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Giant Bamboo Fiber Reinforced Epoxy Composite in Multilayered Ballistic Armor

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The ballistic performance of a multilayered armor with a front ceramic tile backed by a plate of giant bamboo fiber reinforced epoxy composite was assessed. The ceramic layer spalls the projectile, while the bamboo composite dissipates the remaining energy. Ballistic tests were performed with high velocity ammunition and the projectile penetration was evaluated by the intrusion depth in a clay witness. The average depth value of near 18 mm was found well below the limit specified by the NIJ standard of 44 mm and better than that for aramid fabric composite, about 22 mm, with the same thickness of the giant bamboo composite. The giant bamboo composite acts as an efficient barrier for the fragments originated from the ceramic brittle rupture. For practical application in portable armor for personal protection, the layer of giant bamboo composite presents not only a superior ballistic performance but also lightness and economical advantages over the conventional aramid fabric.

Keywords: *ballistic test, multilayered armor, bamboo fiber composite, bullet penetration analysis*

1. Introduction

Personal protection against high velocity (>700 m/s) ammunition, such as the 7.62 × 51 mm caliber bullet, requires a light shielding based on multilayered armor system (MAS) with high impact absorption and resistance to projectile penetration[1]. MAS are usually composed of a harder front ceramic tile with the ability to deform and erode/fracture the projectile[2-5]. Owing to this ceramic frontal layer, a great deal of the projectile energy is dissipated by means of its fragmentation involving mechanisms of nucleation, growth, coalescence and propagation of micro cracks[6]. A second MAS layer backing the ceramic is selected as a lighter composite material, which reduces the impact energy by absorbing part of the blast of fragments from either projectile or ceramic[7]. For this second layer, glass fiber composites have originally been investigated[8]. Aramid fabric such as Kevlar™ and Twaron™[9] as well as ultra high molecular polyethylene (UHMPE) fiber such as Spectra™ and Dyneema™[10,11] are today preferred for the lightweight body armor second layer MAS composites. A MAS system may also include a third metallic layer acting as a final barrier, which restricts the penetration of the projectile or its fragments beyond the maximum standard indentation or intrusion depth of 44 mm, which causes serious injure to a personal body. In some cases, a spall shield is attached on the front of the armor to avoid flight way ceramic fragments[4,5].

As the lighter component of a body armor vest, the intermediate composite layer, usually aramid or UHMPE, is not only intended to provide comfort and mobility to the wearer but also to improve the absorption efficiency of the projectile impact. Lower shock impedance composite like the Kevlar™ standing behind the front interface will cause the proceeding compressive wave to be comparatively lower in transmitted energy. Since the shock impedance is directly related to the material's density, a greater ballistic impact energy reduction should be provided by a comparatively lighter composite backing the ceramic tile[12-15]. The replacement of the aramid fabric by a lower density fiber reinforced composite would be an alternative to improve the impact absorption. A possible candidate might be a lighter polymer composite reinforced with natural fibers obtained from plants, also known as lignocellulosic fibers. In addition to a lower density than aramid fabric, these natural fiber composites are less expensive and regarded as environmentally friendly. Indeed, lignocellulosic fibers are renewable, degradable, recyclable and considered "neutral" with respect CO_2 emissions, responsible for the global warming. With about 55% carbon, they emit a similar amount of CO_2 after degradation as absorbed during cultivation. Furthermore, they are not as energy intensive as synthetic fibers such as glass, carbon and aramid fibers during processing[16]. In the past decades, a great number of works has been dedicated to polymer composites reinforced with lignocellulosic fibers. Several papers reviewed these composites[17-29] that are being applied in industrial sectors, particularly the automotive industry[30,31].

Among the most engineering applied plants, the well known bamboo, with rigid culms, has potential to be used as ballistic resistant material. As any plant, bamboo is basically formed by cellulose microfibrils embedded in hemicellulose and lignin[16-29]. The bamboo culm has a unique microstructure composed of stiff sclerenchyma cells, extending lengthwise as cellulose microfibrils around vessels used to transport water and nutrients. Less dense parenchyma cells surround each bundle of microfibrils and

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vessels, as a soft foam-like matrix[32]. Owing to its relatively low density, 1.03 – 1.21 g/cm^3, and convenient tensile strength, 106-204 MPa[12] the bamboo culm and extracted fiber have been, since long time , used in engineering applications. As an abundant natural resource in tropical and temperate regions, especially Asia and Latin America, bamboo is substituting plastics in civil construction, furniture and lightweight parts of vehicles[33,34]. However, the cylindrical shaped culm limits some direct uses of the bamboo and motivated investigations on bamboo fiber as reinforcement of polymer composites[33-44]. Actually, a bamboo fiber corresponds to many microfibrils (sclerenchyma cells) and vessels, known as vascular bundle, which may be extracted from the parenchyma cell matrix by longitudinal slicing procedure[45]. A stronger specie of giant bamboo (*Dendrocalamus giganteous* Munro) has recently attracted attention for its relevant properties[46-48], including the impact resistance[49].

A systematic investigation on the ballistic properties of natural fiber reinforced polymer composites has already been conducted by Wambua et al.[50]. Relevant information on the ballistic impact velocity and energy related to natural fiber composites was presented by the authors but it was not their scope to assess the performance of natural fiber composites as armor for personal protection.

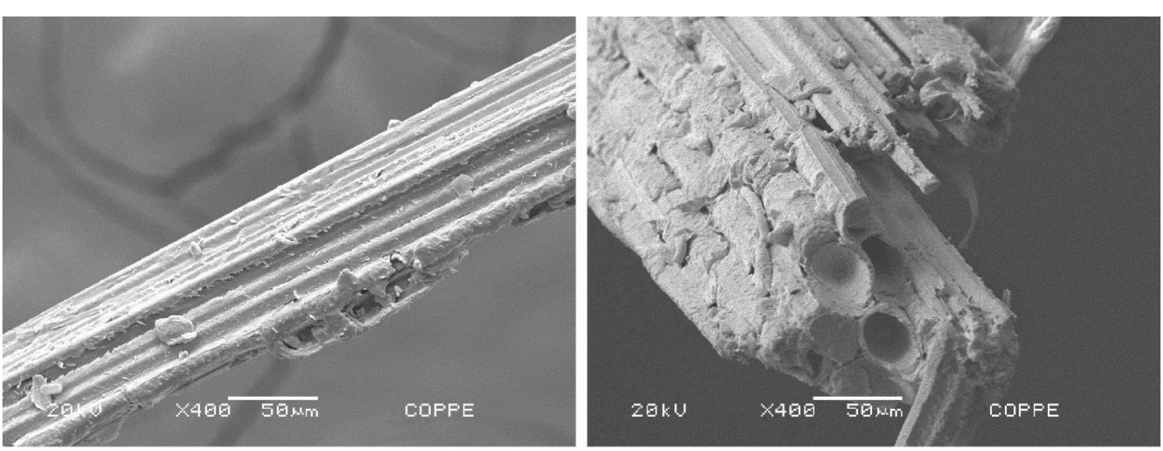
In the present work, the ballistic performance of multilayered armors composed of a front ceramic, an intermediate composite and aluminum layers was investigated in terms of the intrusions caused by the projectile into a clay witness simulating a personal body. Ballistic tests were conducted in MAS's with a front Al_2O_3 ceramic tile. As the following intermediate layer, lighter giant bamboo fiber reinforced epoxy composite plates were compared to plain epoxy plates and aramid fiber plies, all with the same thickness.

2. Material and Methods

The multilayered armor system (MAS) arrangement used in this investigation was the following: the front layer was a 15 mm thick hexagonal tile with 31mm of side dimension made of 4 wt% Nb_2O_5 doped Al_2O_3 brittle ceramic. The ceramic tile was fabricated by sintering Al_2O_3 powder supplied by Treibacher Schleifmittel as commercial purity mixed with Nb_2O_5 powder supplied by CBMM as 99% pro-analysis. Sintering was conducted at 1,400 °C for 3 hour under air in the Ceramic Laboratory of the Military Institute of Engineering (IME), city of Rio de Janeiro, Brazil.

The intermediate layer, with 10 mm in thickness and square sides with 150 mm, was either: (i) 16 plies of aramid fabric, or (ii) a plate of 30 vol % of continuous and aligned giant bamboo fibers reinforced epoxy matrix composite (giant bamboo composite for short), or (iii) a plate of plain epoxy. The aramid fabric plies were supplied by the LFJ Blindagem Com. Serv. S.A., as compressed pieces with very little, less than 1%, epoxy adhesive, as indicated by the supplier. Giant bamboo culms were kindly donated by Prof. Khosrow Ghavami from the plantation existing at the Catholic University of Rio de Janeiro (PUC-Rio). At IME, giant bamboo fibers were smoothly sliced from the culm, starting with a razor and following the continuous tendency to longitudinally separate neighbors vascular bundles. These fibers were obtained with a length corresponding to the extension of the culm, around 15 cm, but with their naturally different diameters. The diameters, average of width and thickness, measured by profile projector, were found to vary from 100 to 700 μm with an average of 400 μm[46]. Figure 1 illustrates: (a) the microstructure of typical thin bamboo fiber with microfibrils and few residual parenchyma cells and (b) the fracture tip of a thicker fiber displaying vascular bundle. No chemical treatment was applied to the individual fibers. Bamboo fibers were dried at 60° C in a laboratory stove for 2 hours and aligned with the correct amount of 30 vol% inside a steel mold. An initially fluid diglycidyl ether of the bisphenol-A (DGEBA) epoxy resin, mixed with a phr 13 stoichiometric fraction of trietylene tetramine (TETA) as hardener, was poured onto the mold. A pressure of 5 MPa was applied and the composite plate cured for 24 hours.

Figure 2 shows: (a) the epoxy composite production scheme with 5 layers of aligned fibers and (b) a finished composite plate. In a similar procedure, plain DGEBA/TETA epoxy plates were also fabricated. The back end-layer was a 150 mm × 150 mm 5052 H34 aluminum alloy (Al) sheet



(a) (b)

Figure 1. The giant bamboo: (a) SEM of a thin bamboo fiber and (b) fracture tip of a thicker bamboo fiber. Source: authors.

with 5 mm in thickness. These layers were bonded together with commercial Sikaflex™ glue from Sika Co.

In direct contact with the Al sheet back end-layer, a block of clay witness simulated a personal body protected by the MAS. The clay witness was warmed to 40°C according to specifications and compressed to avoid air bubbles. The clay was commercially supplied by Americanas Express. The depth of intrusion in the clay duplicates the plastic deformation imposed by the fragments, generated from the projectile impact, on the Al sheet. The corresponding depth, Figure 3, was measured with a special Mitutoyo caliper with an accuracy of 0.01 mm. A minimum of 10 measurements was performed for each depth of intrusion and the values were analyzed by means of the Weibull statistic method. This provided confidence indexes R^2 greater than 0.9. The microstructure of giant bamboo fibers and fracture details of the composites and aramid fabric after ballistic tests were observed by scanning electron microscopy (SEM) in a 6460 LV JEOL and a Quanta FEG 250 FEI microscopes.

Figure 4 illustrates the actual front view of a clamped MAS ready to be ballistic tested. Ballistic tests were carried out at the Brazilian Army shooting range facility, CAEX, in the Marambaia peninsula, Rio de Janeiro. All tests, 10 for each type of MAS, were performed according to the NIJ 0101.03 and NIJ 0101.04 standards using 7.62 × 51 mm NATO military ammunition, with 9.7 g copper projectile shot from a gun barrel.

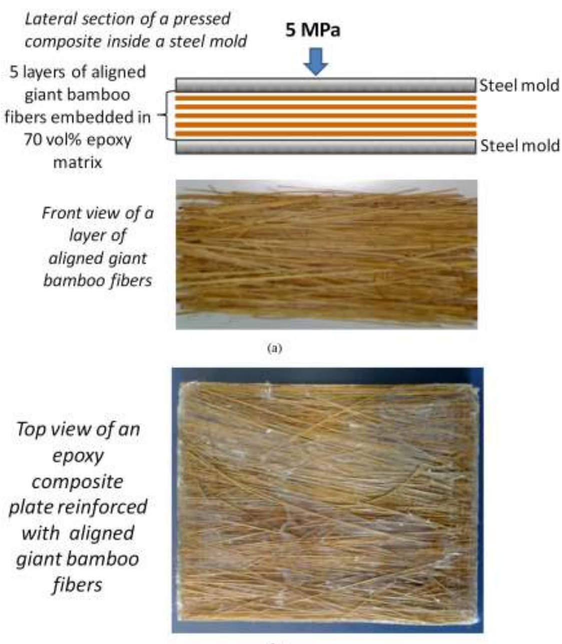


Figure 2. Giant bamboo fiber composite: (a) schematic production and (b) epoxy composite plate. Source: authors.

Figure 3. Measurement of the depth in the clay witness caused by the projectile impact. Source: authors.

3. Results and Discussion

Table 1 presents the average depth of intrusions measured in the clay witness for the different MAS target investigated. In this table, some points are worth discussing. The three materials tested as the intermediate layer that follows the front ceramic layer showed corresponding depth below the NIJ standard 0101.06 limit of 44 mm for serious blunt trauma. Indeed, all ballistic tests conducted in the MAS's failed to

Table 1. Average depth of intrusion in the clay witness backing different multilayered armors.

Intermediate Material Layer	Indentation (mm)
Aramid fabric plies	22.67 ± 2.79
Epoxy composite reinforced with 30% giant bamboo fiber	17.58 ± 1.88
Plain epoxy plate	19.84 ± 1.09

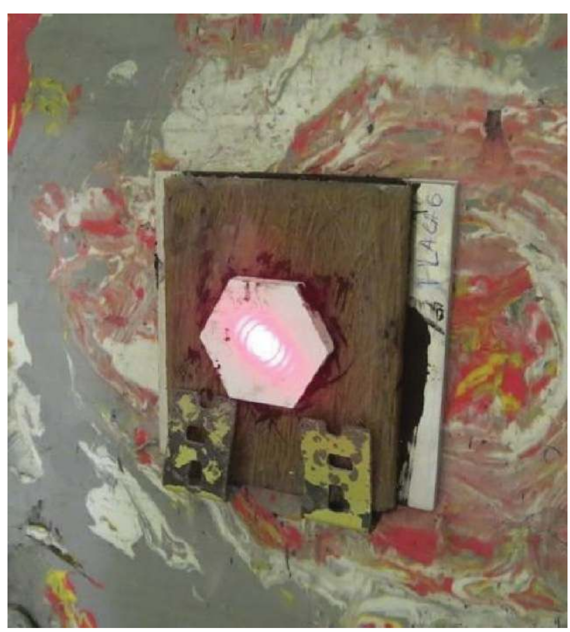
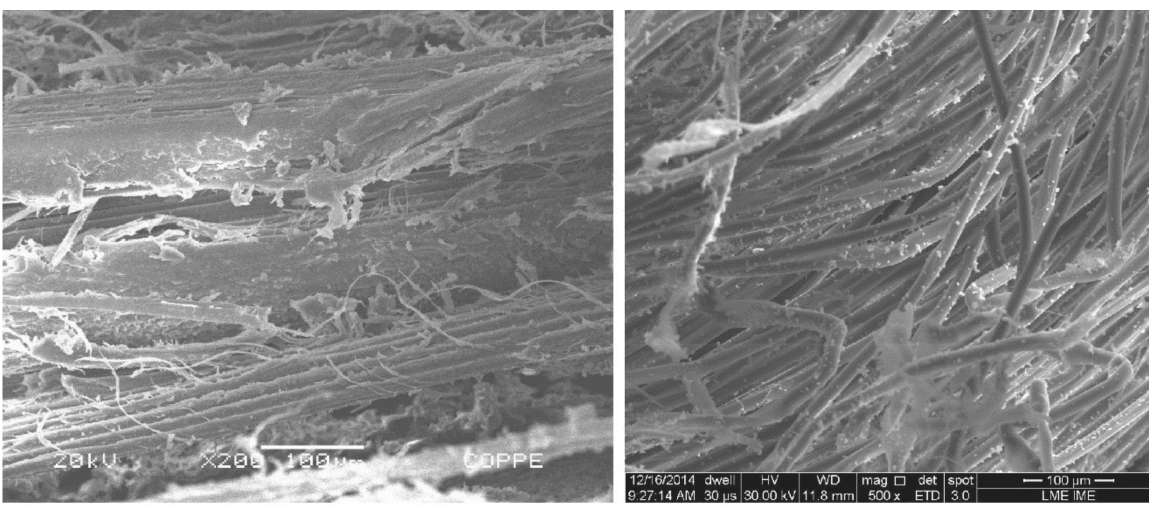


Figure 4. Actual view of a clamped MAS with giant bamboo composite plate ready to be ballistic tested. Laser beam focusing in the center of the ceramic plate as sight. Source: authors.

perforate the target. Consequently, the projectile was always stopped and its kinetic energy was dissipated inside the multilayered armor in association with the depth in the clay witness, as shown in Figure 3. In Table 1, the aramid fabric with 22.67 mm displays the greatest depth in comparison to both the giant bamboo composite with 17.58 mm and the plain epoxy with 19.84 mm.

Within the interval of Weibull precision, the bamboo fiber composite has a statistically smaller depth than the aramid fabric but similar to the plain epoxy. The reason for this behavior can be attributed to a recently proposed mechanism of ballistic fragments captured by the aramid fabric layer[51]. The giant bamboo composite depth corresponds to a 22% better ballistic performance, as compared to the aramid fiber. This is a surprising result since the aramid (~4,000 MPa) is much stronger than the epoxy (~90 MPa) and the giant bamboo fiber (~200 MPa) . However, the capture of fragments and the impact energy absorption by the giant bamboo fiber reinforced composite, Figure 2b, are apparently more effective mechanism than the corresponding in the aramid fabric[51]. Indeed, Figure 5 shows that the composite (a) displays more fragments and decohesion than the aramid fiber (b). Furthermore, the giant bamboo composite is significantly lighter and less expensive than the aramid fabric. These might be considered as practical advantages in favor of giant bamboo composites over aramid fabric plies.

For quantitative discussion, Table 2 presents the parameters that allow a calculation of the weight and cost of each different MAS investigated. Values for the parameters used in this table were given by the suppliers or obtained from the literature[52]. Although the actual Al_2O_3 ceramic used in the armor was a smaller hexagonal tile, for practical condition, its calculated face area was considered covering the whole 15 cm × 15 cm of the target. In Table 2, it should be noticed that the MAS with giant bamboo composite represents more than 4% of decrease in total weight of the armor. In addition, it also corresponds to more than 31% of decrease in total cost. In a real situation, the approximately 22% superior ballistic performance of the giant bamboo composite, Table 1, which is within the NIJ limits, together with 5% lightness and 31% economical advantages, Table 2, favor its substitution for the aramid fiber in a MAS for personal protection.



(a) (b)

Figure 5. SEM of ballistic fracture of (a) giant bamboo fiber reinforced epoxy composite and (b) aramid fabric in a MAS. Source: authors.

Table 2. Evaluation f weight and cost of the different multilayered armors.

Armor component	Volume (cm^3)	Density (g/cm^3)	Weight (kgf)	Price per kg (US dollars)	Component cost (US dollars)
Al_2O_3 ceramic tile	337.5	3.72	1.256	33.00	41.43
Aramid fabric plies	225	1.44	0.324	63.60	20.61
Giant bamboo composite plate	225	1.09	0.245 Epoxy 2.80 (70%)	Fiber 0.74 (30%)	0.53
6061 aluminum sheet	112.5	2.70	0.304	8.50	2.58

Total weight with aramid fabric (kgf)	1.884	Total cost with aramid fabric	64.62
Total weight with giant bamboo fiber composite (kgf)	1.805	Total cost with giant bamboo fiber composite	44.51
% of decrease	4.20	% of decrease	31.1

These comments are restricted to the 7.62 × 51 mm NATO ammunition used in the present ballistic tests.

4. Conclusions

- An epoxy matrix composite reinforced with giant bamboo fiber in substitution for conventional aramid fabric plies, with same total thickness, in a multilayered armor for personal protections attended the NIJ trauma limit after ballistic tests with high velocity 7.62 × 51 mm ammunition.
- The ballistic performance of the giant bamboo composite is 22% superior (lower depth of intrusion in clay witness) than the aramid fabric with the additional advantages of being 4% lighter and 31% cheaper.
- In principle, both technical and economical reasons support the replacement of aramid fabric, as second layer backing the front ceramic in a mass, by giant bamboo reinforced epoxy composite , in which the natural fiber is also environmentally friendly.

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