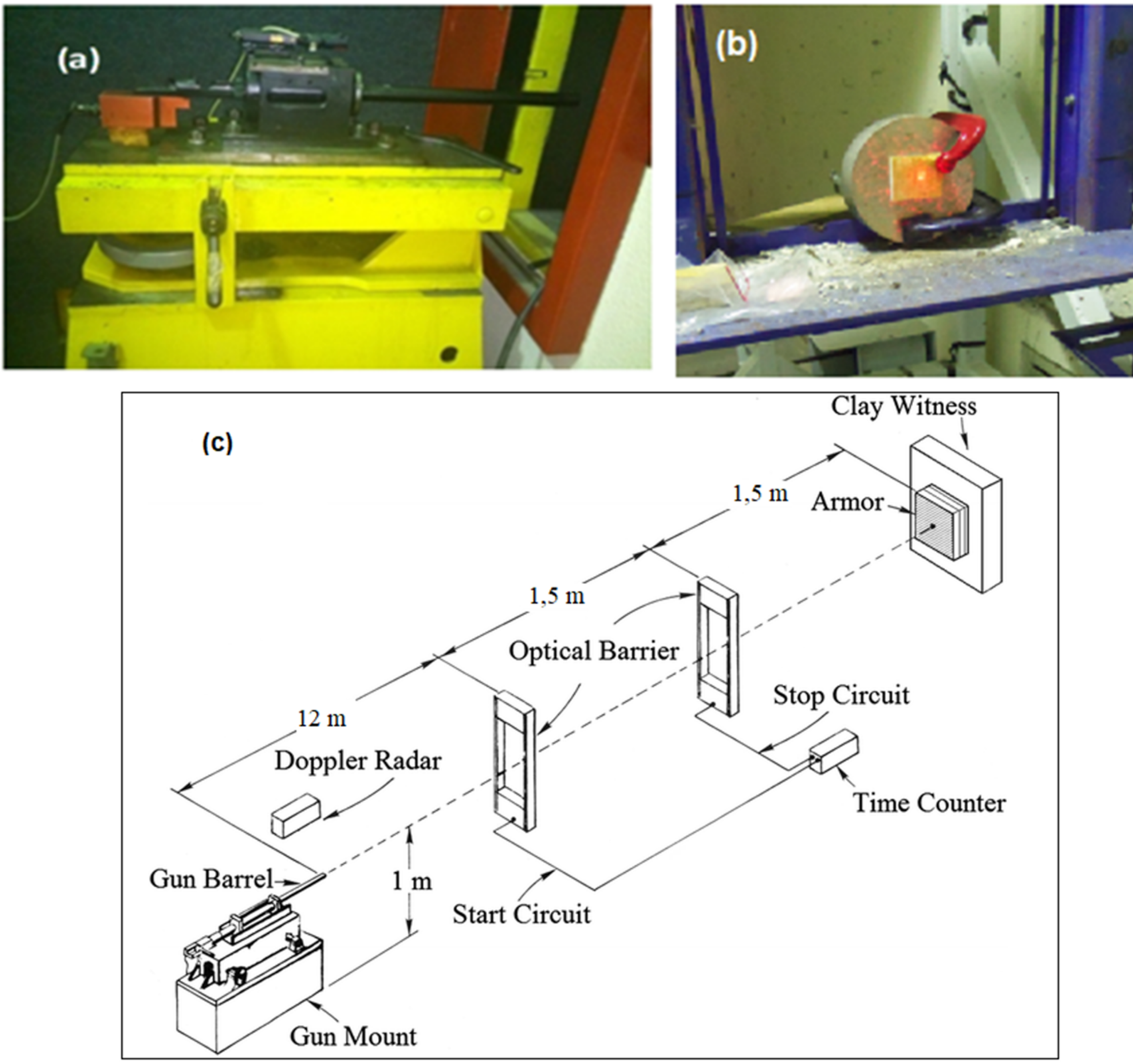


Figure 1. Experimental arrangement of the ballistic test: (a) gun barrel with laser sight; (b) fique composite sample mounted in front of a hollow aluminum block; and (c) schematic view of the ballistic experimental setup.

Where x is the value assumed by the random variable; θ is the scale parameter and β is the shape parameter, also known as Weibull modulus.

3. Results and Discussion

Figure 2 presents a typical Doppler radar reflected image and corresponding processed radar data. 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_i = 867 m/s. Projectile penetration through the target is associated with a vertical (radar blind) straight line at about 0.018 s from the shooting onset. As shown in Fig. 2(b), the projectile emerges from the target (bottom of vertical line) with a residual velocity V_r = 745 m/s. Thereafter, a single decreasing curve indicates that the projectile is intact with continuously decreasing velocity. The values of V_i and V_r, measured in every test, allowed the calculation of the absorbed energy by means of Eq. (1).

Table 2 shows the projectile absorbed energy by the different targets. By considering just the mean values, it might be observed that the type of material influences the absorbed energy, which corresponds to the projectile loss of energy upon its impact against the target.

Based on the results in Table 2 and the reported value of E_{abs} = 262 J for plain polyester plate with same thickness of 10mm[26], Fig. 3 shows the variation of absorbed impact energy, E_{abs}, with volume fraction of fique fibers in polyester composites as target against VIP 7.32mm projectile. In this figure, one may notice the comparatively higher value of absorbed energy for the plain polyester target. This is followed by a marked decrease (~41%) for the 10 vol% fique fiber composite and then a relatively slight decline for 20 and 30 vol%. The largest absorbed energy by the plain polyester

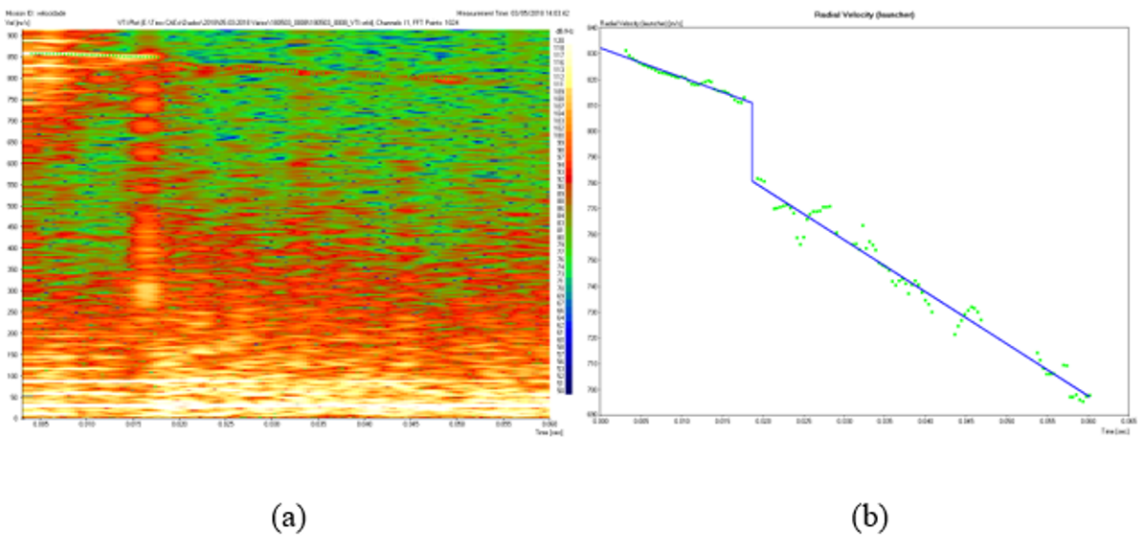


Figure 2. Doppler radar variation of projectile velocity with time from shooting: (a) Windopp fitted projectile radial velocity and (b) treated radar data.

Table 2. Projectile's absorbed energy due to ballistic impact.

	Materials	V_i (m/s)	V_r (m/s)	% E_{abs}	E_{abs} (J)	Reference
	10%	824 ± 6	799 ± 10	4	155 ± 7	PW*
Fiber	20%	824 ± 7	784 ± 9	5	121 ± 11	PW*
	30%	815 ± 3	796 ± 5	4	112 ± 4	PW*
	10%	819 ± 7	792 ± 8	4	154 ± 5	PW*
Fabric	20%	787 ± 15	752 ± 11	6	156 ± 12	PW*
	30%	804 ± 4	794 ± 5	4	97 ± 7	PW*
Aramid fabric		848 ± 6	841 ± 7	1.7	58 ± 29	[25]

* PW - Present Work

in Fig. 3 is due to its accentuated brittle behavior, which causes complete destruction upon the projectile impact in association with larger remaining surface area of fragmented small particles. By contrast, an increasing amount of fique fibers prevents total fragmentation and even maintains the integrity of the composite with 30 vol% fibers.

Figure 4 shows a similar curve of E_{abs} versus volume fraction of fique fabric. The only noticeable difference to Fig. 3 is a slight increase in E_{abs} for the 20 vol% fabric as compared to the other fique fabric composites.

Similar to the 30 vol% fique fiber composite, the 30 vol% fique fabric also maintained its integrity, which can be seen in Fig. 5. In terms of ballistic performance this is an important behavior. Indeed, an armor plate that is not destroyed by the first shooting is able to stand other impacts and continue dissipating energy after multiple shots, as required by standard tests in actual armor vests[1]. As a second layer in a multilayered armor for personal protection this integrity is a major requirement[20,22,28]. A plain polyester plate would not attend this requirement, and it could not be used as second layer.

A relevant point regarding the results in Table 2 is the fact that both 30 vol% fique fiber and 30 vol% fabric polyester composites have a significantly higher E_{abs} than aramid fabric[28]. In other words, the presently investigated composites display a better performance as ballistic armor than Kevlar®.

The Weibull analysis was applied for the values of absorbed energy in order to analyze both fique fiber and fabric polyester composites. Table 3 presents the corresponding Weibull parameters.

As illustrated in the Table 3, the correlation coefficient (R^2) displays values close to or greater than 0.9 for all models studied. This corresponds to a satisfactory data adjustment. Regarding the Weibull's module (β), all values were higher than 3. The higher the value of this parameter, the lower the dispersion in the evaluated absorbed energy and the more reliable the results.

As for the scale parameter (θ), the polyester composites with aligned fiber configuration presented similar values than the polyester composites with laminated fabric, i.e., they dissipated a comparatively greater amount of impact energy from the projectile.

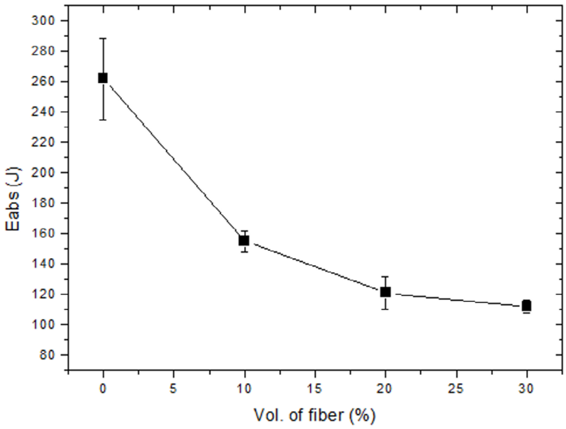


Figure 3. Relation between to the energy absorbed (E_{abs}) and the volume fraction of fique fiber.

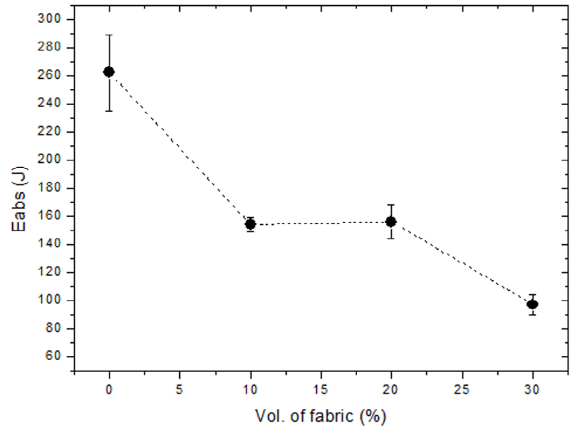
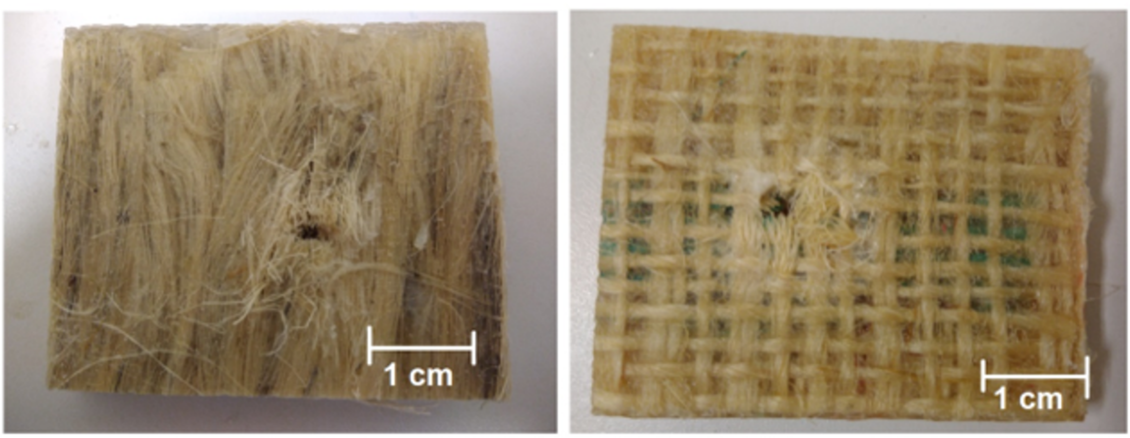


Figure 4. Relation between to the energy absorbed (E_{abs}) and the volume fraction of fique fabric.



(a) (b)

Figure 5. Samples subjected to ballistic impact: (a) fique fiber and (b) fique fabric.

Table 3. Weibull statistical parameters for the value of E_{abs} in ballistic stand-alone tests with polyester composites reinforced with volume fractions of both fique fibers and fabric.

	Intermediate material layer	Weibull modulus (β)	Scale parameter (m/s) (θ)	Correlation coefficient (R^2)
	10%	10.13	158.5	0.98
Fiber	20%	14.68	129.5	0.90
	30%	3.37	109.4	0.89
	10%	7.85	150.4	0.85
Fabric	20%	16.24	161.4	0.91
	30%	4.75	99.7	0.97

4. Conclusions

- Different polyester composites reinforced with 10, 20 and 30 vol% of aligned fique fibers and laminate fique fabric were individually tested by the ballistic impact of VIP 7.62 mm projectiles.
- Both the 30 vol% fique fiber and fabric composites showed an interesting characteristic for multi-hit applications, such as high-energy absorption and good integrity after the impact.
- The ballistic performance of 10 vol% of both fique fiber and fique fabric reinforcing polyester composites is found to be the most effect by dissipating around 150 - 160 J of the impact energy. However, they do not keep integrity after the impact.
- Even polyester composites with 30 vol% of either fique fiber or fabric dissipates around 100 J of the impact energy, which is significantly more than the 58 J dissipate by aramid fabric with same thickness.
- Polyester composites reinforced with both fique fibers and fabrics are potentially able to replace synthetic fabrics, such as Kevlar®, as second layer in multilayered armor systems (MAS) for personal protection. This is justified by the effective fique fiber and fique fiber composites mechanisms of impact energy absorption, as MAS second layer, which are comparable to those of Kevlar®. In addition to the ballistic good performance, the fique fiber and fabric composites are lighter, cheaper and environmentally friendly.

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