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Characteristics of Stab-resistance Panels Made of Twaron Aramid Fabrics

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Abstract: *This paper presents preliminary results and discussion on two aramid fabrics in order to establish their stab resistance when used as panels with different numbers of layers. Twaron fabrics SRM509 and CT736CMP, were arranged in 16 and 20 layers and in a combination of them (10 layers SRM509 and 10 layers CT736CMP). Samples of 130 mm x 130 mm were cut from the fabrics, weighed and measured for thickness. All tests were done for an impact energy of 24 J (the resulting impact velocity being 3 m/s). The blade had the geometry recommended in the standard Stab Resistance of Personal Body Armor NIJ Standard–0115.00 as P1. The conclusion of this analysis is that the better behavior to stab is obtained for panels that have higher gradients in time, for all four characteristics here discussed: force, displacement, absorbed energy and velocity. When using hybrid panels, the results could intermediate those of the components, this solution could be recommended for reasons as price, weight.*

Keywords*: stab resistance, aramid fabrics, hard particles in a polymer matrix*

1. Introduction

Personal armor is designed to face ballistic and stab threats and could be used by many people acting in a risky environment, as law reinforcement police, soldiers and civilians such as journalist, security guards [1, 2].

The quest of the designer is that these threats could act as a combined event, the effect of each threat acting simultaneously or in short time upon the same protection.

There are several criteria for grouping the design solutions for stab-resistant armors [3], including

- base materials used for manufacturing the protective armor:
- their structure, especially for composite (as monoblock component, as fibers arranged in yarns and fabrics with different architecture, but dense and with no loose spaces between yarns),
- their shape as layers (here including knitting, woven fabrics with metallic fibers, polymeric and natural fibers [4-6], glass fibers [7], but also stratified sheets), monoblock plates or animal-mimicked shaped [8] (like scales, turtle tiles, egg-shell [9] etc.),
- the technology involved (from laminates, fabrics to printing fabrication).

Base materials could be metallic alloys, having the disadvantage of high specific weight, inflexibility, polymeric materials as plates or woven fabrics, the last having the advantage of light weight and flexibility and ceramic materials, usually used to faced combined threats as blades and bullets. For stab-resistance, ceramics could be used as adding materials in polymeric matrix of the fabrics or even in composites with polymeric matrix used as coatings to increase the abrasive resistance of the armor against a rigid blade.

Khuyen et al. [10] designed rigid plates made of different fabrics. The laminates were cured at 60°C for 24 h at a pressure of 5 MPa under a press with a controlled temperature. Stab tests were done

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manually on panel with 20 layers of silk bonded by adhesive with a 7.9 ± 0.3 mm thickness and these panels fulfill level 2 requirements (NIJ 0115.0), resulting only a knife penetration of 3 ± 0.2 mm. But tests are manually done, implying a low control of stab energy values in order to compare the results.

The fabrics could be impregnated with adhesives or shear thickening fluids, reinforcement particles [11-14], the number of layers being 2–20.

A design solution tested by several researchers, tried to used shear thickening fluids or gels for improving stab resistance of personal armor. Kang et al. used combined impregnation [15] with shear thickening fluid and sphere and fumed silica particles dispersed in ethylene glycol and polyethene glycol (PEG 200) for improving the stab resistance.

Xu et al. [16] impregnated Twaron fabrics with polyethylene glycol and nano silica, in different concentrations. The fabrics have the following characteristics: plain, 160 g/m^2 areal density, yarn count of 93 tex, yarn density of 8 cm^{-1} and the fabrics thickness of 0.3 mm. Samples were cut in rectangular samples of 120 mm x 240 mm. Stab tests were done on 12-layers panels, for the impact velocity of 3 m/s, meaning 22.5 J impact energy. Two different silica nanoparticle sizes (650 nm and 12 nm) were used in the shear thickening fluid (STF). For both 12 nm and 650 nm particles, three silica weight fractions, 20%, 25% and 30%, were used in STF. The work demonstrated that for the 12-layer fabric panels, the impregnated absorbed at least 58% of the impact energy, compared to the 20% absorption of the impact energy by the untreated panel. On the basis of the same areal density, the impregnated 12-layer panels outperformed the 24-layer untreated panel. The employment of STF in the panels also significantly reduced the back-face deformation caused by the knife impact. These results a better stab resistance of the fabrics with STF.

Mayo et al. [17] reported the behavior in cutting and puncture of thermoplastic impregnated, woven aramid fabric in quasi-static and dynamic conditions. Films of various thicknesses, made of Polyethylene, Surlyn, and polyethylene and Surlyn were laminated into fabrics and compared to simple panels (without films) at close masses and layer number. Film laminated fabrics behaved better under stab and puncture impacts, proved by reducing cut window. This is still a good solution to improve stab resistance for body armor but flexibility and comfort could be reduced.

Li D. X. [18] presents in his book fabrics that could be used for their cut resistance. Their different behavior depends on many factors, such as the way blade acts on fibers (compressing or sliding under compression). He underlined that stabbing, especially with pointed sharp blade, produces a particular failure of fibers and yarns. He wrote that inorganic materials are more resistant to cutting process as compared to organic materials, but their selection implies more other factors. A material could show a dulling effect due to its chemical structure, but also due to fiber/yarn architecture (knitted, woven, unidirectional) and the fabric treatment. The cutting resistance is proportional to material amount in front of the blade, but the stab resistance could alter this proportionality due to the design of the blade, especially for double blade threats. The size of the filament is also important and Kothari and Sreedevi reported that a larger diameter of single filament as a contrast to the small diameter of multifilament yarn of nylon fabrics exhibited higher cut resistance than para-aramid fibers with same weight basis [19], but stab action could make these materials to change their rank for cutting resistance.

Decker at al. [20] reported an experimental study on stab resistance of Kevlar and Nylon fabrics, with shear thickening fluid between layers and test results show improvements as compared to neat fabric panels with same areal density.

Li et al. [21] tested aramid fabrics, neat and impregnated with a shear thickening fluid with multi wall carbon nanotubes but tests were done in a quasi-static stab regime. They noticed that friction increases when yarns were pull out for the impregnated fabrics and panel with treated aramid fabrics absorb a greater amount of energy. They did not report results in dynamic conditions. They used aramid fabrics type Kevlar with plain architecture, 420 g/m^2 and a thickness of 0.56 mm. No backing support was used and the sample was tightly fixed with a ring clamp. The sample were small, 95 mm x 20 mm, in 5 layers and 7 layers, respectively. Qualitatively, the cut length is larger for the neat fabrics, it decreases a little for the fabrics with thickening fluid and the fabrics with shear thickening fluid with nanotubes. It is not reported if the design solution could be translated to actual panel in an armor and if the dynamic tests would give the same tendency.

Test results are difficult to be compared if blade, test parameter as striking energy, and support are not the same. Wei et al. [22] used aramid (200 g/m^2), poly–p–phenylene benzodioxazole (PBO) (206 g/m^2), and carbon fiber (200 g/m^2) fabrics tested in the range of 6…24 J, but blade and support are complying with the Chinese standard GA68-2019, thus the cutting edge has 100 mm in length, 15 mm in width, and 2 mm in thickness), the length of the cutting edge was 12 mm and its hardness was 50–55 HRC. They reported the number of cut layers and underline a better behavior of the same fabrics but impregnated with a shear-thickening fluid.

This paper presents test results in order to compare two types of panels, made of different fabrics in order to evaluate their stab resistance by several characteristics as maximum force during the test, displacement of the blade, absorbed energy and velocity of the blade. It was tested a hybrid panel composed of both type of fabrics in order to evaluate the influence of such a panel on the analysed characteristics.

2. Materials and methods

The selected materials were two type of aramid fabrics, CT 736 CMP and SRM509, supplied by Teijin Aramid B.V. CT 736 CMP is a basket 2x2 fabric, with base yarns Twaron® 2000 1680dtex f1000 (both warp and weft), one-sided coated, with 410 g/m^2 and 0.62 mm as thickness. The resin that sticks yarns together is a PVB (polyvinyl butyral) modified phenolic resin and weights as average 55 g/m^2. Thus, the area density of the fabric is 465 g/m^2. SRM509 is a prepeg composed of an aramid fabric with a particular coating of silicon carbide. The fabric has a plain architecture, 200 g/m^2 with base yarns Twaron® 2040 930dtex f1000 (both warp and weft). The abrasive has at least 95 g/m^2. The prepeg (fabric and coating) has 430 g/m^2.

For having a quality prototype with stab resistance, there are several distinct test stages: preliminary tests at small scales, tests on plates according to national, international or military standards and tests on final product (initially done for fulfill the requirements and then, these are done for quality assessment of production series).

This study presents preliminary tests on several type of plates made of Twaron fabrics SRM509 and CT736CMP and a combination of them. Samples of 130 mm x 130 mm were cut from the fabrics, weighed and measured for thickness.

Twaron® CT microfilament fabric with a silicon carbide coating that is bonded by a special matrix. The functional coating absorbs and dulls the thrust from the blade or needle similar to a solid rock, and the energy from the impact is then absorbed by the high-impact resistance and tenacity of the para-aramid yarn in the fabric underneath. Thanks to the special matrix, the material is flexible and keeps a degree of softness. This functionality is achieved by having a density that is only one-quarter of that of current market solutions (e.g. steel). Twaron® CT736 are both the basic fabric styles for light composite armoring. This fabric can be used either neat - in what is called the ‘wet process’ - or impregnated with PVB resin for composite shell applications so as to offer the highest levels of performance.

Twaron® CT736 is recommended for fabricating modern ballistic helmets, mine boots sandwich constructions and has a good processability with various resin systems.

Twaron® SRM509 is a fabric for both ballistic and stab/puncture threats.

Law enforcement personnel has to face very different stab weapons and the body armor should be lighter enough to fulfill the safety as required by specific standards, but also be as comfortable as possible in terms of comfort and flexibility.

Table 1 presents the tested panels, with several characteristics. The SRM509 sheets of fabrics were arranged successively with the coated surface facing the threat (the blade).

Tests were done on an INSTRON CEAST 9350 droptower impact system, used to develop, fine tune and validate material models [23]. The panel was tightly fixed using a ring clamp. No support material was used for these tests.

Table 1. Characteristics of the tested panels

Material	Layers	Thickness [mm]	Mass [g]	Areal density [kg/m^2]	ΔE [J]
Twaron CT736CMP (150 mm x 150 mm)	16	8.86	292	7.35	24
(130 mm x 130 mm)	20	11.12	165	9.76	24
Twaron SRM509 (150 mm x 150 mm)	16	6.25	286	7.15	24
(130 mm x 130 mm)	20	7.83	166	9.82	24
Hybrid (20 layers) (130 mm x 130 mm) 10 layers (first) Twaron CT736CMP + 10 layers Twaron SRM509	20	10.00	159	9.42	24

The results are reliable and repeatable and the data measured and recorded in time for different parameters could reveal damaging stages. All tests were done for the same input parameter, striking energy of 24 J, meaning the blade reaches the sample with a velocity of 3 m/s, considered as low impact velocity. Similar tests on polymeric plates, but at an impact velocity of 3.6…5.8 m/s for a range of impact energy of 16…36 J were reported in [24].

The desired solution for a personal armor is to face more than one threat and for higher levels. Preliminary tests in laboratory are done for only one threat at a time, the test threat could be a projectile, a blade, a spike or a fragment (usually of regular shape, rarely met in practice) [25]. The blade had the geometry of the double-edged blade recommended in NIJ Standard 0115.01 Stab Resistance of Body Armor, National Institute of Justice, 2020 [25].

The blade was shaped from a band made of steel grade B01 (tool steel with a hardness of 52...55 HRC) and Figure 1 shows how the blade is fixed in the dropping device.

Figure 1. The blade used for stab resistance tests, as fixed on the drop device

3. Results and discussions

A qualitative evaluation of the stab resistance could be done by comparing face and back cuts in the panels.

a) b)

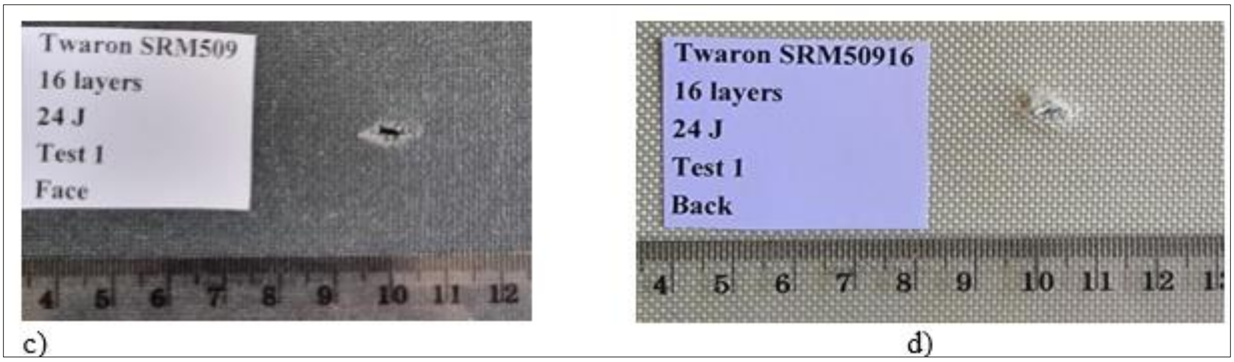

Figure 2. Photos of the panel (200 mm x 200 mm) with 16 layers of Twaron SRM509:
a) face, back, c) detail of the face cut, d) detail of the back

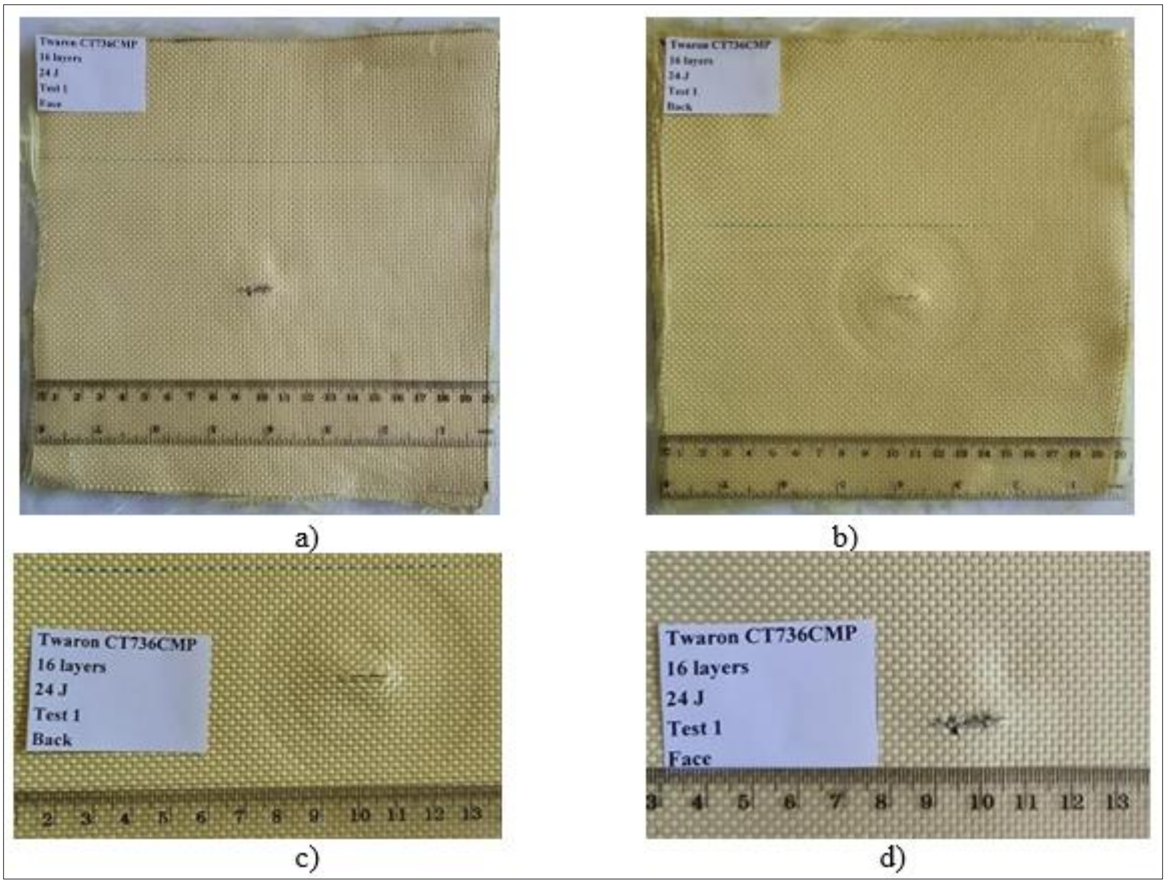

Figure 3. Photos of the hybrid panel (200 mm x 200 mm) with 16 layers of Twaron CT736CMP:
a) face, b) back, c) detail of the face cut, d) detail of the back cut

Figures 2 presents the panel made of 16 layers of SRM509, face (a), back (b) and details of the cut, face (c) and back (d). Same explanations are for panel made of 16 layers of Twaron CT736CPM (Figure 3). When comparing these photos, one may notice that the cut length is smaller for the panel made of Twaron SRM509. It is obvious that the coated layers are more resistant to stab and Table 1 does not offer a consistent difference in areal density. Of course, the price could be higher for the coated fabrics. The following figures (Figure 4 and Figure 5) present SEM images of the tested fabrics.

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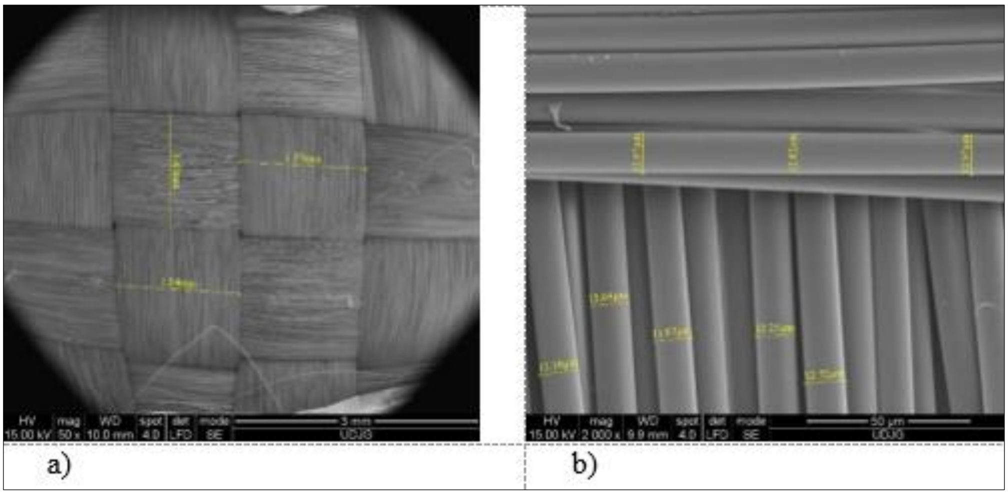


Figure 4. SEM images of CT736CMP

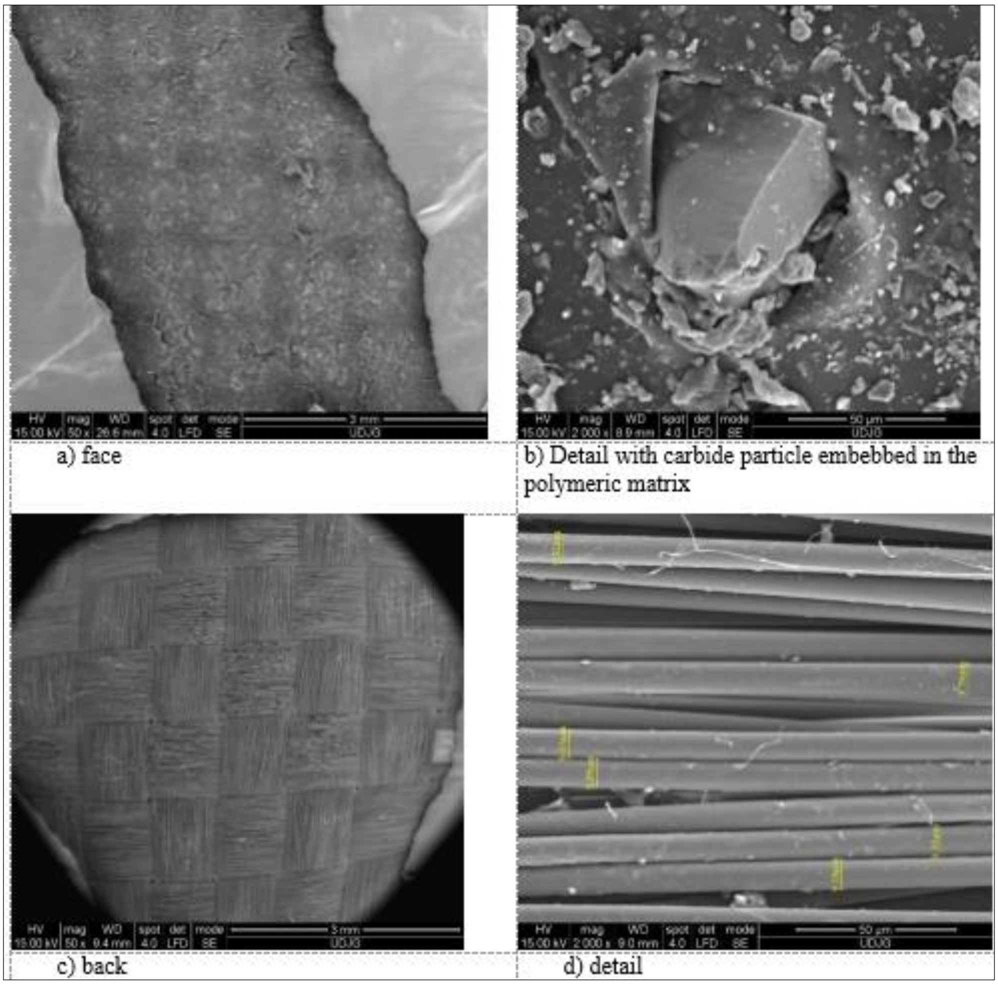


Figure 5. SEM images of Twaron SRM509

Damage processes characterizing the stab action could be very different as compared to failure when facing a projectile type threat [26]. An overview of these processes and test facilities is presented by Adolphe D.C. and Dolez P.I. [27], in a chapter entitled "Advanced strength testing of textiles", but for lower force and areal density of the panel, the applications being focused for gloves used in paper, meat or other materials to be cut, not on threats by cutting blades on human body.

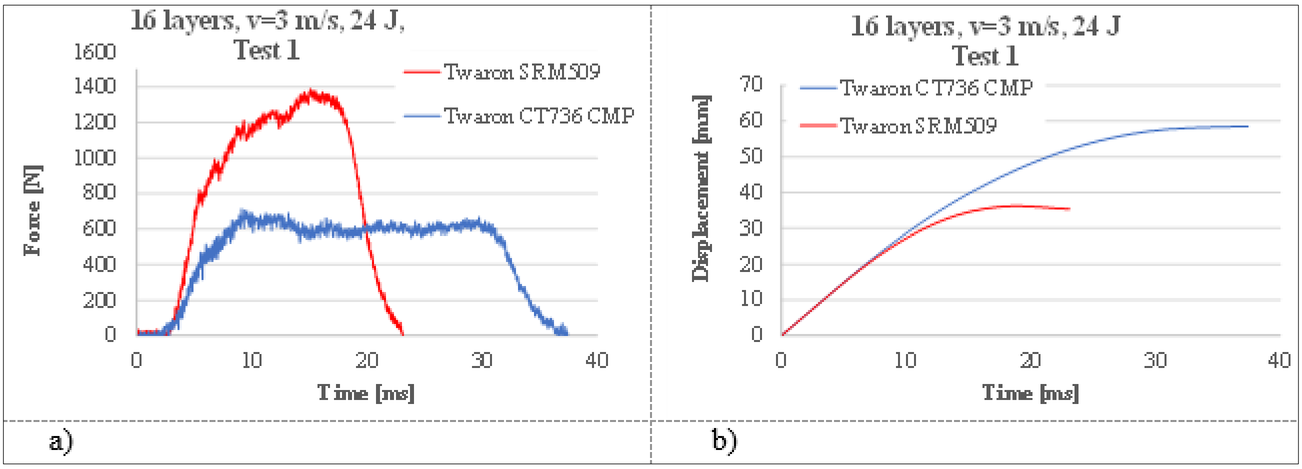
The test machine is capable of measuring and calculating several parameters during the impact, here being discussed four of them, force, displacement, absorbed energy and velocity, all as time functions.

A stab process has successive steps, including a global bending of the panel, the blade tip penetration with compression on the back material without cuts, fiber/yarns failure by a cutting process while still compressing the remaining layers, total penetration, followed by enlarging the cut windows and compression in-plane direction. All above mentioned failure mechanisms are influenced by friction between blade (tip and lateral cutting edges) and components of the panel. The presence of the coating containing abrasive particle increases friction and favors the absorption of kinematic energy of the blade.

Figure 6 presents the results for panels made of 16 layers and Figure 7 presents the results for panels of 20 layers.

Comparing panels with 16 layers of Twaron SRM509 and 16 layers of Twaron CT736CMP (Figure 6), the following conclusions could be drawn:

- the fabric coated with abrasive in a resin matrix shorten the time of penetration (considered till force is zero), this being approximately $23x10^{-3}$ s as compared to that for the simple aramid fabrics, that reaches $37x10^{-3}$ s,
- the coated fabrics has the force peak at approximately 1400 N and the shape of the force is like an asymmetrical parabola, but the other panel presents a much lower values as a plateau: also, the first slope of the force evolution is greater for the coated fabrics as compared to the other fabrics,
- the displacement has two distinct steps: one, considered till 22 mm for these tests, the curves being almost the same for both materials, and the second step where the curve are well differenced; the coated fabrics allows for a much lower displacement (36 mm) as compared to 58 mm at the test end for panels with CT736CMP layers; this is important as low displacement means lower impact effect on body, not considering in this note the penetration of the blade,
- the process of energy absorption is ended at $17…18x10^{-3}$ s for the coated fabrics and for the other panels at $31…32x10^{-3}$ s: it results that the coated fabrics absorb more rapidly the impact energy; analysing the shape of the curves for the energy absorption, the authors could conclude that a greater slope will offer a better protection
- the evolution of velocity of the blade is also important in comparing the results: the coated fabrics stops the blade at $19x10^{-3}$ s, but the other panel is doing the same at $35x10^{-3}$ s; thus, the velocity evolution has a higher gradient for the coated fabrics.



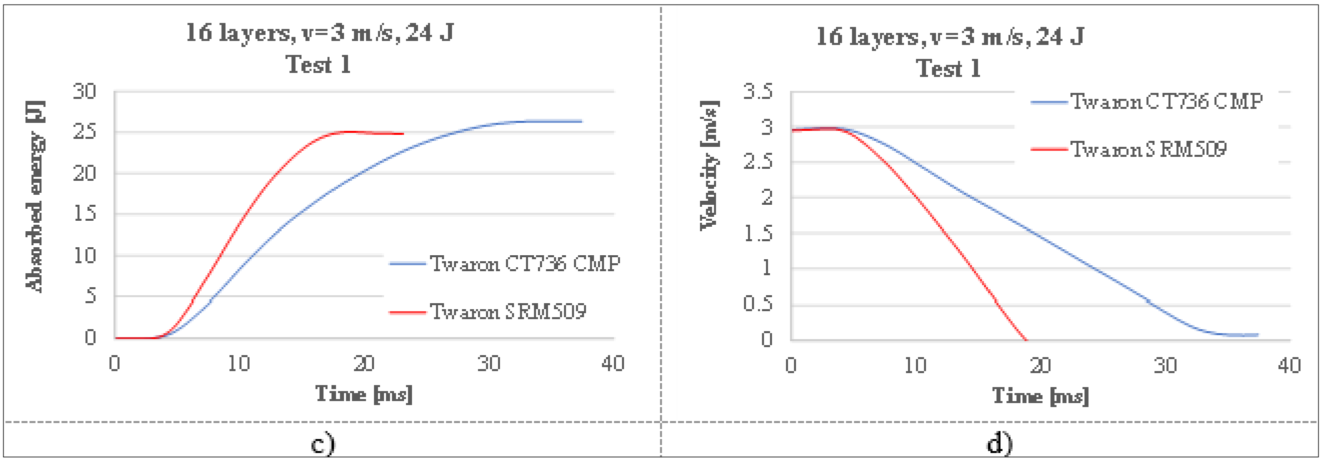
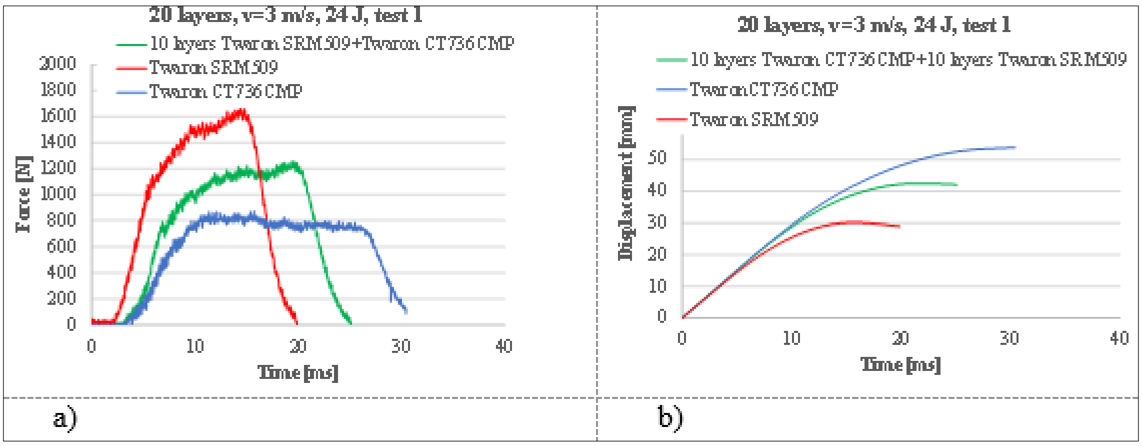


Figure 6. Characteristics of stab behavior for panel with 16 layers of the same fabric

As a conclusion of this analysis, the better behavior to stab is obtained for panels that have higher gradients in time, during the impact, for these four characteristics here discussed: force, displacement, absorbed energy and velocity of impactor.

Recent literature [28-30] presents results of new hybrid structure, based on already produced components (fabrics, adhesive, foils etc.) in order to enhance or to compensate for the weaknesses of each component and the architecture of the panels was optimized.

Hybrid or combined panels, obtained from these two types of aramid fabrics are also tested in order to improve other characteristics as specific weight, flexibility or price. But the behavior of combined panels could differ substantially from those obtained with panels made of the same successive layers and testing is compulsory. Figure 7 presents the results of a hybrid panel made of Twaron SRM509 (first 10 layers) and of Twaron CT736CMP (the following 10 layers, in order of blade impact). The impact duration is approximatively at half the interval of the uniform panels, that is $25x10^{-3}$ s, the shape of the force curve is more similar to the panel made of Twaron SRM509, but the force peak decreases with 400 N. The gradient of the absorbed energy is almost the same as for the better panel, those made of coated fabrics.



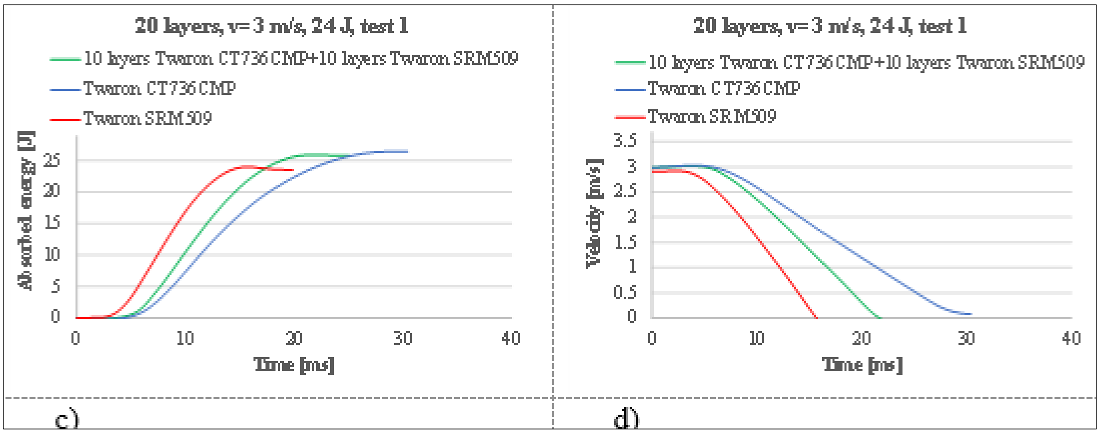


Figure 7. Recorded and calculated parameters for tests with panels with 20 layers, made of the same fabric and a hybrid panel made of 10 layers of SRM509 (in front) and 10 layers of CT36CMP (back)

As the results of the four parameters, the length of the cut in the hybrid panel has also intermediate value between the panels with layers made of a single fabric. Here only the hybrid panel in presented in photos from Figure 8, with details of the cut on the face of the panel and on its back.

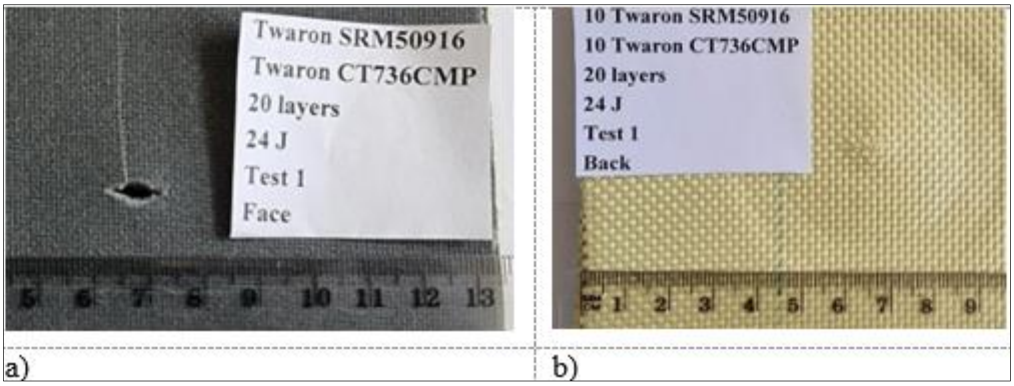


Figure 8. Photos of the hybrid panel (130 mm x 130 mm) with 10 layers of Twaron SRM509 and 10 layers of Twaron CT736CMP: a) detail of the face cut, b) detail of the back

4. Conclusions

Even if these tests are not following standard methods in facing threats [30], the results obtained from tests done on a drop test type machine point out that a better response in stab protection (assessed by width of the cut for full penetration) will be obtained for panels with high slope of the absorbed energy and velocity decrease during impact, high values of the stabbing maximum force with ramp shape, not plateau.

Analysing the shape of the curves for the energy absorption, the authors could conclude that a greater slope in droptests will offer a better protection and recommend these panels for further investigation under standards' or regulations' conditions, that require larger panel and a greater number of tests [25, 31].

As a conclusion of this analysis, the better behavior to stab is obtained for panels that have higher gradients in time, for these four characteristics here discussed: force, displacement, absorbed energy and velocity.

When using hybrid panels, the results could intermediate those of the components, this solution could be recommended for reasons as weight, the panel presenting the same level of protection.

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