Ballistic tests on packs made of stratified aramid fabrics LFT SB1

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Abstract. Ballistic experiments are fundamental for body armor new products and help to identify key factors influencing the damage processes of sophisticated materials these armors are made of. Tests made on packs made of LFT SB1 according to Ballistic Resistance of Body Armor NIJ Standard-0101.06-2008 gave good results for the packs made of 24 layers of this fabric and the backface signature (BFS - the depth of the deformation generated in the support material - ballistic clay) was measured. The average value of 23.11 mm recommends this system for protection level of II and IIA, according to the above-mentioned standard. Macro photography investigations pointed out the penetration process in both slim pack (with total penetration) and thick packs (with partial penetration).

1. Introduction
Ballistic experiments are fundamental for body armour new products and help to identify key factors influencing the damage processes of sophisticated materials these armours are made of Abrate [3], Ünaler [31] and Safta [25].

Industry for ballistic protection is a competitive succession of patents for projectile and protection system [6]. The requirements for ballistic protection systems are many, sophisticated and adapted for offering mobility, resistance against certain threats, an imposed safe index, a good ration between price and performances. The target resistance to an impact when it has been hit by a projectile has become of interest in several major fields of activity of the mankind: military, aerospace, nuclear and civil engineering [28].

The ballistic tests are crucial for introducing a new solution, for understanding the complex processes of the penetration, for identifying the key parameters influencing the impact resistance, both for body armours [15], [25] and protection plates [2]. The challenge between projectile and target intensifies the research work on both subjects. Even if the modelling and simulation have become close to reality of ballistic impact [21], the experimental work has to be the final step to introduce new materials, to prove that the protecting system is functional. The bullets are still a major threat for life and physical integrity of solders, police officers and even for civilians. There are many variable parameters describing a bullet, including mass, speed, shape, materials for core and jacket etc. There is practically impossible to design an individual protection system offering total safety against any existing bullet, taking also into account the limitation of this system mass [25].

The fabrics, woven or unidirectional are introduced as layers in stratified structures designed to protect against ballistic impact. At low speed, even glass fibers could have satisfactory results, but for
higher speed and for a better protection of the human body, the aramid yarns are better characteristics [8].

In order to assess the ballistic impact resistance of the protection packs, there are reference standards proposing method of testing and evaluating the results, as, for instance, NIJ Standard-0101.06/2008 [6]. For packs having as destination a body armor, the standards require the absence of the total perforation and a limitation of the deformation generated in the support material and the packs have been hit. The standard Ballistic Resistance of Body Armor, NIJ Standard-0101.06, U.S. Department of Justice Office of Justice Programs National Institute of Justice, 2008 [1] gives a maximum values for this deformation, named the backface signature (BFS), of 44 mm, this being considered as extreme for the vulnerability of the human body.

Any theoretical results and simulation has to be validated by experimental work. Due to experimental work, researchers have identified new mechanisms of energy absorption during the impact on ballistic fabrics [22], types of failure and they could quantify the influence of many factors on the ballistic response of a system. Some experiments pointed out the change in the material behaviour under high speed of deformation [4], [13], [14], [30].

Colakoglu et al. [10] reported the performances of composites made of Kevlar 29/polyvinyl butyral and polyethylene, used for light armors, as determined by experimental tests, but also by numerical models. BFS, simulated and experimental, were close, but the limit velocities were different: for the pack made of Kevlar 29/polyvinyl butyral, \( V_{50} = 680 \) m/s and for the pack made of polyethylene, \( V_{50} = 480 \) m/s.

Specialised literature offer information on testing fibers [5], [9], [11], yarns [5] and fabrics [17], [23], for one layer or multiple layers, for different arrangement of the yarns (unidirectional [16] or woven). Initially, tests are done on small packs, then on packs with dimensions imposed by regulations and, finally, on the protection equipment as it will be delivered.

Luan et al. [18] noticed that the initial shape of the pack made of stratified fabrics is pyramidal and then it becomes conical, its asymmetrical aspect depending on the anisotropy of the fabrics. Carr [7] studied the fabric failure with the help of SEM investigation. Sun et al. [29] used steel balls with velocities up to 1000 m/s to impact Kevlar fabrics and concluded that the materials having a higher velocity of the transversal waves are more favorable for dissipating the impact energy as the stress and strain propagate faster to the enamouring yarns. Shockey et al. [27] reported numerous experimental data on ballistic impact on fabrics, including load evolution, dependence stress-strain, the absorption of energy, the residual velocity and the influence of fabric characteristics on the ballistic resistance and evidenced failure mechanisms of the fibers. Their research with work included tensile test on yarns, low impact tests on fabrics and tests with gas gun on aircraft shells for evaluating the energy absorption. Cumniff [12] has a database for different materials (nylon, Kevlar, Spectra etc.) and projectiles (cylindrical, spherical, ogival) and the material they are made of (tungsten and steel) and a relationship between \( V_{50} \) and the residual velocity and other impact parameters. Shim et al. [26] investigated the impact on Twaron fabrics by spheres of 12 mm, for different impact velocities and impact angles and concluded that for low impact angles and velocities, a slippage of the projectile occurs along the fabrics, helping to dissipate more energy.

For ballistic resistance, tests could be grouped in laboratory tests, tests with standard procedures and tests on the finite product.

The experimental tests offer an important and reliable source of information and they help to validate theoretical approaches [19], [20].

This research has as objectives to test stratified composites made of aramid fabrics type SB1, supplied by Teijin Aramids, sewed on lateral sides, in order to supply information on the protection level as introduced by Ballistic Resistance of Body Armor NIJ Standard-0101.06-2008 [1]. The paper analyses the deformations caused by the impact in the back support (ballistic clay) and evaluates this parameter.
2. Materials and test method
Light weight packs were obtained with 8, 16 and 24 layers for LFT SB1 (Table 1, Table 2), respectively, by sewing on two lateral sides of packs having 500 mm x 500 mm each. A SEM investigation on the cut section of a pack is given in figure 3. They were tested with 9 mm FMJ (full metal jacket) bullet at the laboratory of Scientific Research Centre for CBRN Defence and Ecology, using a ballistic barrel (velocity of 400...410 m/s). All tests conditions were the same for all packs and fires were repeated for each packs.

![Diagram of bullet impact](image)

**Figure 1.** Measuring method for BFS [1]

**Table 1.** Characteristics of fabric LFT SB1

| Main application | Linear density \([\text{d tex}_{\text{nom}}]\) | Twaron grade | Mass for unit area \([\text{g/m}^2]\) | Construction |
|------------------|-----------------|--------------|-----------------|--------------|
| individual armor | 930 f1000        | 2040         | 220             | 2 layers of de Twaron fabrics (0 and 90 orientation) + 3 layers of PE film |

**Table 2.** Calculated mass of the tested packs

| Pack made of | Number of layers | Calculated mass of the pack \([\text{g}]\) |
|--------------|------------------|---------------------------------|
| LFT          | 8                | 440                             |
| SB1          | 16               | 880                             |
|              | 24               | 1320                            |
The test program aims to evaluate these individual protection packs under the impact of bullets of 9 mm FMJ, with the help of laboratory fires according to the standard Ballistic Resistance of Body Armor, NIJ Standard-0101.06, U.S. Department of Justice Office of Justice Programs National Institute of Justice, 2008 [1]. The impact velocity (just before hitting the target) was measured with the help of a system including a chronograph Oehler model 43, stable for the temperature range of 5-40°C and having an accuracy of 0.3 %. Other measurement devices used for these tests were: rigid support for ballistic barrel; a ballistic barrel for bullets of 9 mm FMJ (fulfilling the requirements of NIJ 0101.04/2000); hygrometer with an accuracy of 1%; barometer with an accuracy of 1 mm Hg; thermometer with an accuracy of 1°C; box for the ballistic clay; oven, allowing for tempering at 20 ± 5°C; firing table with compensated kick.

Test conditions were: temperature: 19...23 ± 5°C; relative humidity: 50 - 70%; atmospheric pressure: 760...764 ± 15 mm.

The box for the ballistic clay has a metallic frame for making easier the clay levelling and the dimensions 610 mm x 610 mm x 140 mm ± 2 mm. The clay grade was Roma Plastilina no. 1. After the fire, the projectile or their fragments were removed from the clay. The clay was added anytime needed, after measuring the backface signature (BFS).

These tests were done taking into account the American standard NIJ 0101.04/2004 [1] (figure 1), and STANAG 2920: the projectile was a bullet of 9 mm FMJ, initial velocity being measured in the range of 400 - 420 m/s, and the target was fixed at 3 m (normal conditions). All fires were done in the specialized laboratory of CCSACBRNE, by specialized personnel.

The backface signature was measured with a depth calipers, having the accuracy of ±0.1 mm. After each measurement, the calipers were cleaned for avoiding eventually adhered clay on the active measuring element. All measure needed for personnel protection and safe were taken.

The pack behavior was evaluated by the number of failed (broken) layers and by the values of Back Face Signature (BFS). Figure 1 presents the method of measuring the depth of the impact deformation within the support material.

3. Results

Table 1 presents the values of BFS for the packs made of 24 layers of LFT SB1 and figure 3 gives this information on a plot with the maximum admitted value of BFS from NIJ Standard-0101.06:2008 [1] in order to point out that the designed packs is far from the admitted limit for BFS (44 mm). These results could offer the possibility of reducing the number of layers for this type of fabrics, but still to
fulfil the requirement of NIJ Standard-0101.06:2008. This reduction in weight of the pack has to be tested for each number of layers of the future pack.

Table 3. BFS for packs made of 24 layers of LFT SB1

| Pack symbol | Fire 1 | Fire 2 | Fire 3 |
|-------------|--------|--------|--------|
| I           | 24     | 22     | 21     |
| II          | 21     | 27     | 31     |
| III         | 23     | 22     | 23     |
| IV          | 19     | 24     | 21     |
| V           | 22     | 26     | 24     |
| VI          | 17     | 23     | 26     |

Figure 3. BFS for packs made of 24 layers of LFT SB1

Figure 3 presents the values of backface signature (BFS) for the tested packs made of 24 layers of fabrics LFT SB1. The bold line for 44 mm is the accepted limit for BFS according to NIJ Standard-0101.06-2008 and one may notice that the BFS values suggest a further decrease of the layer number without overpassing this limit but tests are necessary to confirm this idea. The average value for BFS, $\bar{Y}$, for a number of fire $N = 18$, is

$$\bar{Y} = \frac{1}{N} \sum_{i=1}^{N} Y_i = 23,111 \text{ mm}$$

$Y_i$ being the value of each BSF (given in figure 1). The results recommend the packs made of 24 layers of LFT SB1 for a protection level II and IIA.

A study has been done for evidencing the failure mechanisms of fabric layers and yarns. Figure 4 presents the frontal view of the packs made of 24 layers of LFT SB1. There was obtained a partial penetration with the failure of the first 6 layers of the packs. The details in figure 5 give the images of each layer. These photos underline the uniform behavior of the packs when the fire is repeated three times on the same pack.
**Figure 4.** View of pack (sample III) made of 24 layers of LFT SB1
On layer 1, the local break of the yarns is noticed and the orifice made by the bullet is smaller as compared to the observed orifices on the following layers (see, especially the third layer and the following ones).

On layer 2, the passing orifice is small and there are 4 broken main yarns on the front of this layer. Layers 2 and 3 have the shape of the orifices very similar, indifferent of the fire (1, 2 and 3). These layers dissipate the energy, also by their friction with the other layers in contact. Analysing the size of the orifices, one may presume that, from layer 2 to layer 4, their greater size is caused by the bullet deformation.

On layer 5, the pull-out process of the yarns becomes visible. The orifice becomes greater also because the secondary yarns are laterally pushed by the bullet during its flattening process. One may notice that the yarns/fibers are elongated, meaning a lower shear rate (caused by a smaller velocity of the bullet). From this pack, in the layer 6 there were found the bullets from fires 2 and 3; the bullet from fire 1 was found on the surface of layer 7 (see detail in figure 5).

On layer 7, one may notice traces of compressing process of the bullets, without the break of the yarns. These traces are visible also on the front of the layer 8. Each trace has a shape almost circular because of the fabric architecture (the first sublayer has the yarns oriented perpendicular to those of the second sublayer, commonly coded 0/90), and not pyramidal, as reported for woven orthotropic fabrics.

Figure 5 shows that, for this type of fabric, the repeated fires on the same pack, have, as result, similar penetration holes on each layer and it could be concluded that, for this type of fires (three on a pack), at a distance of at least 100 mm one from another, the fabric has a similar response.

The following photos were taken with the help of optical microscope OPTIKA, model SZM-A1, having a camera connected to a computer using the soft OPTIKA Vision Lite 1.04. The calibration was done with the help of a line having units of 0.01 mm.

Figure 6 presents details of the orifice made in one of the packs made of 8 layers of LFT SB1. For this packs the penetration was total for all the fires. On the front face of layer 1, 4 yarns are broken (the so called main yarns) on the front sublayer, but also 4 yarns are broken on the sublayer visible on the back of the same layer 1 (remember that a layer is formed by two sublayers, with yarns oriented at 0 and 90° one to each other.

On the back of layer 1, one may notice a yarn failure similar to that obtained on the model of impacting a yarn with a 9 mm FMJ bullet [24], that is the break of the yarn, not in the central zone of

![Layer 6](image1)

![Layer 7](image2)

![Layer 8](image3)

**Figure 5.** Photos of the perforated layers for the packs made of 24 layers of LFT SB1
the impact, but somewhere between the central point and the impact perimeter. The failed main yarns are broken on the same side of the penetration and there were counted maximum 4 yarns (some are partially destroyed. The secondary yarns (the yarns next the main broken ones) are not laterally pushed, as one may notice on the following layers. On the layers VII and VIII, the yarns have the fibers spatially spread but the yarns have some fibers broken and the others only put away and the broken ones are destroyed in different positions zone. For the layer 4 and the following, the yarns are not completely broken, as one may notice on layers 1, 2 and 3 and the location of the broken fibers are different. The yarns on layer 5 and the following ones are like a bow and there is visible the pull out of the yarns resulted from the bullet forcing the yarns in its moving direction.

For the packs made of 24 layers of LFT SB1, the orifice details are given in figure 7. The layers 1 and 2 are resemble to layers 1 and 2 from the pack with 8 layers and this could assume that the initial stage of the impact process is less dependent of the number of layers of the pack. The orifice has been generated by breaking 4 yarns, too, on the layer 1. For the pack with 8 layers, starting from layer 5, the yarns are tangled on the layer back and have the bow aspect and on the back of layers 4 and 5 the pull-out of the yarns could be noticed.

On layer VII (figure 7) from the pack made of 24 layers of LFT SB1, one may notice only a yarn partially broken only on the front sublayer of the fabric (approximately half of the fibers of the yarn were broken, the other main yarns being only pushed away), the displacement of the yarns on the back sub-layer being less. On the front side of the layer VIII, one may notice the compression of the polyethylene film, but the yarn arrangement is not disturb.

![Figure 6](image_url)

**Figure 6.** Details of the orifice done in a pack with 8 layers of LFT SB1 (total penetration)
4. Conclusion
This study underlines the necessity of testing ballistic protection packs against a certain threat in order to assess their resistance to this specific threat. Tests made on packs made of LFT SB1 according to NIJ Standard-0101.06-2008 gave good results for the packs made of 24 layers of this fabric and the BFS was measured. The average value of 23.11 mm recommends this system for protection level of II and IIA, according to the above-mentioned standard.

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