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COMPOSITES THEORY AND PRACTICE

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TEST OF BALLISTIC RESISTANCE OF COMPOSITE MATERIALS USED FOR PROTECTION OF SPECIAL VEHICLE CREWS

Model composites were made, for which the following components were selected: epoxy resin reinforced with layers of NCF (non-crimped fabric) with appropriately oriented glass, carbon and aramid fibres. The fabrics for the test were selected so as to allow the comparison of ballistic resistance depending on the type of material, thickness and sequence of fabric. Resin infusion technology was used in preparing the composites. The resistance of the composite models was tested for penetration with: 9x19 mm FMJ projectiles, at a bullet impact speed of ca. 360 m/s, fragment simulating projectiles (FSP) with a mass of 1.1 g and fragments of a model IED improvised explosive device containing fragments in the form of 3/16" bearing balls. Carbon composites have the highest resistance to perforation with a 1.1 g FSP fragment simulating projectiles of all the materials tested. The ballistic limit of a four-directional carbon composite with a surface density of 5.5 kg/m^2 is 305 m/s, and for a surface density of 21 kg/m^2 the ballistic limit is 780 m/s. The ballistic resistance of the carbon composite is related to its high shear strength - the highest of all the materials tested. In reference to the model of composite damage by the projectile, this means that the first stage of penetration, in which the material is compressed and subject to shearing force, is the determining factor in resistance to perforation.

Keywords: **ballistic resistance, carbon composite, aramid composite, fibreglass composite, NCF fabrics, resin infusion**

BADANIE ODPORNOŚCI BALISTYCZNEJ KOMPOZYTÓW PRZEZNACZONYCH DO OCHRONY ZAŁÓG POJAZDÓW SPECJALNYCH

Wykonano modelowe kompozyty, do budowy których wybrano: żywicę epoksydową zbrojoną warstwami tkanin NCF (non-crimped fabric) o odpowiednio zorientowanych włóknach szklanych, węglowych i aramidowych. Do wytworzenia kompozytu wykorzystana została technologia infuzji żywicy. Zbadano odporność wykonanych modeli kompozytów na przebicie: pociskami kalibru 9x19 mm FMJ, przy prędkości uderzenia pocisków ok. 360 m/s, pociskami symulującymi odłamek (FSP) o masie 1,1 g, odłamkami modelowego improwizowanego urządzenia wybuchowego zawierającego odłamki w postaci kulek łożyskowych 3/16". Spośród zbadanych materiałów kompozyty węglowe charakteryzują się największą odpornością na przebicie pociskami symulującymi odłamek FSP 1,1 g. Granica balistyczna kompozytu węglowego czterokierunkowego o gęstości powierzchniowej 5,5 kg/m^2 wynosi 305 m/s, a o gęstości powierzchniowej 21 kg/m^2 granica balistyczna wynosi 780 m/s. Odporność balistyczna kompozytu węglowego jest związana z jego wysoką wytrzymałością na ścinanie, najwyższą ze wszystkich zbadanych materiałów. W odniesieniu do modelu niszczenia kompozytów przez pociski oznacza to, że pierwszy etap penetracji, w którym kompozyt jest ściskany i ścinany, jest dominującym etapem mającym wpływ na odporność na perforację.

Słowa kluczowe: **odporność balistyczna, kompozyt węglowy, kompozyt aramidowy, kompozyt szklany, tkaniny NCF, infuzja żywicy**

INTRODUCTION

Ballistic protection requirements for military vehicles should be considered in parallel with the requirements of maintaining high mobility and transportability of the vehicles [1]. This points toward the need to use light material solutions. Among light materials expected to significantly reduce the mass of military vehicles, and hence also fuel consumption and operation costs, most often mentioned are: new steels, new aluminium alloys, magnesium and titanium alloys as well as composites with a metal and polymer matrix [2-5]. The last of these groups includes composites with a reinforcement of unidirectional fibres.

The mechanical properties which the composite component should feature largely depend on the function it should fulfil and the manner of use. If the composite is only used for additional protection, greatest importance should be assigned to forces perpendicular to its surface, predominantly impact forces. When assuming that the composite is to serve as a structural component, the material should possess appropriate strength in other directions, along the plane of the composite. On the other hand, however, fulfilment of the structural component function requires the material to have a certain level of rigidity and durability. The task, therefore, is to find the optimum values of surface density and durability of the composite and levels of ballistic resistance.

A major advantage of using a unidirectional layout of fibres is the ability to design composites with the exactly required amount of appropriately oriented layers. This entails savings in terms of the weight of the composite. In comparison to woven fabrics, unidirectional layers have better mechanical properties due to the lack of binding between individual fibres. Unidirectional fibres for use in composites can be found in two forms. In the form of fibres laid unidirectionally in a layer, pre-impregnated with a resin which ensures maintaining the geometry and layout of a sheet (prepregs) and in the form of sewn fabrics, where the mass percentage of the threads keeping the fibres in the appropriate position in the mass of the entire sheet is several percent at most.

In general, the ability of the material to effectively counteract ballistic impact depends on the hardness of the materials, which is critical for the deformation of projectiles and the strain at which the material is damaged, due to the material's ability to absorb energy by fracturing, in the case of ceramics and composites, and plastic deformation in the case of certain metals.

For composites where the fibres are bound by a polymer matrix, the process of composite destruction can be divided in two stages. Initially, the projectile as it penetrates the material, destroys it as a result of compression and shear of the top layers. In the second stage, when the velocity of the penetrating projectile decreases, the remaining part of the "thinned out" material deforms, and destruction of the material results from delamination and pulling fibres from the matrix as a result of stretching [6-9].

MATERIALS FOR STUDY

Carbon, fibreglass and aramid NCFs (non-crimped fabrics) were used to make the composite material, all provided by Saertex, as presented in Table 1.

TABLE 1. **Materials used for tests**
TABELA 1. **Materiały użyte do badań**

No.	Material	Layup	Commercial name
1.	CARBON	[–45,45]	S32CX010-00410
2.	CARBON	[–45,45]	S32CX010-00580
3.	CARBON	[–45,0,45,90]	V95757-00590
4.	CARBON	[–45,0,45,90]	V97583-01100
5.	GLASS	[45, –45]	S32EX010-00430
6.	GLASS	[–45,45]	S32EX010-00600
7.	GLASS	[–45,0,45,90]	S35EQ290-00620
8.	GLASS	[–45,0,45,90]	S33EQ250-01130
9.	ARAMID	[–45,45]	V100956-00330
10.	ARAMID	[–45,45]	S32AX010-00450

The fabrics for the test were chosen in such a way as to allow comparison of ballistic resistance depending on the type of material, thickness, and layup of fabric.

Araldite LY 1564 epoxy resin from Huntsman was used for the matrix, as is used in the production of high-load components. After mixing with a hardener, the resin is characterised by low viscosity, at the level of 200÷300 mPas. It is designed for RTM and resin infusion technologies.

RESISTANCE OF COMPOSITES TO IMPACT WITH 9X19 mm FMJ PROJECTILES

At the first stage of the study, the amount of energy lost by a 9x19 mm projectile during the perforation of 6-layer composite panels was measured. The test was conducted in accordance with PN-V-87000:1999 "Light ballistic shields. Bulletproof and fragment-proof vests. General requirements and tests" for Level II of bulletproof properties.

Image recording with a high-speed camera was used in testing. Figure 1 presents an example of quadruple frame photography of a 9x19 mm bullet in flight, before hitting the composite. This method was used for measuring the speed of impact.

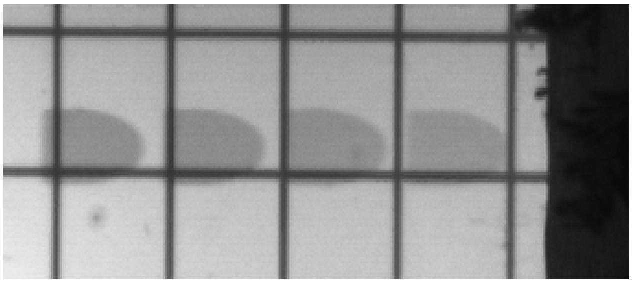

Fig. 1. Quadruple frame photography of projectile, interval between exposures 50 μs. Scale - 20 mm

Rys. 1. Fotografia pocisku z poczwórnym doświetleniem, kolejne kadry w odstępie 50 μs. Skala - 20 mm

Figure 2 presents an example photograph of composite perforation.

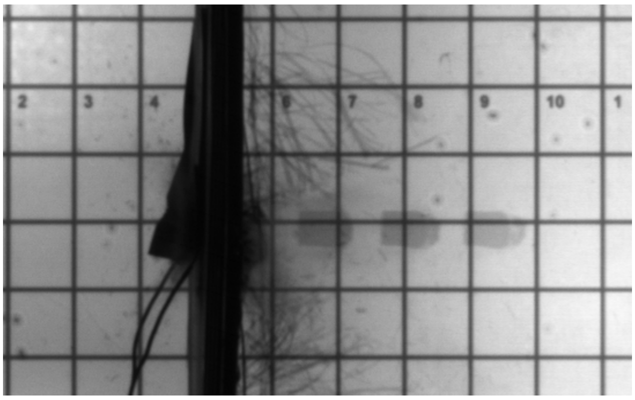

Fig. 2. Image of composite after perforation, subsequent frames exposed at 60 μs intervals. Scale - 20 mm

Rys. 2. Fotografia kompozytu po perforacji, kolejne kadry doświetlane w odstępach 60 μs. Skala - 20 mm

Table 2 presents the results grouped by the composite characteristics being compared.

TABLE 2. **Test results of composites resistance to perforation by 9x19 mm bullet**
TABELA 2. **Wyniki badań odporności kompozytów na przebicie pociskami 9x19 mm**

	Type of fabric	Impact velocity [m/s]	Residual velocity [m/s]	Energy absorbed [J]	Density of surface [kg/m^2]
Type of fibres	Aramid S32AX010-00450	357.7	293.8	15.4	5.6
	Glass S32EX010-00430	364.1	326.8	5.4	5.3
	Carbon S32CX010-00410	360.4	333.5	2.7	4.9
Fabric thickness	Aramid S32AX010-00450	357.7	293.8	15.4	5.6
	Aramid V100965-00330	347.7	310.8	5.3	6.8
	Glass S32EX010-00600	358.5	311.8	8.2	5.1
	Glass S32EX010-00430	364.1	326.8	5.4	5.3
	Carbon V95757-00580	361.8	314.5	8.6	5.5
	Carbon S32CX010-00410	360.4	333.5	2.7	4.9
Layup	Glass S32EX010-00600	358.5	311.8	8.2	5.1
	Glass S35EQ290-00620	357.3	312.0	7.7	5.1

RESISTANCE OF MATERIALS TO PERFORATION WITH 1.1 g FRAGMENT SIMULATING PROJECTILE (FSP) - DETERMINING V_{50} BALLISTIC LIMIT

With regard to fragment resistance, a recognised test allowing the comparison of different materials, primarily in terms of their surface density, is to determine the V_{50} ballistic limit with a fragment simulating a projectile with a mass of 1.1g, described as a standard fragment. The main NATO document containing the requirements for conducting the test is STANAG 2920 “Ballistic test method for personal armour”. The test is also described in Polish standard PN-V-87000 [10-12].

Table 3 presents the test results of the ballistic limit for composites of different thickness (in three series), produced from all the selected types of fabrics. The impact energy corresponding to the ballistic limit was determined, as was the impact energy/surface density ratio, which allows materials in each series to be compared. The table presents the mean values for each series.

TABLE 3. **Test results of composites resistance to perforation with 1.1 g FSP**
TABELA 3. **Wyniki badań materiałów z użyciem FSP 1,1 g**

Series no., fabric layers multiplier (x):	Impact energy Eu [J]	Eu/AZ ratio
CARBON [–45,0,45,90] V97583-1100		
Series I (x1)	49.83	8.73
Series II (x2)	101.70	9.78
Series III (x4)	276.47	13.87
CARBON [–45,0,45,90] V95757-00590		
Series I (x1)	48.51	8.54
Series II (x2)	131.52	11.68
Series III (x4)	333.76	15.86
CARBON [–45,45] S32CX010-00580		
Series I (x1)	51.16	9.37
Series II (x2)	123.57	11.39
Series III (x4)	316.01	14.87
CARBON [–45,45] S32CX010-00410		
Series I (x1)	42.20	8.54
Series II (x2)	103.12	10.67
Series III (x4)	293.90	15.36
GLASS [45,0,–45,90] S33EQ250-01130		
Series I (x1)	43.74	7.82
Series II (x2)	109.40	9.42
Series III (x4)	267.19	12.30
GLASS [45,0,–45,90] S35EQ290-00620		
Series I (x1)	27.60	5.45
Series II (x2)	79.84	7.98
Series III (x4)	242.49	12.20
GLASS [45,–45] S32EX010-00600		
Series I (x1)	32.21	6.37
Series II (x2)	86.68	8.20
Series III (x4)	183.75	8.85
GLASS [45,–45] S32EX010-00430		
Series I (x1)	28.59	5.40
Series II (x2)	86.25	8.39
Series III (x4)	187.58	9.19
ARAMID [45,–45] S32AX010-00450		
Series I (x1)	46.57	8.35
Series II (x2)	177.44	11.78
Series III (x3)	210.06	13.21
ARAMID [45,–45] V100956-00330		
Series I (x1)	48.51	7.19
Series II (x2)	141.94	10.76
Series III (x3)	242.49	13.14

Figure 3 presents the results obtained in a graphical format. A trend line is drawn for each data series, with a forecast for the value of the x axis, equal to 35 kg/m^2. The ballistic limit values of the composites were put together on the chart. They were compared to the test results of St3 steel and High Hardness Steel, as well as the PA6 aluminium alloy. The ballistic limit of most composites is higher than that of the materials mentioned above.

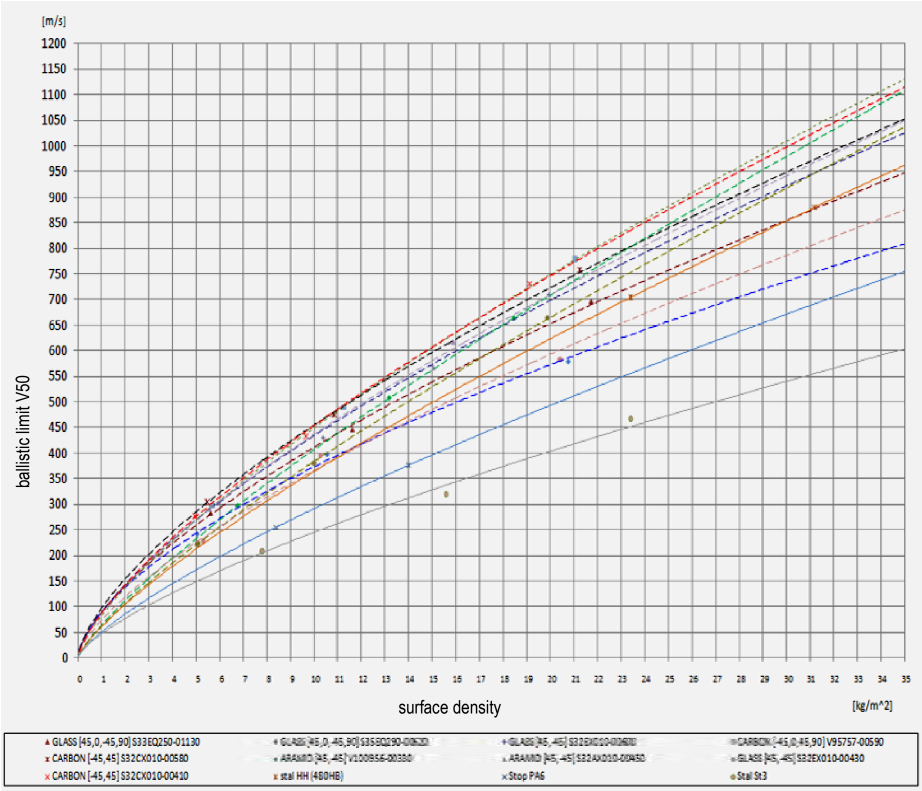

Fig. 3. Ballistic limit of tested composites

Rys. 3. Granica balistyczna badanych materiałów

RESISTANCE TO PERFORATION USING IED MODEL

As determining the ballistic limit of a material using a fragment simulating projectile does not reflect the actual condition of multiple impacts of fragments in the shield material, accompanied by simultaneous operation of the overpressure wave, the NATO standardisation agreement - STANAG 4569 “Protection levels for occupants of logistic and light armoured vehicles” [13] is in force regarding the protection of crews of military vehicles, which requires, at the first level of protection, that the crew should be protected against the results of hand grenade, anti-personnel mine and small IED detonations. As there is an immense quantity and diversity of ordnance in that range being produced nowadays, a model IED has been proposed as an appendix for STANAG 4569 (Fig. 4).

It was assumed that the fragments generated from the model charge (minimum of 750 bearing balls with a mass of 0.4 g and 300 g of explosive) should have a velocity of 1150÷1200 m/s.

Resistance was tested on a high-hardness steel sheet with a thickness of 3.5 mm, to perforation with 3/16” bearing balls, which are the fragments in a model IED charge.

From a distance of 300 mm, on a 500x500 panel, multiple perforations of the plate were obtained. Only balls hitting at a small angle, at the edges of the plate, failed to perforate the steel.

a) b)

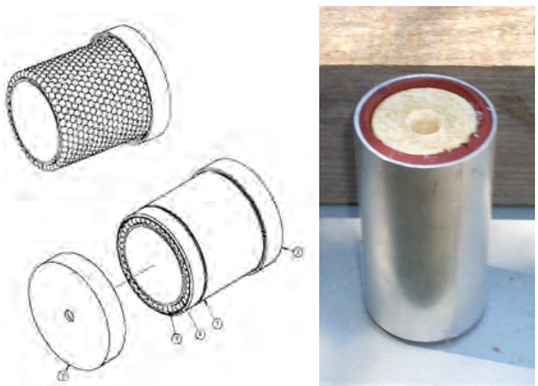

Fig. 4. Schematic diagrams of model charge (a) and device used in WITPiS tests (b)

Rys. 4. Schemat ładunku modelowego (a) i ładunek improwizowany użyty w testach WITPiS (b)

Tests conducted with plates of a greater thickness indicated that 100% perforation resistance, under the given test conditions, was provided by a 6 mm steel plate.

In the same manner, perforation resistance was tested on selected composites, made with four-directional fabrics. Of those, the carbon composite was the one with the lowest surface density (Fig. 5).

In order to measure the critical value of impact velocity of a 3/16” bearing ball for the 3.5 mm (27.3 kg/m^2) armour steel, it was shot individually with bearing balls, using the method and testing rig for V_{50} ballistic limit tests (Fig. 6).

a) b)

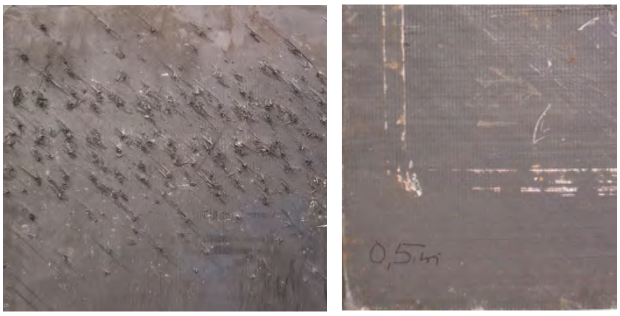

Fig. 5. Front (a) and back (b) sides of carbon composite after tests with model IED charge

Rys. 5. Frontowa (a) i tylna (b) strona kompozytu węglowego po teście z użyciem modelowego IED

a) b)

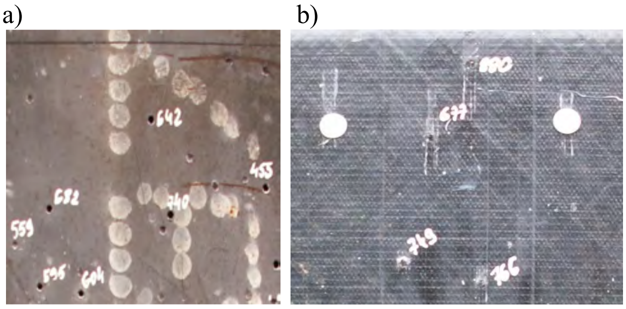

Fig. 6. Test results of puncture resistance to bearing balls: a) armour steel, b) carbon composite

Rys. 6. Wyniki badań odporności na przebicie kulką łożyskową: a) stal pancerna, b) kompozyt węglowy

The ballistic limit of armour steel is 580 m/s.

In the same way, the carbon composite was tested, which was resistant to perforation with bearing balls in the test using the model IED. For this composite, perforation did not occur even at the velocity of 880 m/s (upper limit of velocity which can be achieved on the test rig used).

SUMMARY

Between ten and twenty versions of composites were prepared, differing in type, thickness and amount of fabric. The tests conducted allowed the composite models to be tested for fulfilment of the requirements in regards to ballistic resistance.

The tests demonstrated that composites made with four-directional fabrics possess the greatest resistance to impact loads. Carbon composites have the highest value of ballistic limit. The ballistic resistance of the composite is related to its high shear strength, the highest of all the materials tested. Referring to the model of composite damage by the projectile, this means that the penetration phase, in which the material is compressed and sheared is the determining factor in resistance to perforation.

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