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ASPECTS OF BALLISTIC PANELS MADE OF UNIDIRECTIONAL ARAMID FABRICS, TESTED AGAINST 9 mm FMJ PROJECTILE

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Abstract: *This paper presents aspects of designing personal armors against ballistic attacks. The study presents tests on relatively new materials on the protective system market. There are pointed out aspects of experimental results. This type of study could reduce design and testing costs and time for the development of new protection systems through numerical simulations and preliminary tests loops. Because of the complexity of materials involved in fabricating ballistic armors or panels, but also because of the complexity of processes that occur at very high speeds, the tests to evaluate ballistic protective systems are very diversified in the laboratory, but they all end with tests on the finished product, under very close conditions of use. By carrying out a loop procedure of developing individual protective systems, the results obtained can be applied by end-users, economic and governmental organizations, which by the nature of their activities, require high-performance, lightweight and cost-effective ballistic protection systems.*

Keywords: ballistic protection, 9 mm FMJ, quadriaxial aramid fabric, BFS (backface signature)

1. About Body Armor

War has been and still remains an escalation of economic and social conflicts, and the protection of soldiers, civilians and military equipment is an activity that is 'intertwined' with the development of destruction [1, 2]. The dynamics of these conflicts, from those of antiquity to the contemporary variants, which includes terrorism, also involve exposure to high-velocity threats (bullets, fragments of projectiles from explosions, etc.) or lower velocity impact of cutting/stabbing elements.

Body armor is designed to absorb, mitigate or deflect physical attacks [3, 4].

Academia and researchers have been working to improve individual protective materials, one argument being the importance of protecting police, justice personnel, not just military personnel. In the field of personal protection research, access to information is different from civilian fields of activity. There is classified information, but also information available as reports, articles, brochures from manufacturers of semi-finished and finished products, standards and regulations at national level,

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at economic alliances (such as the European Union) or military alliances (such as NATO), communications from users from military, police and justice or academia [4].
Individual armour [5-7] may be flexible or rigid (using inserts of rigid materials or plates of steel, Aluminium, ceramic or polymers of high impact resistance).
Today wars have been developing in different ways, from direct confrontation to combinations of economic, military and informational attacks and defence or/and counterattacks imply a fast and efficient action. Any war participant tries to preserve the human resources and equipment; thus, protection should be a weapon itself [9], generating of alternating development of weapons and protections against them.
Better protection for personnel and equipment increases the chances of a successful intervention, as it also increases psychological support for the personnel.
The discovery of high-strength organic fibres revolutionised the concept of personal protective equipment, as can be seen from the bibliographic references [10-13].
Unlike other areas, the evaluation of body protective equipment is done in terms of "totally stops the projectile" or not. If, for specified projectiles, the equipment stops them and also meets other conditions, such as material deformation within certain limits, under certain environmental and temperature conditions, the equipment has good quality. The emergence of another type of threat (another projectile) will obviously involve further testing and re-design of the equipment to withstand this new threat. The moral wear of this type of equipment depends largely on threats it has to face and the rate with which industry is able produce, on a convenient scale, new materials and equipment, and less on economic issues.
Experimental studies on personal protective equipment were reported in [14-18]. Hybrid metal-ceramic-polymeric composite armour is still under study, although some solutions have already been put into service. These armors use hard ceramics for the face plate, and the metal plate serves as a structural element and a fragment pick-up element. A composite polymer material is also used to capture any splinters that might pass through the metal plate.

2. Developing New or Re-Engineered Solutions for Body Armors

The performance of a protection system depends on both used materials and their geometric and technological arrangement. The design and optimization of protection systems can be accelerated in terms of cost and time by going through the scheme in Figure 1, through an interdisciplinary approach, as there is a tendency to replace the design - test - redesign process with faster iterations of modelling and simulation and reducing the (design - simulation - test - prototype redesign) time.

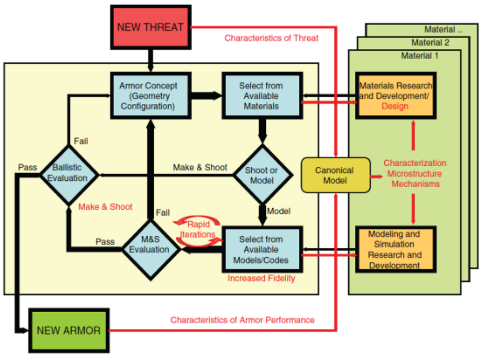


Figure 1: Diagram of stages in developing a protection system [19]

Standards and test programs are the basis for approving a new product in this field. When manufacturers wish to achieve compliance with certain standards for their product, and the protective system contains original materials or new design solutions not anticipated by standards, the specialists who developed the standard can modify the test methods to take these into account [20].
The scheme for developing a new protection system involves coupling knowledge from materials, manufacturing technology, simulation and testing. This approach can address the issue of restricting the information flow in this field. The

components of the protection system may not have a high degree of novelty, but the resulting protective system may be original.

3. Experimental Methodology

3.1. Materials for the Panels

Ballistic packages can be built from a single type of material or from two or more types combined. The placement and number of layers of each type in the architecture of ballistic package influences its ballistic performance. Many solutions for personal armors imply combinations of ballistic materials and the term hybrid armor is adequate. Thus, it is very difficult to compare these solutions only taking into account the number of failed layers of the ballistic panel or the ratio of damaged depth and the entire thickness of the protective structure. More effective is to compare the attack effect on a backing support that assimilates the effect of the hit on the human body, as backface deformation (BFD) in the American standard in force now [21], synonymous with former backface signature (BFS) in the former standard [22].

The way in which the ballistic package is assembled into a unitary whole differs from one manufacturer to another. The tested panel were sewed on two sides, on a line at 10 mm from the panel edge.

Twaron LFT SB1 and LFT SB1plus are produced continuously on rolls, which leads to better handling during manufacturing and provides a more economical variant to create ballistic panels. By using lamination technology, an advanced constant temperature pressing process, it has been possible to create a surface that provides a soft textile material. Ballistic fabrics can be used individually or in combination with resins or other materials [23].

3.2. Test Method

The projectile velocity just before the impact was measured with the help of a chronograph Oehler 43. A fast camera FastCam SA4 was used to film the impact and frame from these films were extracted. The backing support was Roma Plastilina no.1, as recommended by [22]. The print in the ballistic plastiline was measured with a depth vernier calliper (accuracy of ±0.1 mm) [22].

Environmental conditions were: temperature 21±5°C, atmospheric pressure: 764 ±15 mm Hg, relative humidity: 60%.

Fires were carried out from a table for the ballistic barrel, for the selected ammunition, 9 mm FMJ. Distance between barrel nose and the target was 5 m. For reasons of cost, access to equipment and accuracy, any study of ballistic impact protection performance takes a statistical approach, based on a limited number of shots.

The designer has to test and analyze whether the ballistic panel could face a certain type of ammunition, and if so, to select the fabrication process that is most technically and economically advantageous, especially in large series of products.

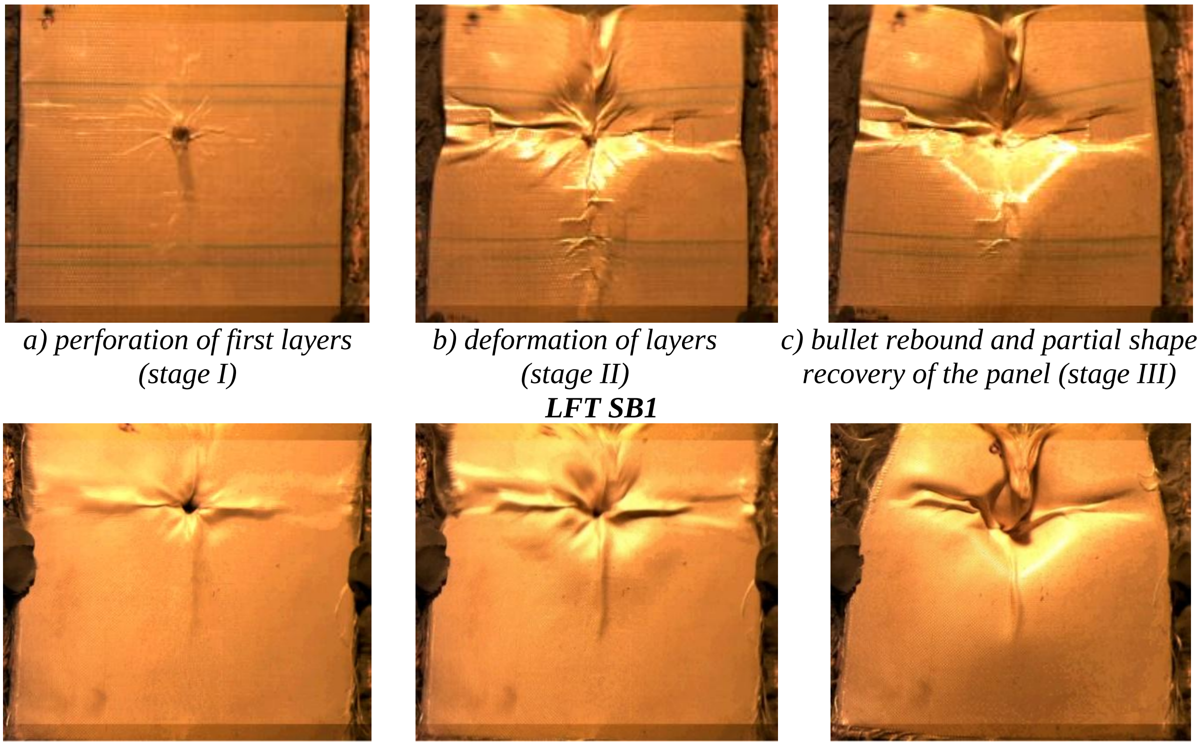
4. Results on Testing Flexible Panels Made of Unidirectional Aramid Fabrics

Taking into account reference works [25-27], the following stages were identified on the fast camera recorded movies.

- Stage I consists of deformation and energy dissipation mechanisms; kinetic momentum transfer between bullet and panel generates an increase of the kinetic energy of the panel, visible as a pyramidal or conical deformation (depending on the architecture of the fabrics in the panel). The fibers within yarns begin to elongate as the longitudinal wave propagates along them (statistical process). The bundle grip influences the friction between the wires and their reorientation, which is a significant energy dissipation process.

Table 1: Fabrics prepeg characteristics [23]

Material (prepeg)	Linear density [$dtex_{nom}$]	Twaron	Mass for surface unit, [g/m^2]	Design
LFT SB1	930 f1000	2040	220	2 layers of Twaron fabrics + 3 PE foils
LFT SB1plus	930 f1000	2040	430	4 layers of Twaron fabrics + 5 PE foils



a) perforation of first layers (stage I) *b) deformation of layers (stage II)* *c) bullet rebound and partial shape recovery of the panel (stage III)*

LFT SB1

d) perforation of first layers (stage I) *e) deformation of layers (stage II)* *f) bullet rebound and partial shape recovery of the panel (stage III)*

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Figure 2: Imagines during the impact of two different panels with 9 mm FJM (fast camera with 4500 frame/s) [26]

- Stage II consists of main yarns (fibers) failure (breakage, pull-out), the projectile advancing in the panel being influenced by friction; one or more yarns may be pulled out of the fabric and an amount of energy is dissipated by the friction; yarn pulling-out promotes the fabric opening process, with the bullet pushing the already broken main yarns and the secondary ones sideways. The weave architecture (here, quadriaxial) could favor maintaining the compactness of the panel (by stitching or sparse braiding with other types of fibers, thus keeping the areal density of the fabric).

- Stage III is considered a post-impact one, for non-penetrating impact, where the bullet is stopped in the panel. For total penetration, it could be considered starting when all layers are broken, but the bullet advances and stresses the broken fibers especially by bending (generating the so-called whipping effect).

Depending on projectile (materials, mass and shape) and impact parameters (velocity, kinetic energy), these stages may be differentiated in appearance and duration.

There are also other energy dissipation mechanisms, including bullet deformation, local thermal energy, acoustic energy, air entrainment, transverse deformation of the yarn, and friction between yarn fibres and between yarns.

Figure 3 presents layer 1 and layer 5 of the panel made of 12 layers SB1 plus, after being tested, with details of the hit location for all the three fires.

Analyzing panel with 12 layers of LFT SB1plus and those with 24 layers of LFT SB1, one may point out the differences [26]:

- bullets are arrested on the layer 5 for LFT SB1plus and on layer 8 for the panel made of LFT SB1,
- the fabrics quality (for both of fabrics) is pointed out by the fact that bullets were stopped on the same layer of the tested panel,
- the largest differences of BFS among successive hits on a panel made of 12 layers of LFT SB1 plus is 2…7 mm and 3…10 mm for the panels made of 24 layers of LFT SB1,

a) front view of layer 1 *b) Frontal view of layer 5, sample III*

Figure 3: Photos of the layers of interest (layer 1 and layer the bullet is stopped on) and details of the hits, for the panel with 12 layers of LFT SB1plus.

Table 2: Comparison data

Panel	BFS [mm]			Theoretical mass, [g]
	Average	Upper value	Standard deviation	
24 layers of LFT SB1	23.11	27.49	3.14	1320
12 layers of LFT SB1plus	19.44	25.93	4.65	1290

- analyzing the characteristics of BFS in Figure 5, it is obvious that LFT SB1plus offers a better protection,
- the time for producing the panels will be different: cutting, weighing will be shorter as time operations, but sewing the panel could be more difficult for LFT SB1plus,
- the difference in panel cost due to fabric type could not be analyzed as the rolls were supplied as research materials.

Table 2 presents several characteristics for both panels. Taking into account the average of BFS, it was obvious that LFT SB1plus could offer a better protection in term of lower values for the average BFS. The upper values and the standard deviation of BFS are close, but the average value is in the favor of quadriaxial aramid fabric. Even the theoretical mass of the panels has only a very small difference of 30 g. The

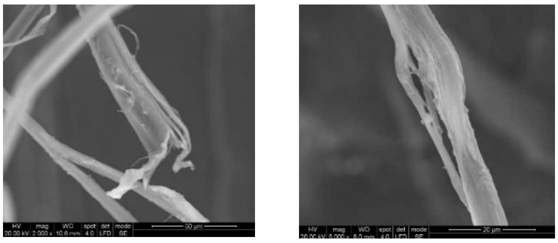
difference would be given by the reduced time for manufacturing the product.
A recent trend in improving the response of aramid fabrics to ballistic impact is to use 3D architecture of yarns [25, 27], but fabrics with multiaxial directions of yarns are also intensively used for the body armor structure, due to the fact that the strength of the yarns is not "wasted" in bending when they cross over the other yarns in woven 2D or 3D fabrics. Of course, the technological solution of this pre-pegs has to use adequate films between sublayers and auxiliary yarns for maintaining pre-peg structure.
This study presents aspects of testing particular panels made of 12 layers of LFT SB1 plus and 24 layers of LFT SB1 (having theoretically close mass, Table 2), when they were hit with a 9 mm FMJ projectile. There were identified as failure mechanisms, a panel compression under the projectile, a compression in the target volume surrounding the impacted zone, pyramidal or almost conical deformation on the panel, loading the main yarns which face the highest stress and strain (the main yarns break when the tensile strain of yarns' fibers reaches their strain at break, deformation, displacement and/or twisting of secondary yarns, local delamination between sublayers, especially for those towards the back of the panel, shear plugging, spalling of coating films,especially where yarns have already been broken, friction between projectile and panel and friction between yarns and layers. The fibers in secondary yarns are not broken, but deorganized, they absorb energy by deforming by being stressed under their strength limit and highest values are found near the top face of the cone produced by the impactor.
In Ballistic Resistance of Body Armor NIJ Standard-0101.04 [22], "…the probability that no BFS measurement exceeds 44 mm must be at least 80 %... and the required confidence is 95 %..." [22]. This is why, in Figure 5, this limit is draw with a red line on the web plots, in order to point out the lower values obtained on the tested panels.
The average value for BFS, $\bar{Y}$, was calculated as

$$\bar{Y} = \frac{1}{N}\sum_{i=1}^{N} Y_i$$

N is the number of hits and also the number of measured BFS and Y_i is the value of i-th BFS. $\bar{Y}_{SB\,1plus} = 19{,}44$ mm and $\bar{Y}_{SB1} = 25{,}93\ mm$. The standard deviation of measured BFS was calculated with:

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(Y_i - \bar{Y})^2}$$

resulting $s_{SB\,1plus} = 4{,}65$ mm and $s_{SB\,1} = 3{,}14$ mm.
SEM images in Figure 4 presents typical aspect of damaged aramid fibers.

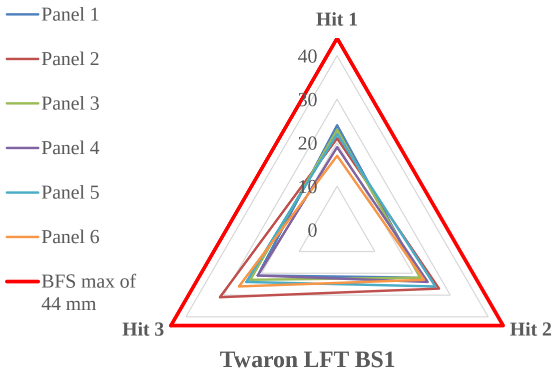


a) ×2.000 *b) ×5.000*

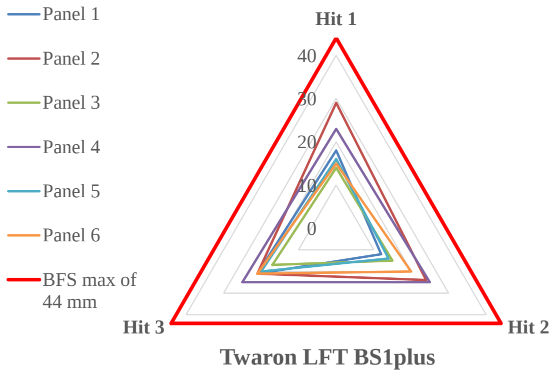
Figure 4: Aspects of broken aramid fibers in fibriles, from the 2nd layer of the LFT SB1 plus panel: a) broken end of a fiber, b) non-uniform fibrilation and necking near the broken end (not in the SEM image)

Conclusions

The aim of this study was to compare panels made of two different prepegs of unidirectional aramid fabrics, LFT SB1 and LFT SB1 plus, respectively, having as criterion the back face signature (BFS).
This approach can shorten the time for development of new protection systems, with rapid implementation based on laboratory tests and in accordance with the results of numerical simulations and compliance with standards, thus providing advantages for users (military, aerospace, but also civil).



a) *24 layers of SB1*



b) 12 layers of SB1plus

Figure 5: BFS measured for six panels made of unidirectional aramid fabrics [26]

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