

## **COMPOSITE DEFORMABLE ARMOR SYSTEMS BASED ON SMALL-SIZE CERAMICS RESISTANT TO 5.7X28 MM SS190 PROJECTILES FOR PERSONAL AND VEHICLE ARMOR APPLICATIONS**

**Abstract:** The article introduces the problem of protection against new pistol ammunition with armor piercing capabilities. As an answer to this threat the idea of deformable composite armor is presented. The construction of modern composite armor system, the materials used as well as the role of each element in stopping the projectile are briefly described. Results of ballistic test of soft fiber-based fabrics and composite armor samples containing alumina and silicon carbide ceramics against 5.7x28 mm SS190 projectiles are shown and discussed. The authors also suggest possible applications of these deformable armor systems.

Keywords: Composite armor, Ceramics, Armor piercing projectiles, Ballistic protection test.

## **KOMPOZYTOWE, ODKSZTAŁCALNE OSŁONY BALISTYCZNE NA BAZIE MAŁOGABARYTOWEJ CERAMIKI, ODPORNE NA POCISKI 5,7X28 MM SS190 DO ZASTOSOWAŃ W OSŁONACH OSOBISTYCH ORAZ POJAZDACH**

**Streszczenie:** Artykuł porusza zagadnienie ochrony przed nowoczesną amunicją pistoletową o właściwościach przeciwpancernych. Jako odpowiedź na to zagrożenie, zaprezentowana zostaje idea odkształcalnego pancerza kompozytowego. Budowa nowoczesnych osłon balistycznych, stosowane materiały oraz rola elementów pancerza w zatrzymaniu pocisku zostaje omówiona. Przedstawione zostają wyniki ostrzału miękkich tkanin balistycznych oraz układów kompozytowych pociskami 5,7x28 mm SS190. Autorzy sugerują także możliwe zastosowania odkształcalnych pancerzy kompozytowych.

Słowa kluczowe: Pancerz kompozytowy, Ceramika, Pociski przeciwpancerne, Badania odporności balistycznej.

### **1.Introduction**

#### **1.1 The demand for modern light armor**

As new types of ammunition appear on the market there is a constant need for development of new armor systems. A new threat for personal body armors as well as for vehicles is the introduction of hand-gun ammunition with armor-piercing projectiles. Among them are 5.7x28 mm SS190 and 4.6x30 mm DM31 projectiles. This article focuses on the first one therefore it will be described in more detail. 5.7x28 mm ammunition fits in the special bulletproof class according to the Polish Standard PN-V-87000:2011[1]. There are several

types of this ammunition but among them the SS190 seems to be most dangerous for body armor because of its armor piercing capabilities. The projectile consists of a steel cone on top of aluminum core fitted in brass jacket. Typical firearms of the 5.7 mm caliber are P90 sub-machine gun and Five-seveN pistol produced by FN Herstal. The weapons and the cross-section of SS190 projectile are presented below.



**Fig 1. Weapons of 5.7 caliber and 5.7x28 mm SS190 projectile.[2]**

The projectile can be fired with velocities exceeding 600m/s, which together with its armor-piercing capabilities make it difficult to be stopped by traditional vest made of soft ballistic panels. For that reason hard ceramic materials must be used. It is however a challenge to create an armor effective against AP projectiles and at the same time adjustable to the body of the user. A possible answer to that problem is use of small-size ceramic elements such as square and hexagonal tiles or spheres instead of one large hard plate. The advantage of such system also comes in increased multi-hit protection as only a few tiles are destroyed during projectiles impact. First possible application of such armor systems are concealed body armor vest with increased bulletproof capabilities for security forces. These vest are usually worn under clothing and must be deformable in order to adjust to the body and not be seen outside. Another possible application of deformable armor are add-on systems for elements of complex shapes for vehicles and helicopters.

## 1.2 Composite armor materials

Wide range of materials is in use in composite armor construction. These include traditional armor steels, ceramics, fiber-reinforced polymers or fiber-based fabrics. The designers are attempting to use the best combination of these materials to minimize the shot damage of the armor system. Besides ballistic materials an important role is also played by the adhesive layer used to bond them. [3]

### 1.2.1 Ceramics

In recent years the use of ceramics in personnel and vehicle armor has increased due to attractive combination of mechanical properties especially high hardness and relatively low density. Typical armor ceramic materials are alumina ( $Al_2O_3$ ), silicon carbide (SiC), boron carbide ( $B_4C$ ), titanium boride ( $TiB_2$ ), aluminum nitride (AlN), but the first three are the ones most widely used. Alumina combines low production cost and relatively low density, half lower than steel. The carbides possess much higher mechanical properties and even lower density however their use is limited by cost of production. Silicon and boron carbides have been more often used in personnel armor systems while alumina can be found in vehicle armor applications. [3,4]

### 1.2.2 Fiber-reinforced composites and fabrics

Fiber reinforced composites serve as backing layer for ceramics in composite armor structure. They are usually made of layers of fabrics or fiber based multi-direction structures. Glass Fiber Reinforced Polymer (GFRP) is an example of relatively cheap and effective ballistic material, but the most widely used and promising are aramid and polyethylene fiber

based composites. Dyneema™ seems to be a material of choice for personnel armor application due to low areal density and good mechanical properties.[3]

### 1.2.3 Metals and others

Despite of high density rolled homogenous steel armor remains in wide use due to its availability and relatively low cost. Armor metal materials also include aluminum alloys which are preferred for vehicles that require a high degree of mobility. Other materials for armor application are rubber, polyurethane used as fillers between layers and different types of adhesives to provide better energy dissipation over the backing plate.[3]

### 1.3 Composite armor construction, energy absorption mechanisms

Composite armor system is a multi-layered structure in which every layer has its role. A variety of materials in different proportions are being used but the idea of layered structure remains the same for all. Modern armor systems consist of hard ceramic front layer and fiber-based backing layer. Other materials as anti-trauma layer or additional front composite layers preventing spalling of ceramics can also be applied. Each element of the laminated structure plays a role in stopping of the projectile. Ceramic front layer absorbs kinetic energy of the projectile by fracture mechanism, while the backing layer works as a net which catches the fragments of the projectile and absorbs residual energy through combination of elastic strain, fiber pull-out and delaminating. The adhesive bonds the layers together but is also responsible for dissipation the energy over large area of the backing layer. Typical construction of composite armor system is shown on the picture below.[4,6,7]

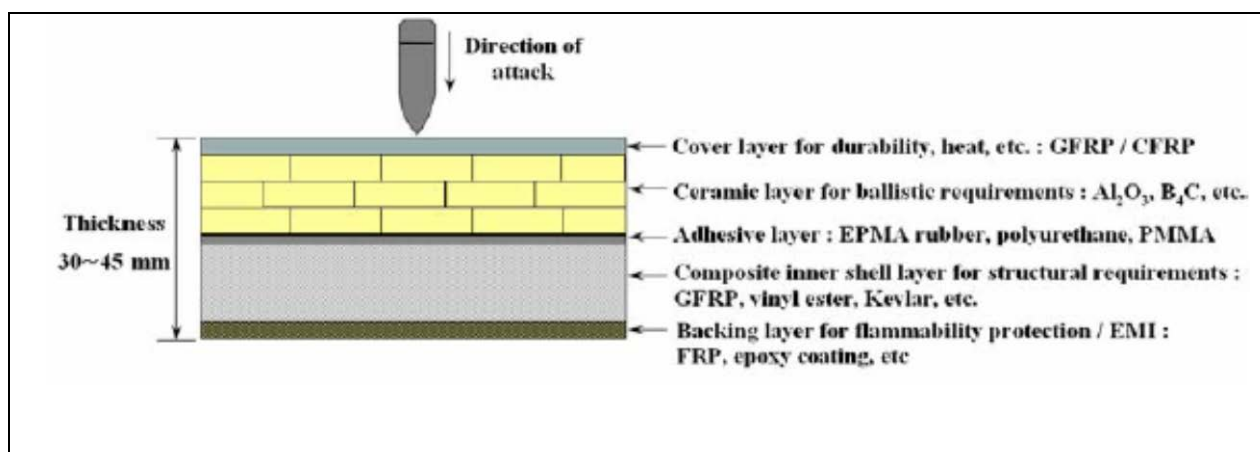


Fig 2. Composite armor construction [3]

## 2. Experimental Procedure

The carried out experiments can be divided into two stages:

- Ballistic test of soft fiber-based materials
- Ballistic test of composite samples

The experimental condition were the same for both and will be described further in the text.

### 2.1 Materials used

A variety of soft fiber based materials were used in the first stage of experiments. These were: Dyneema™ SB21, Modular Aramid Goldflex™ GF4, Aramid Fabric Twaron™ CT714, Aramid Fabric 802, Aramid Fabric 310. For composite samples Dyneema SB21 and Aramid Fabric 310 were chosen because of the lowest areal density. As for ceramics, two types were used in ballistic test: alumina and silicon carbide. For bonding ceramics and

aramid fabric a thin layer of elastic adhesive film was used. Important mechanical properties according to data provided by the producer of alumina and silicon carbide ceramics material are listed in Table 1, areal densities of single layer of each tested soft fabric are presented in the Table 2.

Table 1. Mechanical properties of ceramic materials used for sample preparation.

	Unit	Al <sub>2</sub> O <sub>3</sub>	SiC
Density	g/cm <sup>3</sup>	3.92	3.12
Young Module	GPa	340	440
Hardness $H_v$	MPa	1650	2800
Flexural strength (20°C)	MPa	310	390
Compression strength (20°C)	MPa	2200	1800
Fracture toughness $K_{Ic}$	MPa·m <sup>1/2</sup>	4.2	3.9

Table 2. Areal densities of tested soft materials.

	SB21	GF4	CT714	802	310
Areal density kg/m <sup>2</sup>	0.14	0.23	0.18	0.19	0.12

## 2.2 Sample preparation

In case of soft fiber based materials samples 400x400 mm were used. The layers were not bonded together but held on the edges by strong technical tape. The samples thickness started at 150 layers of fabric and was adjusted according to results of the firing tests. The composite samples were prepared in two stages. First the square ceramic tiles 10x10x4 mm were placed between two layers of 310 aramid fabric bonded to its surface by elastic adhesive thin film. The samples measured 50x50 mm each made from 25 ceramic tiles. Same method was used for Al<sub>2</sub>O<sub>3</sub> and SiC samples. Additional alumina samples were prepared with aramid fabric wrapped around on the outside of the ceramic tiles. A sample with a single ceramic tile 50x50x4 mm on 40 layers of GF4 was also prepared for comparison reasons. In case of ceramic spheres a different approach was used. The spheres were placed in a silicon form and covered with elastic polyurethane matrix. After curing the ceramic/polyurethane composition was bonded between aramid 310 fabric. The prepared ceramic/aramid sets were placed without bonding on soft backing layer of Dyneema™ SB21. Most samples had two layers of ceramics on 21 layers of SB21. Different combinations of tiles and spheres of both alumina and silicon carbide were used in ballistic test. The pictures below show sample preparation and silicon form used for making samples with spheres.

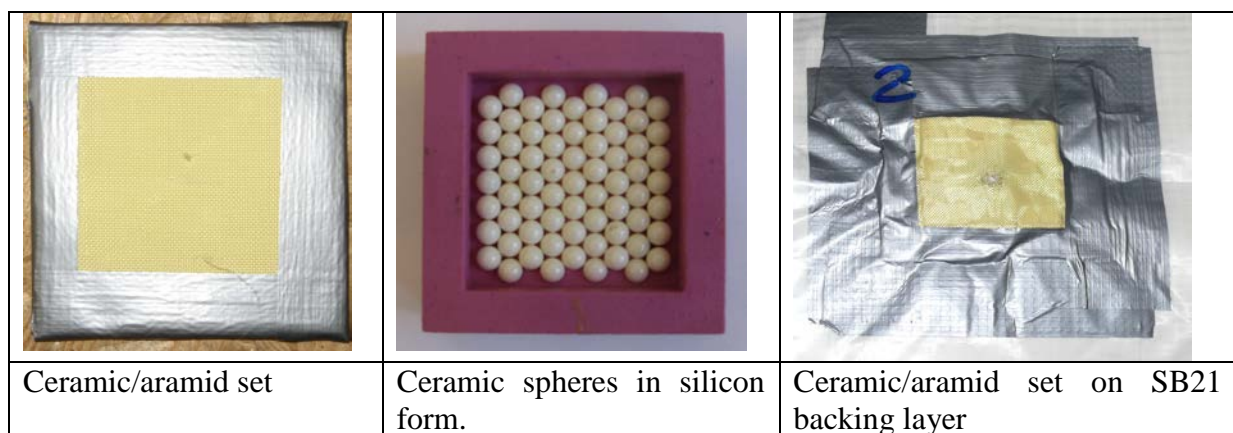


Fig 3. Sample preparation.

### 2.3 Experimental conditions

All experiments took place in the ballistic tunnel. The firing tests were carried out with the use of 5.7x28 mm velocity test barrel SN 2628. The distance between firing stand and target was 9m. The samples were placed on the base of clay. Ammunition used was 5.7x28 mm SS190. In case of soft fiber based materials the targets were hit several times until the stopping effect was achieved while the composite samples were hit once only. All test were carried out in stable atmospheric conditions.

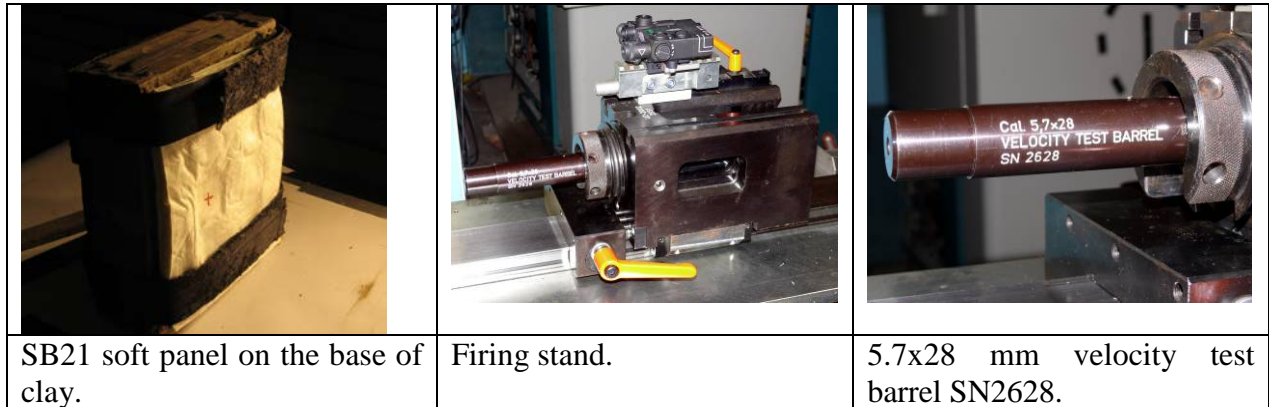


Fig 4. Sample on clay backing and 5.7x28 mm velocity test barrel.

### 2.4 Measured Values

The areal density of each composite sample was calculated and its thickness was measured. All samples showed the ability to deform under stress. Velocity of the projectile was measured 2m from the target. Each sample as well as trauma in clay was photographed after the test. Trauma depth in clay was also measured. Additionally each sample was examined with the use of X-ray diagnostic system MV17F 225-9 YXLON to determine the destruction area and interaction between projectile and ballistic material. The samples were afterwards disassembled and carefully examined, the pieces of the projectiles were retrieved and the layer in which the projectile was stopped was determined.

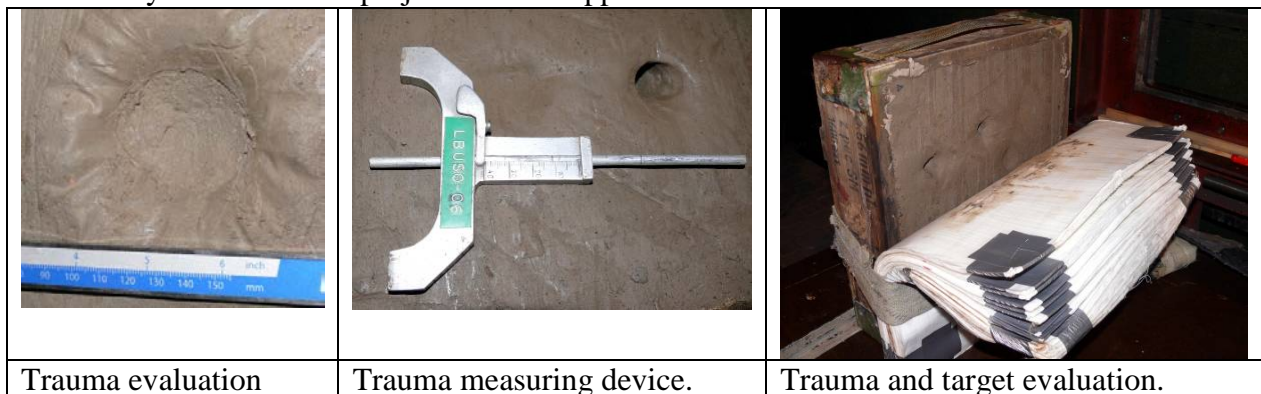


Fig 5. Trauma evaluation in clay backing and trauma depth measuring device.

## 3. Results and discussion

Table 3. Results of ballistic test for soft fiber-based fabrics

Nr	V [m/s]	Target	Number of layers	Result
1	706	SB21	150	Perforation
2	701	SB21	150	Perforation
3	705	SB21	180	Projectile stopped at 145 layer
4	708	SB21	165	Projectile stopped at 140 layer

5	702	SB21	150	<u>Projectile stopped at 135 layer</u>
10	710	GF4	150	Perforation
11	705	GF4	180	<u>Projectile stopped at 170 layer</u>
12	708	802	150	Perforation
13	714	802	180	Perforation
14	711	802	220	Perforation
15	712	CT714	150	Perforation
16	710	CT714	220	Perforation
17	709	310	150	Perforation
18	713	310	220	Perforation

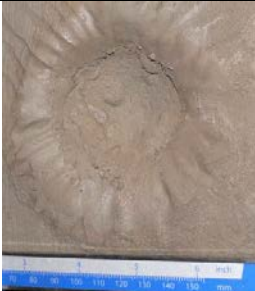
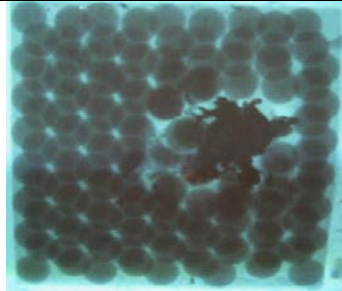

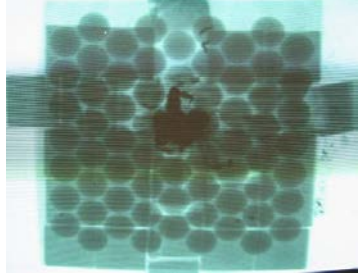
The results show ineffectiveness of traditional soft fabric materials against the SS190 projectile. These fabrics were not used as backing layers for composite samples. The two materials showing promising results were modular fabrics Dyneema™ SB21 and Goldflex™. The comparison between these two materials is shown below.


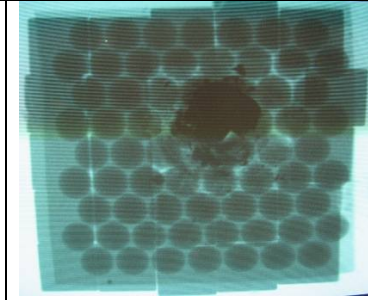

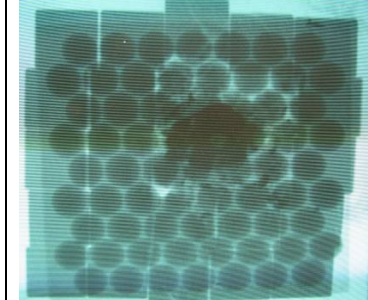

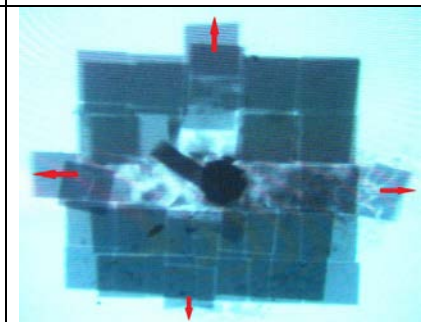

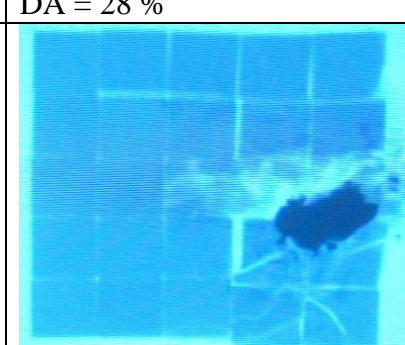
Table 4. Soft fiber based sets resistant to 5.7x28 mm SS190 projectiles

Target	Number of layers	Areal density [ $\text{kg/m}^2$ ]	Thickness [mm]
SB21	150	21	30
GF4	180	41	36

Resulting from this Dyneema™ SB21 was chosen as the best material for the backing layer of composite samples due to lower areal density and thickness. It must be mentioned that thickness is not a typical factor for evaluation of functional characteristics of the armor but in case of concealed vest it must be considered. For both materials the thickness value is too high for them to be used alone for the construction of vest therefore use of ceramic material is necessary. The results of selected ballistic tests of composite samples as well as trauma and x-ray photographs are shown in tables 5 and 6.


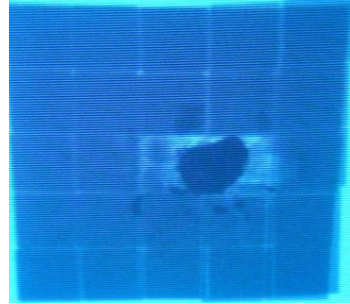

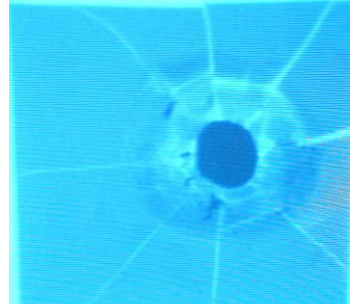
Table 5. Results of ballistic tests of composite samples

<p><b>1.</b>  <math>\text{Al}_2\text{O}_3(\text{S}) + \text{SiC}(\text{S}) + 21 \times \text{SB21}</math>  <math>M = 32.2 \text{ kg/m}^2</math>  <math>t = 16 \text{ mm}</math>  <math>V_0 = 725 \text{ m/s}</math></p>	 DT = 20 mm, DP = 18	 DA = 16 %
<p><b>2.</b>  <math>\text{SiC}(\text{S}) + \text{Al}_2\text{O}_3(\text{T}) + 21 \times \text{SB21}</math>  <math>M = 32.4 \text{ kg/m}^2</math>  <math>t = 14 \text{ mm}</math>  <math>V_0 = 710 \text{ m/s}</math></p>	 DT = 19 mm, DP = 11	 DA = 30 %

<p><b>3.</b> SiC(S) + SiC(T) + 21xSB21</p> <p><math>M = 29.6 \text{ kg/m}^2</math> <math>t = 14 \text{ mm}</math> <math>V_0 = 714 \text{ m/s}</math></p>	 <p>DT = 22 mm, DP = 12</p>	 <p>DA = 27 %</p>
<p><b>4.</b> <math>\text{Al}_2\text{O}_3(\text{S}) + \text{SiC}(\text{T}) + 21\text{xSB21}</math></p> <p><math>M = 31.8 \text{ kg/m}^2</math> <math>t = 14 \text{ mm}</math> <math>V_0 = 714 \text{ m/s}</math></p>	 <p>DT = 19 mm, DP = 13</p>	 <p>DA = 16 %</p>
<p><b>5.</b> <math>\text{Al}_2\text{O}_3(\text{T}) + \text{Al}_2\text{O}_3(\text{T}) + 21\text{xSB21}</math></p> <p><math>M = 34.3 \text{ kg/m}^2</math> <math>t = 14 \text{ mm}</math> <math>V_0 = 713 \text{ m/s}</math></p>	 <p>DT = 20 mm, DP = 17</p>	 <p>DA = 28 %</p>
<p><b>6.</b> SiC(T) + 42xSB21</p> <p><math>M = 18.6 \text{ kg/m}^2</math> <math>t = 12 \text{ mm}</math> <math>V_0 = 708 \text{ m/s}</math></p>	 <p>DT = 21 mm, DP = 39</p>	 <p>DA = 29 %</p>

Samples with one layer of alumina ceramics or two layers of spheres of the same type were also tested in same conditions but did not stop the projectile. As it can be seen the only sample with single ceramic layer that stopped the projectile was sample no. 6 containing SiC tiles. Silicon carbide possesses much higher hardness than alumina and therefore it can more easily destroy the core of the projectile. It was also the sample with lowest areal density. In sample no. 5 a phenomena of pushing ceramic tiles in four directions outside occurs increasing the area of destruction. For that reason a special sample no. 7 with two layers of alumina ceramic tiles wrapped on the sides with aramid fabric was prepared. Also a sample where small tiles were replaced by single ceramic piece was tested.

Table 6. Results of ballistic test of special composite samples

<p><b>7.</b>  <math>2x Al_2O_3 (T)^* + 21xSB21</math>   <math>M = 34.8 \text{ kg/m}^2</math>  <math>t = 14 \text{ mm}</math>  <math>V_0 = 733 \text{ m/s}</math>                       *tiles wrapped on sides with aramid fabric 310</p>	 DT = 19 mm, DP = 19	 DA = 8 %
<p><b>8.</b>  <math>Al_2O_3</math> single tile + 40xGF4   <math>M = 24.9 \text{ kg/m}^2</math>  <math>t = 12 \text{ mm}</math>  <math>V_0 = 709 \text{ m/s}</math></p>	 DT = 15 mm, DP = 9	 DA = 100 %

M - areal density, t - thickness,  $V_0$  - impact velocity, DT - trauma, DP - depth of penetration (layer in which projectile stopped), DA - area of destruction, S -sphere, T - tile.

In the first case it was confirmed that supporting ceramic tiles on the sides improves ballistic performance of the armor system as the destruction area is limited to two tiles only and the effect of pushing tiles in two perpendicular directions outside the impact area does not occur. The second sample shows advantage of using small size ceramics over a single piece for achieving multi-hit capabilities. Although this composite set has stopped the projectile the whole area is considered destroyed.

The tested samples with two layers of ceramic tiles can provide relatively low areal density, being at the same time flexible. Because of the ability to deform these armor systems could prove effective as easy to mount add-on armor for curved shapes. For vest application, sample no. 6 could be an attractive solution, compromising the strength of silicon carbide, good flexibility of the structure and relatively low areal density. Further investigation of these materials as well as ballistic resistance of composite armor systems and finally vest design should be carried out.

#### 4. Conclusions

1. A variety of composite armor samples and soft ballistic materials were tested and proved effective against the 5.7x28 mm SS190 projectile.
2. Due to armor piercing capabilities of the 5.7x28 mm SS190 projectile, the use of soft fiber-based materials is inefficient for concealed vest application as the thickness of the vest would be too high.
3. The use of small-sized ceramics as the front layer, makes it possible to stop the SS 190 projectile. It also increases multi-hit protection. The minimum destruction area had reached a value of 8 percent.
4. Supporting ceramic tiles on the sides has highly increased their multi-hit capabilities as the area of destruction limited.
5. Silicon carbide should be a material of choice for vest application as it gives 20% weight reduction to alumina. Future research should concentrate on silicon or boron carbide.



6. Modular Aramid Goldflex™ GF4 showed potential anti-trauma characteristics being at a same time a ballistic material. Further investigation should be carried out in this matter.

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