23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

A NEW CLASS FOR ARMOUR MATERIALS FROM RECYCLED ARAMID

Aline Marques de Oliveira
Viviane Cristina Munhoz
Elvis Carneiro Monteiro
Universidade Federal de Minas Gerais, Graduate Studies Program in Mechanical Engineering, 6627 Antonio Carlos Avenue, Belo Horizonte, Minas Gerais, 31270-901, Brazil.
marqsaline@gmail.com - vivismunhoz@gmail.com - elvis.c.monteiro@hotmail.com

Antonio Ferreira Ávila
Universidade Federal de Minas Gerais, Mechanical Engineering Department, 6627 Antonio Carlos Avenue, Belo Horizonte, Minas Gerais, 31270-901, Brazil.
avila529@hotmail.com

Abstract. *Composite materials are a valuable alternative to conventional ballistic materials due to their high specific mechanical properties. The use of aramid reinforced composites presents one of the best protections to weight ratio for impact applications. However, the high cost of these fibers and the international regulations of replace all bulletproof vests every five years with a proper treatment is a disadvantage. This paper reports new applications for aramid fabrics from discarded bulletproof vests and its application as ballistic shield. The new ballistic composite material is a hybrid laminate, where recycled aramid fibers are consolidated by epoxy resin and the nano-reinforcement are nanoclay particles and two shear thickening fluid (STF), composed of silica nano-particles and nanoclay particles, respectively. Both STF used ethylene glycol as medium to disperse the particles and were diluted with ethanol to improve the fabric wettability. Ballistic tests were performed with two types of ammunition – 9 mm FMJ and 357 Magnum JSP. The results demonstrated an enhancement close to 25% in ballistic penetration resistance due to the addition of STF to the fabrics and indicated that a combination between nanosilica and nanoclay could be a good option for a new type of STF even for recycled aramid fibers.*

Keywords: *composite armour, ballistic performance, shear thickening fluid, recycled aramid*

1. INTRODUCTION

The urban violent growth in large cities, mainly in Latin America, has put security as one of the most important global issues. The increase in trafficking of more powerful weapons and consequent easier access to them emphasized the need to improve the impact resistance of bulletproof vehicles used by security forces. Moreover, the capacity to resist to low and high velocities impacts is an important characteristic not only to the military sector, but many applications require safety structures capable to absorbing large quantities of energy during impact and remain stable.

As mentioned by Ultracki (2010), in mid-70's DuPont introduced Kevlar®, a polymeric fiber based on Poly-paraphenylene terephthalamide that possess high tensile strength and impact resistance, low density and negative thermal expansion coefficient in the longitudinal direction, which guarantee dimensional stability. Kevlar® fibers, are widely used as composite material not only in military protections, but also is employed in aerospace and naval applications where necessary lightweight structures with high mechanical resistance (Mallick, 2007).

According to Abrate (2011), the ballistic performance of a composite focuses on the capacity of energy absorption of structures during an impact. The mainly factors that affect ballistic behavior are: material properties of reinforcement and matrix, the interaction between multiple plies, number distribution and orientation of layers, velocity and projectile geometry. High performance fibers used in ballistic products usually are characterized by low density, high strength, and high energy absorption capability and, according to Silva Junior *et al*. (2004), the use of aramid reinforced composites presents one of the best protections to weight ratio for impact applications. Although aramid (Kevlar®) and ultra-high molecular weight polyethylene (Spectra®) have been introduced as base materials for ballistic protection, the amount of fabrics required to reach the protection requirements for typical ballistic threats and the high cost of these fibers are disadvantages. Moreover, due to international regulations and for safety reasons, all bulletproof vests must be replaced every five years. It is estimated that in Brazil between 75,000 and 100,000 bulletproof vests must be replaced each year. As these bulletproof vests cannot be discarded without proper treatment, a recycling procedure is urgent.

A remarkable solution to the impacts protection is based on composite materials, due to high rigidity and specific resistance values, thereby providing an increase in efficiency of materials and reduction of energy consumption, both of vital importance in structural engineering design considerations (Herakovich, 1998). In order to improve the strength and rigidity of the matrix, nanoparticles can be typically added in composite introducing new properties for the material (Thostenson *et al*., 2005).

Avila *et al*. (2007) studied the addition of nanoclay, a organically modified montmorillonite ceramic, and expandable graphite nanoflakes to fiber glass/epoxy laminates showing an increase on the high velocity impact resistance of such composites and a great influence of failure mechanism once the presence of nanoparticles increased the friction coefficient between projectile and target, inducing an addition deformation to the bullet and increasing the energy absorption. Another research groups have been worked on the application of shear thickening fluid (STF) into aramid fabrics for improving the impact, puncture or stab resistance performances. As discussed by Majumdar *et al*. (2013), these STF's are non-Newtonian fluids which show drastic increase in viscosity beyond a critical shear rate facilitating the impact energy absorption. Lee *et al*. (2003) showed that aramid fabrics impregnated with silica-ethylene glycol based STF results in significant increase in the energy dissipation and it increases with the volume of STF whereas, aramid fabrics treated with ethylene glycol alone absorbs lower amount of impact energy than the untreated aramid fabrics due to decreasing yarn to yarn friction. Kang *et al.* (2012) impregnated Kevlar® fabrics with the STF and investigated the stab and ballistic resistances of those targets. According to them, the energy dissipation percentage (EDP) is related to the percentage of silica dispersed. However, an asymptotic behavior was detected. Thus, to obtain a 96% EDP, the concentration of silica/nanosilica was close to 400%. Majumdar *et al*. (2014) investigated the effect of padding pressure on low velocity ballistic performance of a composite formed by Kevlar® fibers treated with STF based on silica nanoparticles. They reported that higher padding pressure enhances the impact energy absorption by the STF treated Kevlar® fabrics although it does not influence the amount of STF added significantly. Hassan *et al*. (2010) synthesized a shear thickening fluid using a combination of hard metal oxide particles suspended in a liquid polymer in a single step reaction by ultra-sonication. They found that the spike resistance of Kevlar® fabrics increased from 85 N to 573 N after the treatment with STF. Park *et al*. (2012), made panels with different fabric counts of aramid impregnated with STF and tested them against 9 mm bullets at 436 m/s for body armor application. They reported that panels with higher fabric count dissipated a higher fraction of the given impact energy through tensile dissipation and this led to a lower back face signature. Zielinska *et al*. (2014) impregnated fumed silica based STF into para-aramid woven fabric showing a significantly increase in the stab resistance at quasi-static conditions with a reduction in the number of layers of the fabric in the designed system.

So far, most of the scientific work has focused on the synthesis and performance investigation of aramid-STF composites. However, none of them refer to the recycling procedure aramid from bulletproof vests. The objective of this paper is to investigate the ballistic performance of recycled aramid fabrics added of a nanomodified epoxy system and impregnated with two different STF's, as a potential application to protection shields inside patrol cars or shields for Special Forces for protesters containment.

2. EXPERIMENTAL PROCEDURES

2.1 Materials and methods

Aramid fabrics from bulletproof with an areal density of approximately 300 g/m^2 (12.6 oz./yd^2) and new glass fibers that have also the same plain weave configuration and approximately the same areal density have been used in this research. The epoxy system is an amine-cured bisphenol-A-diglycidyl ether epoxy resin and a hardener, triethylenetetramine, both from Barracudatec Inc. The average viscosity is around 1257 cPs and the fiber/epoxy ratio was kept constant and equals to 60 wt.%, while the nano-reinforcements were montmorillonite (MMT) nanoclay (Cloisite 30B), with an average diameter of 8-10 μm, provided by Southern Clay Inc. The nanostructures were incorporated into the epoxy system using two different approaches, i.e. high shear mixing (around 13500 RPM) and sonication at 42 Khz, that combined allow the nanoclay to be exfoliated and uniformly dispersed into the epoxy system.

For the STF were used silica nanoparticles (70-100 nm), in aqueous dispersion, obtained from Nissan Chemicals and dry powder of MMT nanoclay (Cloisite 30B). Ethylene glycol (surface tension = 47.7 dyne/cm) was used in the STF synthesis process as the dispersing medium for the nanosilica and nanoclay particles and was chosen as a solvent due to its low volatility and thermal stability. Moreover, the index of refraction of ethylene glycol is close to that of the silica particles, providing enhanced colloidal stability and it is easily available in bulk quantities, which make it useful for bulk production. Ethanol (surface tension 22.0 dyne/cm) was used to reduce the surface tension and to improve the wettability of the aramid fabrics with STF's. The surface chemical structures of SiO_2 and nanoclay particles were investigated by scanning electron microscopy (SEM). To be able to perform SEM analysis, the ethylene glycol was removed prior to imaging by drying the sample at 200 ^oC for 5 hours, leaving only the nanosilica, MMT nanoclay particles and aramid fibers. The microphotographs were taken using an FEG Quanta 200 FEI SEM.

The STF's composition was selected to provide discontinuous shear thickening properties. STF1 was prepared dispersing spherical silica nanoparticles with an average diameter of 70-100 nm in ethylene glycol and the particles concentration was set to 60 wt.%. The nanosilica concentration follows the Park *et al*. (2013) suggestion and some previous experiments. STF2 was prepared by dispersing the nanoclay in ethylene glycol and the particles concentration was set to 20 wt.% (saturation limit based on previous experiments). The ethylene glycol and the particles were firstly hand-mixed to obtain a homogeneous fluid at the desired concentration. To facilitate the impregnation of the STF's into the aramid fabrics, ethanol was added to the original STF's at the mass ratio of 1:1. Finally, samples were sonicated at 42 KHz for 30 minutes and then stirred at a speed of 1200 RPM for 30 minutes to disperse the particles. Neat recycled aramid fabric was impregnated manually by immersion with the diluted STF dispersion and then dried at 80 ^{o}C until the weight of the specimen reached a constant value.

The first target group was made by five types of plates that were cut to 300 mm x 400 mm. They were fabricated using a hand lay up process for laminated composites. Plate 1 consisted in 24 layers of recycled aramid fibers and 40 wt.% of epoxy resin and a hardener covering all fibers extension. Plates 2 and 3 consisted in 12 layers of recycled aramid fibers intercalated with 12 layers of new glass fibers and 40 wt.% of epoxy system. For plate 3 the epoxy system was nanomodified uniformly dispersing nanoclay particles through a high shear mixing (around 13500 RPM) and sonication at 42 Khz. Plates 4 and 5 consisted in 36 layers of recycled aramid fibers which were laminated using the epoxy system, respectively, at 10 wt.%, covering only the edges and 40 wt.%, covering all fibers extension.

The second target group was made by plates, which were treated with STF systems. Two sets of 12, 18 and 24 aramid layers were cut approximately to 240 mm x 150 mm and impregnated, with 70 wt.% of STF1 and 70 wt.% of STF2. To prevent leakage of STF out of the target assembly and because aramid is known be sensitive to moisture, heat-sealed polyethylene film, which doesn't provide any measurable ballistic resistance, was used to encapsulate the targets. Eight pieces of approximately 300 mm x 210 mm of recycled aramid fibers were used to encapsulate the targets using a hand lay up process for laminated composites. The targets were assembled between two hard shells (four layers of aramid/epoxy with 60/40 mass ratio) forming a "tea-bag" like configuration.

The followed sequences used for both target groups are showed at Fig 1.

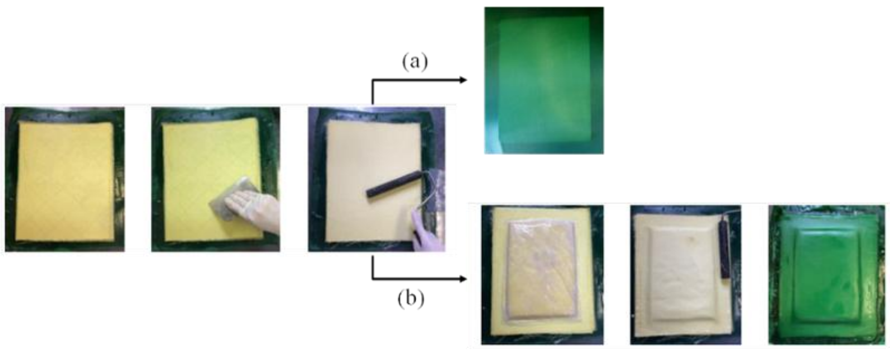


Figure 1. Steps to the preparation of plates containing recycled aramid fibers, i.e., (a) types 1, 2, 3, 4 and 5 and (b) recycled aramid fibers previously treated with STF.

The hybrid composites were arranged into multilayer targets, as shown in Tab 1.

Table 1. Plates characteristics.

First target group		Second target group	
P1	(Epoxy system) 40wt% + 24 layers of aramid fibers	P6	STF1 70wt% of fibers + 12 layers of aramid fibers
P2	(Epoxy system) 40wt% + 12 layers of aramid fibers intercalated with 12 layers of glass fibers	P7	STF1 70wt% of fibers + 18 layers of aramid fibers
P3	(Epoxy system + 5wt% nanoclay) 40wt% + 12 layers of aramid fibers intercalated with 12 layers of glass fibers	P8	STF1 70wt% of fibers + 24 layers of aramid fibers
P4	(Epoxy system) 10wt% + 36 layers of aramid fibers	P9	STF2 70wt% of fibers + 12 layers of aramid fibers
P5	(Epoxy system) 40wt% + 36 layers of aramid fibers	P10	STF2 70wt% of fibers + 18 layers of aramid fibers
-	-	P11	STF2 70wt% of fibers + 24 layers of aramid fibers

2.2 Ballistic tests

The ballistic tests were performed according to the NIJ-STD 0101.04 (1985). Hence, an oil-based clay (Roma Plastilina No.1) witness of 130 mm thickness backed with removable plywood was used as a backing material to measure the depth of indentation. Each target panel (300 mm x 210 mm) was held to be in full contact with the backing material and secured to the backing material fixture using a strip of adhesive tape. To validate the test results, both pre-drop and post-drop tests were conducted on the conditioned clay with a 1.043 kg steel sphere at the height of 2 m. All tests were performed at room temperature for a type II classification, thus two types of ammunition are considered, i.e. 9 mm Full Metal Jacketed (FMJ), consisting of a metal cylinder of 8.0 grams and 9.02 mm diameter, and 357 Magnum Jacketed Soft Point (JSP), consisting of a metal cylinder of 10.2 grams and 9.1 mm diameter. The impact velocity of each projectile was measured with a chronograph immediately before impacting the target and is showed at Tab. 2 as well the energy of each impact.

Table 2. Projectiles information.

Test ID	Type	Mass [g]	Speed [m/s]	Energy [J]	Test ID	Type	Mass [g]	Speed [m/s]	Energy [J]
1	9 mm FMJ	8.0	349.00	487.19	20	9 mm FMJ	8.0	355.09	504.36
2	9 mm FMJ	8.0	353.57	500.04	21	9 mm FMJ	8.0	359.05	515.68
3	357 Magnum	10.2	427.33	931.31	22	9 mm FMJ	8.0	352.35	496.6
4	357 Magnum	10.2	421.23	904.93	23	357 Magnum	10.2	407.52	846.96
5	357 Magnum	10.2	420.32	901.01	24	357 Magnum	10.2	427.02	929.99
6	9 mm FMJ	8.0	358.14	513.06	25	357 Magnum	10.2	427.94	933.97
7	9 mm FMJ	8.0	353.26	499.18	26	357 Magnum	10.2	441.35	993.43
8	9 mm FMJ	8.0	349.91	489.75	27	9 mm FMJ	8.0	365.46	534.23
9	357 Magnum	10.2	422.45	910.18	28	357 Magnum	10.2	417.88	890.58
10	357 Magnum	10.2	429.46	940.64	29	9 mm FMJ	8.0	363.93	529.78
11	9 mm FMJ	8.0	351.43	494.02	30	357 Magnum	10.2	418.19	891.88
12	9 mm FMJ	8.0	348.69	486.34	31	357 Magnum	10.2	419.1	895.79
13	9 mm FMJ	8.0	353.26	499.18	32	9 mm FMJ	8.0	359.05	515.68
14	357 Magnum	10.2	424.59	919.4	33	9 mm FMJ	8.0	365.15	533.34
15	357 Magnum	10.2	430.38	944.65	34	357 Magnum	10.2	438.3	979.76
16	9 mm FMJ	8.0	356.62	508.7	35	9 mm FMJ	8.0	356.92	509.57
17	9 mm FMJ	8.0	364.85	532.45	36	357 Magnum	10.2	426.72	928.66
18	357 Magnum	10.2	426.72	928.66	37	9 mm FMJ	8.0	363.02	527.12
19	357 Magnum	10.2	432.21	952.69	38	357 Magnum	10.2	410.26	858.4

To avoid the edge effect, the shot locations at panels were over 76 mm away from the target edges (Fig 2). Once the tests were performed the damaged areas were measured by image processing using the public domain software ImageJ 1.64 (2006).

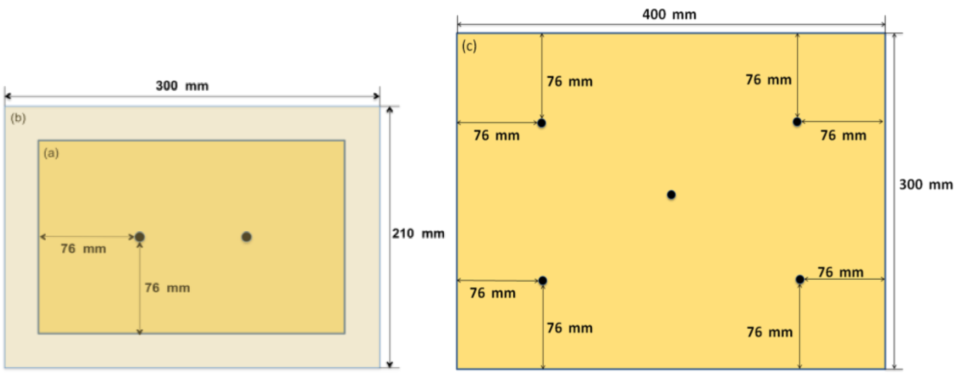
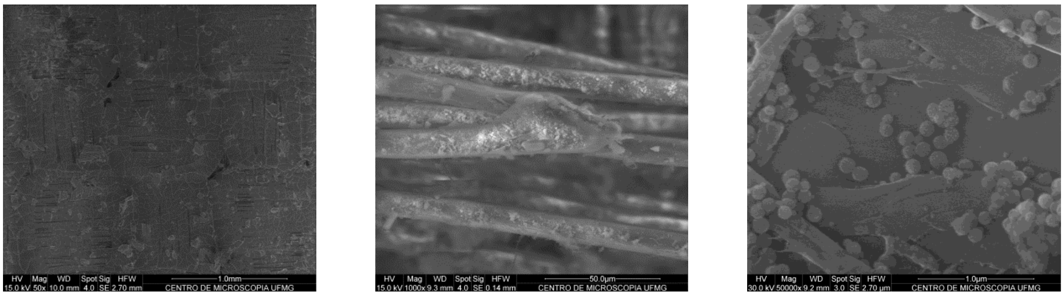


Figure 2. Shot locations at the ballistic impact tests. (a) Encapsulated aramid fibers impregnated with STF and (b) external fibers laminated with epoxy system without STF; (c) Fibers laminated with epoxy system without STF.

3. RESULTS AND DISCUSSION

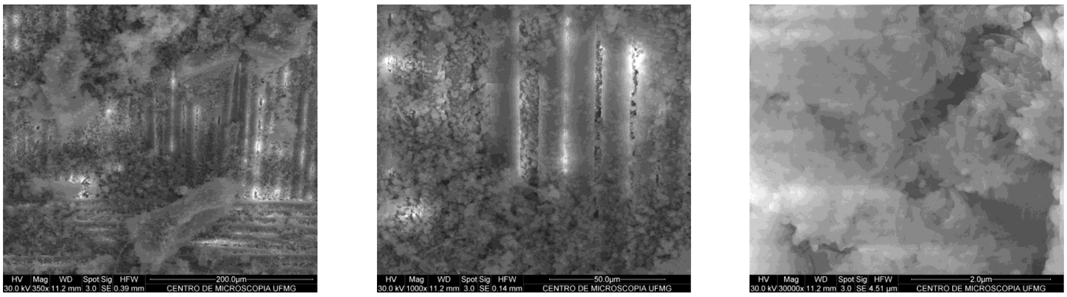
3.1 Surface characterization of nanosilica and nanoclay particles

SEM analysis was performed to investigate the nanosilica and nanoclay surfaces. The SEM micrographs presented in Fig. 3 and Fig. 4 show pictures of STF1/aramid and STF2/aramid composite samples at different magnifications. Figure 3a clearly shows that STF1 is well dispersed over the entire surface on the aramid sheet; it can be seen in Fig. 3b that STF is fully incorporated between the individual aramid fibers within each yarn. Moreover, no nanosilica agglomeration was detected (see Fig. 3c). For the SFT2 was observed a different morphology, instead of a fully dispersed fiber/nanoparticles, the STF2/aramid system formed large concentrations of MMT clusters surrounding the fibers. Figure 4a show this phenomenon. In addition to such phenomenon large concentration of MMT clusters are formed (Fig. 4b) in a dense morphology (see Fig. 4c). From the morphology point of view, denser nanostructures will offer more resistance to penetration. To confirm or reject such hypothesis, a ballistic test must be performed.



(a) (b) (c)

Figure 3. SEM microphotographs of the surface of recycled aramid fabrics impregnated with STF1. (a) Fiber/STF1 overview; (b) nanosilica/fiber impregnation; (c) nanosilica dispersion.



(a) (b) (c)

Figure 4. SEM microphotographs of the surface of recycled aramid fabrics impregnated with STF2. (a) Fiber/STF2 overview; (b) MMT/fiber impregnation; (c) MMT agglomeration.

3.2 Ballistic properties of hybrid composites

Tables 3 and 4 summarize the data obtained after each fire test. Each damaged area was measured by image processing technique; at least 6 measurements were performed. The delaminated area, back (BA) and front (FA), its ratio μ (BA/FA), and the back elastic deformation (BED) were measured. Projectile impact and delamination areas, which according to Silva Jr. *et al*. (2004), are the most common mechanism of energy absorption, were observed. The existence of perforation was also detected. To be able to identify possible internal damage, e.g. fiber damage, delamination of the hard shells (the four outer layers on both sides of the aramid/STF system), a thermal analysis using a thermo-camera was performed (Tab. 5 and Tab. 6).

As it can be observed at Tab. 3 and Tab. 5, for the first target group, 24 layers rigid plate – P1, was able to hold a 9 mm FMJ projectile but 357 Magnum pass through the plate, showing that the increase of plate hardness deteriorates its ballistic performance when compared with the bulletproof vest which the aramid fabrics are soft. The BED measurements for P1 were 35.3 and 39.8 mm for 9 mm projectiles. These values agree with Minas Gerais State Police Standards (2015), once a new bullet proof vest with 24 layers of aramid fibers with diagonal seams must have BED between 17 and 25 mm for the 9 mm FMJ projectile and between 25 and 36 mm for the 357 Magnum. In all cases, if the BED is equal or larger than 44 mm the bulletproof vest is rejected.

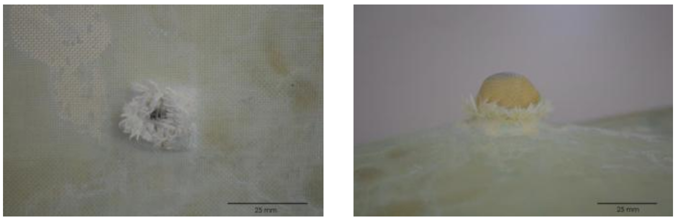
P2 and P3 were able to hold only a 9 mm FMJ projectile fired at the middle of the plate among the three others 9mm FMJ projectiles that were fired. In addition, all the 357 Magnum projectiles have passed through the both plates. The thermograms with localized damage for these two plates are showed at Tab. 5. This plates contains about a half layers of aramid fibers than a common bulletproof vest, therefore were expected an reduction on the ballistic resistance, but even with less resistance, the addition of nanoclay particles allowed to hold a 9mm FMJ projectile with a BED of 16,3 mm while without the nanoclay particles, the BED was 18,5 mm. Both values are in compliance to Minas Gerais State Police Standards (2015).

P4 and P5 were made using 36 layers of aramid fibers; however the epoxy system application covers only the edges of P4 and all the surface of P5. Hence, P4 is a soft plate at the middle whereas P5 is a rigid plate. As the amount of aramid fibers is higher than in a common bulletproof vest, this plate was able to hold all fired projectiles, with BED's according to Minas Gerais State Police Standards (2015). However, P5 wasn't able to hold two of four faired 357 Magnum, due to its hardness, but is important to notice that the test 26 was above the reference velocity of NIJ standard. It can be noticed that for all faired 9mm FMJ and 357 Magnum that was hold the BED values are according to Minas Gerais State Police Standards (2015).

As it can be observed at Tab. 3 and Tab. 4, for the 12 layers plate with SFT1 (nanosilica), P6, the two projectiles (9 mm and 357 Magnum) went through with high localized damage. The FA and BA areas are small, notice that due to

357 Magnum projectile designs the back area damage was bigger. This fact was expected as described in Carr *et al*. (2014), 357 Magnum is an projectile with a soft point flat nose which mushroomed forcing more debris out. Although the 12 layers was not enough to hold neither 9 mm and 357 Magnum, the nanoclay particles seems to generated a larger damage due to its densification as can be seen on the thermograms from Tab. 6.

The 18 layers STF systems (with STF1 or SFT2) presented distinct behavior, i.e. one was capable of sustain the ballistic impact and the other no. The STF1 was able to disperse enough energy and avoid the perforation. As it can be notice by the damaged area and the thermal signature, the damage inside was extensive, which explain the no perforation. The BED measurements for the 18 layers-STF1 system were 25.3 and 32.5 mm for 9 mm and 357 Magnum projectiles, respectively (see Fig. 5a and Fig. 5b). Notice that for 9 mm FMJ projectile the BED result is close to upper limit commonly observed by Minas Gerais State Police Standards (2015) and some issues must be addressed. First, the number of layers is 25% less the original one; it is a recycled aramid fiber (at least five years old); the original one has seams in diagonal holding all fibers while the tested systems do not have it. The internal damage for the 18 layers/STF2 system was also extensive but not enough to hold neither of the two projectiles. It seems that although the MMT densification was good enough to dissipate a large area of damage, the energy dissipation was not enough to avoid perforation.



(a) (b)

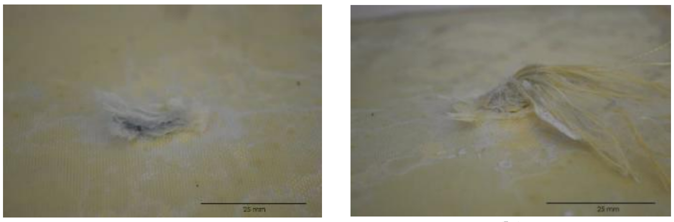
Figure 5. 18 Layers + STF1 system. (a) 9 mm back face; (b) 357 Magnum back face.

When the 24 layers + SFT systems were tested another interesting phenomenon was observed. The 24 layers + STF1 system was able to hold a 357 Magnum projectile but 9 mm FMJ projectile pass through the plate. Two are the possible reasons for such behavior. First, the 357 Magnum project was fired initially, which brought large internal damage to the plate, and when the 9 mm FMJ projectile was fired, the internal damage was big enough to let the projectile go through. As consequence of such large internal damage the out layers edges delaminated and a complete separation was observed. Figures 6a-c identify the 9 mm FMJ and 357 back faces and the out layers damage on edges.

(a) (b) (b)

Figure 6. 24 Layers + STF1 system. (a) 9 mm back face; (b) 357 Magnum back face; (c) Target failure (out-layers on edge).

The 24 layers + STF2 system was able to withstand the 357 Magnum projectile but not a 9 mm FMJ. Again the explanation to this phenomenon is the projectile design. The 9 mm FMJ is traditionally a perforation projectile, which brings the idea of localized damage, while the 357 Magnum is damage intensive projectile due to the mushroom effect caused by the hollow point configuration. Figures 7a-b show the two back face damage caused by the 9 mm FMJ and the 357 Magnum.



(a) (b)

Figure 7. 24 Layers + STF2 system. (a) 9 mm back face; (b) 357 Magnum back face.

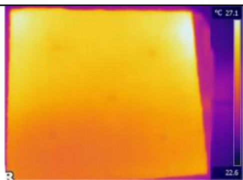
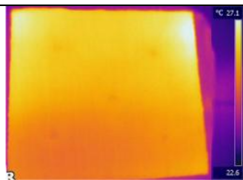
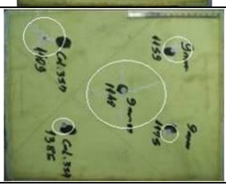
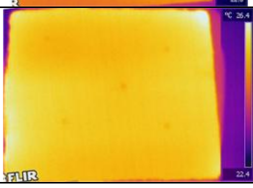
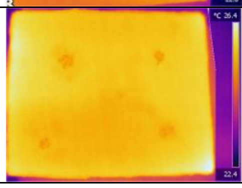
Table 3. Ballistic test results.

Test ID	Plate ID	BED [mm]	Perforation
1	P1	35,3	NO
2	P1	39,8	NO
3	P1	-----	YES
4	P1	-----	YES
5	P1		NO
6	P2	-----	YES
7	P2	-----	YES
8	P2	18,5	NO
9	P2	-----	YES
10	P2	-----	YES
11	P3	-----	YES
12	P3	-----	YES
13	P3	16,3	NO
14	P3	-----	YES
15	P3	-----	YES
16	P4	12,0	NO
17	P4	19,0	NO
18	P4	25,5	NO
19	P4	24,3	NO
20	P5	20,8	NO
21	P5	14,2	NO
22	P5	17,0	NO
23	P5	19,0	NO
24	P5	32,7	NO
25	P5	-----	YES
26	P5	-----	YES
27	P6	-----	YES
28	P6	-----	YES
29	P7	25,3	NO
30	P7	32,5	NO
31	P8	33,0	NO
32	P8	-----	YES
33	P9	-----	YES
34	P9	-----	YES
35	P10	-----	YES
36	P10	-----	YES
37	P11	-----	YES
38	P11	62,0	NO

Table 4. Damaged areas.

Test ID	Plate ID	FA [mm^2]	BA [mm^2]	μ
1	P1	6057,45	15142,39	2,50
2	P1	11226,44	8354,18	0,74
3	P1	5218,72	6407,50	1,23
4	P1	11775,28	8878,10	0,75
5	P1	18977,04	17388,27	0,92
6	P2	249,68	10846,79	43,44
7	P2	2632,79	11307,20	4,29
8	P2	10611,17	18620,95	1,75
9	P2	200,55	6105,20	30,44
10	P2	4436,53	8332,82	1,88
11	P3	353,90	3859,75	10,91
12	P3	16013,54	16886,67	1,05
13	P3	8368,93	16090,87	1,92
14	P3	575,62	5345,59	9,29
15	P3	1743,15	9087,46	5,21
16	P4	10635,04	1059,85	0,10
17	P4	16329,23	2210,25	0,14
18	P4	17723,68	28743,53	1,62
19	P4	20297,58	31844,48	1,57
20	P5	3718,81	1421,17	0,38
21	P5	1774,24	3727,44	2,10
22	P5	5851,62	1387,72	0,24
23	P5	6324,04	1572,13	0,25
24	P5	3314,84	1717,06	0,52
25	P5	2019,68	5223,01	2,59
26	P5	293,38	4470,41	15,24
27	P6	364,79	2717,18	7,45
28	P6	567,05	5284,70	9,32
29	P7	5993,89	4932,27	0,82
30	P7	16348,57	19482,08	1,19
31	P8	4204,91	9946,97	2,37
32	P8	3043,05	1792,18	0,59
33	P9	2094,45	1503,78	0,72
34	P9	2957,80	3748,26	1,27
35	P10	3995,10	1986,39	0,50
36	P10	6726,06	5798,90	0,86
37	P11	3161,81	2199,61	0,70
38	P11	4779,44	9416,39	1,97

Table 5. First target plates group (photos and thermograms) after ballistic tests showing front and back sides.

ID	Front	Front – Thermo	Back	Back – Thermo
P1				
P2				

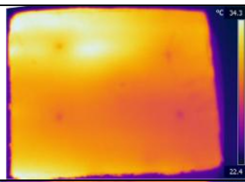
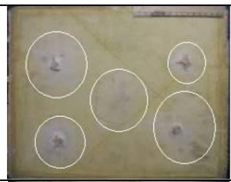
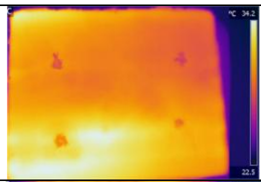
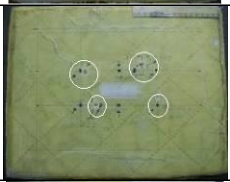
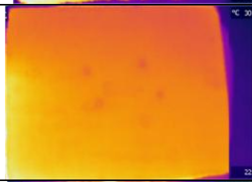
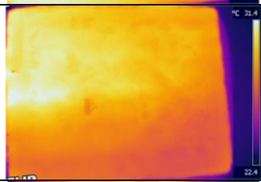
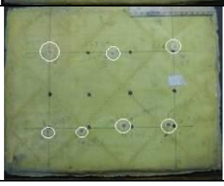
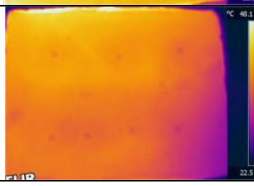
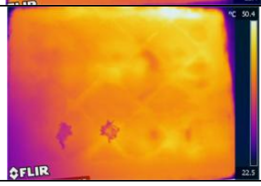
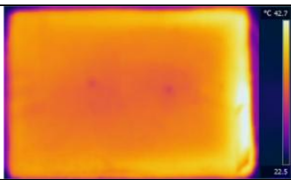
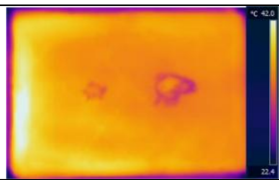
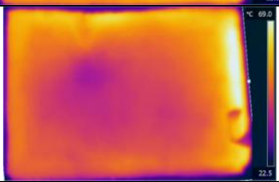
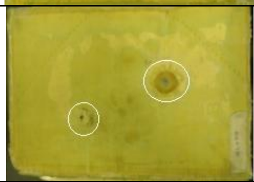
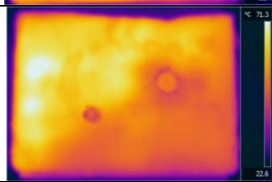
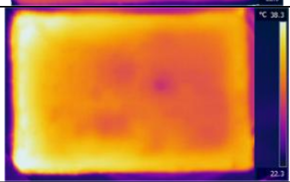
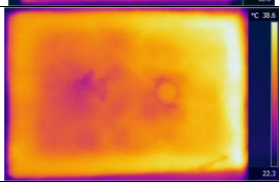
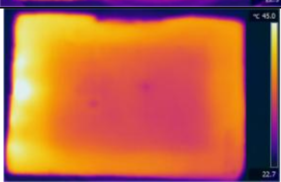
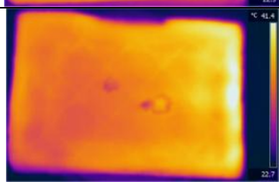
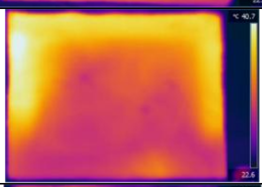
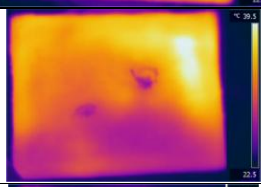
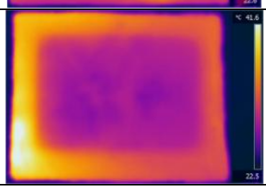
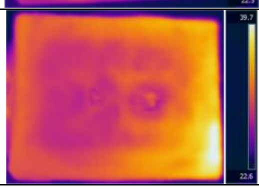
P3				
P4				
P5				

Table 6. Second target plates group (photos and thermograms) after ballistic tests showing front and back sides.

ID	Front	Front – Thermo	Back	Back – Thermo
P6				
P7				
P8				
P9				
P10				
P11				

4. CONCLUSIONS

The investigation on recycled aramid fibers from bulletproof vests was performed. The addition of nanostructures, i.e., nanoclay particles and shear thickening fluid systems, allowed these fibers to stand impact from 9 mm FMJ and

357 Magnum projectiles. The nanomodified epoxy system improved the failure mechanism and damage areas on the plates, despite of only the increase on the plate hardness, even with the addition of a nanomodified epoxy system, is not enough to dissipate the energy from all the fired projectiles. The STF systems employed were based on nanosilica and nanoclay particles. It was observed that although the fibers are at least five years old, without seams to hold the entire group of fibers, the STF systems provided enough energy dissipation that it was possible to decrease the number of aramid layers into 25% and keep the same ballistic protection. The usage of nanoclay as STF provided a broader damage into the STF + aramid fibers systems which were contained by four layers of out layers of aramid epoxy composite materials. The results obtained, so far, indicate that a possible combination between nanosilica and nanoclay could be a good option for a new type of STF even for recycled aramid fibers that become possible the usage of recycled aramid fibers associated to STF systems as a viable option for ballistic shields and ballistic protection systems for patrol car, for example.

5. ACKNOWLEDGEMENTS

This research was supported in part by the Brazilian Research Council (CNPq) under grants number 304646/2014-8 and the Air Force Office of Scientific Research grant FA9550-14-1-0377. The authors are grateful to the UFMG's Center of Microscopy and Microanalysis for the technical support. Finally, we would like to express our gratitude to all personnel involved during the ballistic tests at Minas Gerais State Police Department.

6. REFERENCES

Avila, A.F., Alves, M., Azevedo, R.L. An investigation on nanocomposites behaviour under ballistic impact. In: 16th international conference on composite materials. 2007.

Carr, D., Kieser, J., Mabbott, A., Mott, C., Champion, S., Girvan, E. Damage to apparel layers and underlying tissue due to hand-gun bullets. International Journal of Legal Medicine, Vol. 128, No. 1, pp. 83-93, 2014.

Hassan, T.A., Rangari, V.K., Jeelani, S. "Synthesis, processing and characterization of shear thickening fluid (STF) impregnated fabric composites". Materials Science and Engineering A, Vol. 527, pp 2892-2899, 2010.

Herakovich, C. T. Mechanics of fibrous Composites. New York, USA: John Wiley & Sons, Inc., 1998. 460 p.

Kang, T.J., Kim, C.Y., Hong, K.H. "Rheological Behavior of Concentrated Silica Suspension and Its Application to Soft Armor". Journal of Applied Polymer Science, Vol. 124, pp 1534-1541, 2012.

Lee, Y.S., Wetzel, E.D., Wagner, N.J. "The ballistic impact characteristics of Kevlar® woven fabrics impregnated with a colloidal shear thickening fluid". Journal of Materials Science, Vol. 38, pp 2825-2833, 2003.

Majumdar, A., Butola, B.S., Srivastava, A. "Development of soft composite materials with improved impact resistance using Kevlar fabric and nano-silica based shear thickening fluid". Materials and Design, Vol. 54, pp 295-300, 2014.

Majumdar, A., Butola, B.S., Srivastava, A. "Optimal designing of soft body armour materials using shear thickening fluid". Materials and Design, Vol. 46, pp 191-198, 2013.

Mallick, P. K. Fiber-Reinforces Composites: Materials, Manufacturing, and Design. Third edition. [S.l.]: Taylor & Francis Group, 2007.

NIJ Standard 0108.01 "Ballistic resistance protective materials." U.S. Department of Justice, National Institute of Justice, Washington DC, pp 1-16, 1985.

Park, J.L., Yoon, B.I., Paik, J.G., Kang, T.J. "Ballistic performance of p-aramid fabrics impregnated with shear thickening fluid; Part II – Effect of fabric count and shot location". Textile Research Journal, Vol. 82, No. 6, pp 542-557, 2012.

PMMG – Minas Gerais State Police Department . Minimum requirements for bullet proof vest performance evaluation. PMMG Internal Report and Standards. 2015.

Rasband W. ImageJ 2006. < http://imagej.nih.gov/ij/>.

Silva Junior, J.E.L., Paciornik, S., d'Almeida, J.R.M. "Evaluation of effect of ballistic damaged area on the residual impact strength and tensile stiffness of glass- fabric composite materials." Composite Structures, Vol. 64, No. 1, pp 123-127, 2004.

Thostenson, E. T., Li, C., Chou, T-W. "Nanocomposites in context". Composites Science and Technology, Vol. 65, No. 3-4, pp. 491-516, 2005.

Ultracki, L. A. Rigid ballistic composites (Review of literature). NRC Industrial Materials Institute. Canadá, 2010.

Zielinska, D., Delczyk-Olejniczak, B., Wierzbicki, L. Wilbik-Hałgas, B., Struszczyk, M.H., Leonowicz, M. "Investigation of the effect of para-aramid fabric impregnation with shear thickening fluid on quasi-static stab resistance". Textile Research Journal, Vol. 84, No. 15, pp 1569-1577, 2014.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.