Experimental Investigations Regarding the Behaviour of Composite Panels Based on Polyurea and Kevlar or Dyneema Layers Under Blast and Fragments

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This paper presents an experimental study to determine the behaviour of composite panels, made of polyurea sprayed on Kevlar or Dyneema support layers, under blast and fragments produced by an improvised explosive device (IED). The fragments used for tests were steel bearing balls of 8 and 10 mm propelled by a plastic explosive charge and bullets cal. 7.62 mm, type Full Metal Jacketed Armor Piercing (FMJ AP) and Hollow Point Boat Tail (HPBT), with impact velocity greater than 500 m/s. To determine the fragments attenuation, their velocities before and after the impact with the composite panel were measured and compared. In order to assess the blast attenuation, the reflected pressures measured by two face-on sensors, one of which was covered by the composite panel, were compared. Also, to explain the behaviour of composite panels under blast, the shock polars of materials in the panel's composition were plotted. The results have shown that the composite panels have a low rate of attenuation of fragment velocities but a very good ability to attenuate the pressure and impulse associated with the shock wave.

Keywords: soft targets, composite panel, blast, fragments, attenuation

The increasing number of recent terrorist attacks, particularly on soft targets (unprotected objectives) and in public places, requires a continuous concern from national safety authorities. Among the unprotected objectives, the most common targets are the civil airports. Their protection against attacks with improvised explosive devices (IED) is imperative when considering their very large spaces, very large number of passengers and airport staff. In case of an attack, the blast and fragments can be spread at large distances. If a ballistic multi-layered panel is placed between different crowded areas, then it would be possible to partition these spaces and stop/mitigate the spread of the shock waves and fragments. This ballistic panel has been designed to consist of two symmetrical layers of porous material in order to particularly mitigate the fragments and a central composite panel capable of attenuating in particular the shock wave. The central composite panel, which is the subject of the present paper, was made by spraying the polyurea onto Kevlar or Dyneema support layers, according to the process outlined in [1].

By combining the advantages of an hyperelastic behaviour with an easily application as an additional layer on fabrics or metallic plates, the use of polyurea for composite panels is in line with the current trend towards finding modern solutions to reduce the effects associated with impact or explosion [1-7].

Thus, the results obtained from some experimental tests on ballistic protection plates made of Kevlar® and ceramic layers covered with different thicknesses of pulverized layers of polyurea, are presented in [1]. The projectiles used were .44 Magnum Semi Jacketed Hollow Point (SJHP) and have an average impact velocity of 430 m/s. The results have shown that this configuration of the protection plates offered a III A protection level according to NIJ standard [8]. In the case of IED, the fragments can be of different shapes (nuts, bolts, steel balls, nails, etc.) and their speed exceeds 430 m/s, which requires additional research to determine the behaviour of the composite panels at higher speeds.

Most of the tests performed on materials and structures designed for ballistic protection aim either to determine the ballistic limit [9-12] or energy absorbed in the penetration process [13]. Due to the constraints imposed on the thickness of the composite panel (maximum 3 cm) and the high velocity of the fragments resulting from the detonation of an IED, in the present case there is no question of determining the ballistic limit of the composite panel, but only its ability to attenuate the fragments velocity.

Devices used to propel the impactors to determine the ballistic limit or absorbed energy were represented by the gas gun [11] and the high-speed gas gun [10], resulting in a velocity of up to 450 m/s. Also, Borvik et al. [9] used different rifles to fire the projectiles with initial velocity of up to 920 m/s, while Harris et al. [7] have used shock tubes to test the polyurethane mitigation capacity. Regarding the shock wave attenuation by the composite panel, the focus falls on the polyurea layers. Research has shown that a 4 mm thick polyurea pad can reduce the normalized peak pressure and impulse by about 74% and 49%, respectively [7].

Under these conditions, the present paper aims to make an assessment of the behaviour of polyurea composite panels under fragments impact in terms of: the type of support layers (Kevlar or Dyneema), the type of the projectile (deformable or non-deformable) and the velocity impact (over 500 m/s). At the same time, an evaluation of the capacity of composite panels to attenuate the blast waves was also carried out.

Experimental part
Materials used for panels

Two types of composite panels were used for tests. They were made by spraying polyurea (Europol ®) on Kevlar or Dyneema support layers. The polyurea was sprayed through a pressurized container at approximately 150 bar and 70-90 °C. The Kevlar Prepreg (composite based on Kevlar fibre and a phenolic resin) and Dyneema type HB24 (Ultra-High Molecular Weight Polyethylene based

composite laminate) have been used as support layers. The Composite Panel based on Kevlar - CPK consisted of 10 layers of Kevlar and 10 polyurea layers. Also, Composite Panel based on Dyneema - CPD, consisted of 5 layers of Dyneema and 6 layers of polyurea. The densities of composite panels were approximately 870 kg/m³ for CPK and 910 kg/m³ for CPD and all composite panels have the dimensions of 500 mm x 500 mm x 2.4 mm (Fig. 1).
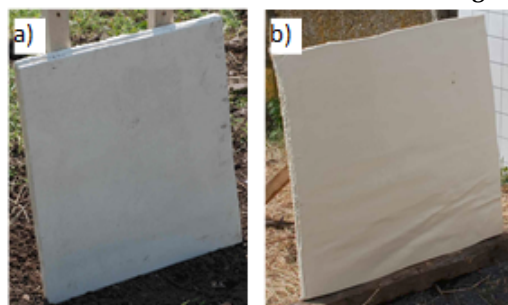

Fig. 1. Composite panels: a) CPK and b) CPD

Types of fragments and projectiles

In order to determine the types of fragments and projectiles, there were considered: i) the types of impactors used in literature [7-9] (sphere, flat, hemispherical, conical and ogival heads), and ii) the existing cases of IED attacks. Preformed fragments of IED used in the terrorist attacks in London, Madrid, Saint Petersburg were steel bearing balls or nuts whose size did not exceed φ10 mm or M20. Also, in the tests there were used 7.62 mm x 51 mm bullets according to standard NIJ 0101.06 [8], whose characteristics are presented in table 1.For the tests performed on the CPK and CPD panels, two types of fragments and projectiles were selected: a) deformable (HPBT bullets) and b) non-deformable (steel bearing balls and FMJ bullets). Of the possible fragments to be used, steel balls were preferred due to their spherical shape and their homogeneity as compared to any other type of fragments. The diameter of the steel balls used for the tests was 8 mm and 10 mm.

The initial velocity of the steel balls was estimated using the Gurney equation for an asymmetric sandwich configuration [14]:

$$\frac{V_p}{\sqrt{2E_G}} = \left[\frac{(1+2 \cdot \mu)^3 + 1}{6(1+\mu)} + \mu \right]^{-1/2} \quad (1)$$

where: V_p is the initial velocity of the steel balls, in m/s; $\sqrt{2E_G}$ is the Gurney's constant for the explosive used, in m/s; $\mu = M/M_e$ is the ratio of the metallic mass, M (mass of the steel balls) and M_e is the mass of explosive charge. The steel balls placed in contact with the plastic explosive do not form a continuous mass as in the case of a metal plate. With consideration in this regard, the calculated speed of the steel balls was multiplied by a coefficient which takes into account the ratio of the cross-sectional area of the balls and the cross-sectional area of the explosive charge. Also, the ratio μ was modified based on the actual mass involved in the propulsion of the balls [15]. The estimated values of the steel balls according to equation (1) are shown in table 2.

Test setup description
Test setup for steel bearing balls impact

In order to determine the composite panels' attenuation capacity of the metal balls, a test configuration was used to measure the speed before and after passing through the panel. This configuration consisted of the CPK panel, the explosive to propel balls device and the high speed camera (Fig. 2).
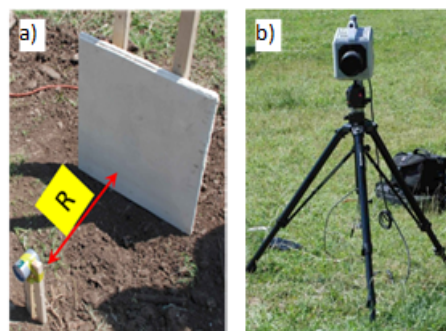

Fig. 2. Test configuration for CPK attenuation under bearing balls impact: a) explosive device and CPK; b) high-speed camera

The explosive balls propulsion devices were preferred to gas gun because it allows a higher velocity of the balls. This device consisted of a PVC tube with outer diameter of 50 mm, plastic explosive charge of Hitex (detonation velocity of 7000 m/s at density of 1.5 g/m³) and steel bearing balls. The ratio *i* between the masses of the balls and the explosive charge was 0.869 for the 8 mm diameter and 1.087 for the 10 mm diameter, respectively. Standoff distance *R* was 3.70 m for both 8 and 10 mm ball configurations. For measuring the velocity of the steel balls before and after the perforation of the composite panel, a FASTCAM SA-X2 type 1080-C3 high-speed camera was used, as is presented in figure 2b.

Test setup for ammunition cal. 7.62 mm

For testing the attenuation capacity of composite panels under 7.62 mm ammunition there were used: rifle, ammunition (according to table 1), CPK and CPD, high-speed camera and ballistic radar for measuring bullet velocity as recommended in NIJ 0101.06 [8], as is shown in figure 3.
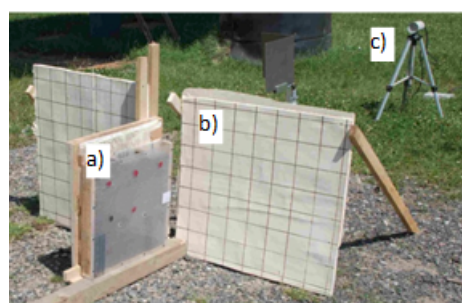

Fig. 3. Testing configuration for composite panels attenuation under bullet impact: a) composite panel; b) grid for high speed camera; c) Doppler radar

Test setup for blast attenuation

To determine the shock wave attenuation capacity of CPK and CPD composite panels, a test facility consisting of: a) explosive charge support, b) explosive charge of 20 g plastic explosive; c) wooden plate with 1 m x 1 m x 0.01 m dimensions and with a central opening of 0.4 m x 0.4 m

Characteristics	Bullet mass [g]	Initial velocity [m/s]	Maximum energy [J]
Bullet type			
Cal. 7.62 mm HPBT	11.34	785	3494
Cal. 7.62 mm FMJ AP	10.70	860	3957

Table 1
AMMUNITION CHARACTERISTICS USED FOR TESTS

(Fig. 4). The overpressure was measured by sensors S1 and S3 (PCB 113B26) for face-on pressure and by sensor S2 (PCB 113B27) for side-on pressure. The sensors were disposed at the same distance from the explosive charge, respectively 50 cm. The mass of explosive and the standoff distance to the sensors were chosen to provide a level of the reflected overpressure by approximately 1 MPa, comparable to that obtained in [7]. The sensors were connected to a Genesis type GEN7I-2 high speed data acquisition system with a sampling rate of 2MS/s. The attenuation rate was determined by comparing the reflected pressure recorded by the sensor S3, and the reflected pressure recorded by sensor S1, after passing the shock wave through the composite panels.
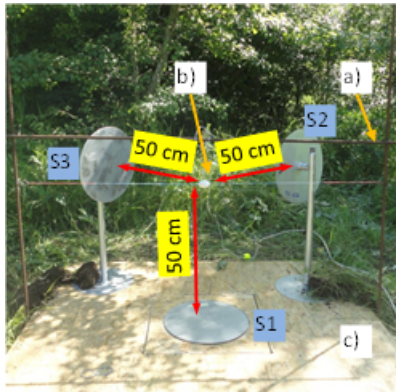

Fig. 4. Testing configuration for composite panels blast attenuation: a) charge support; b) explosive charge; c) wooden plate; S1, S2 and S3 pressure sensor

Results and discussions

Bearing balls attenuation

Only composite panels with Kevlar support were used for this test. These panels were perforated by the 8 and 10 mm diameter balls. Figure 5 shows that in all cases the balls are attenuated by the Kevlar support layer and the main mechanism is delamination, as described by Alil et al. [16] and Balaganesan et al. in [10]. This attenuation mechanism consists of melting, bulging and streaming of fibres, the last feature of which can be seen in figures 5b and 5d.
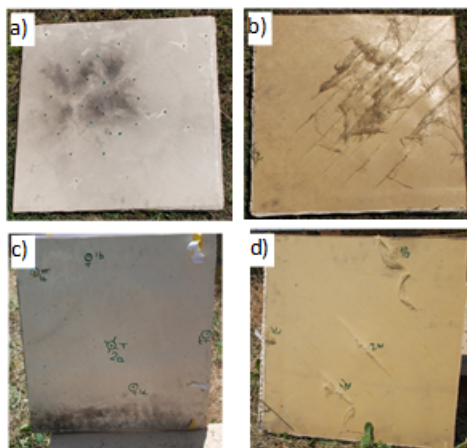

Fig. 5. Impact effects on CPK of 8 mm (5a and 5 b) and 10 mm (5c and 5d) bearing balls. Pictures a) and c) represent front face and b) and d) the back face

The attenuation capacity of the CPK is shown in table 2. The attenuation of 8 mm balls is less than the 10 mm balls attenuation due to the impact velocity on the one hand and the contact surface on the other. Thus, if the attenuation produced on the 10 mm balls is multiplied by the ratio of the 8 mm cross-sectional area and that of the 10 mm balls, an attenuation of 28.23% is obtained which is approximately equal to that for the 8 mm balls. This shows that penetration depends both on the impact velocity of the fragment and on the impact surface.

Bullet attenuation

The experimental tests to determine composite panels attenuation of explosive propelled bearing balls have the advantage of being close to real situations, but have the disadvantage that they are no reproducible. For this reason, NIJ 0101.06 recommendations [8] have been used to test fragments attenuation. Thus, the ability of Kevlar or Dyneema composite panels to attenuate FMJ and HPBT bullets (their characteristics are presented in table 1) was tested. Due to the higher speed and internal structure, the FMJ bullet attenuation by the panels CPK and CPD was less than 3%.

For HPBT deformable bullets, the results obtained are shown in figure 6. Attenuation of bullet velocity was 7.79% for Kevlar composite panels and 7.13% for composite panels with Dyneema. This results indicate that the inclusion of Kevlar and Dyneema layers and their dispersion among the polyurea layers does not allow the mitigation of fragment velocity by elastic deformation mechanism (free movement of the layers of Kevlar and Dyneema is prevented due to the polyurea layers).
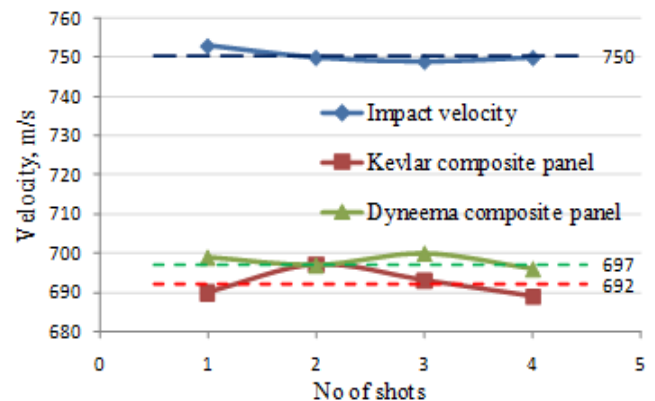

Fig. 6. Attenuation of CPK and CPD under HPBT bullet impact

These results are in line with those reported in the literature for the attenuation of projectiles with speeds of around 270 m/s by 8 layers of Kevlar [17]. In addition, the capacity of ballistic composite panels made of porous steel slag layers and CPK or CPD to mitigate HPBT bullets was tested. The results show that two exterior 2 layers of 3 cm thickness of steel slag and a CPK or CPD as central panel have a 82% attenuation capacity for HPBT bullets. For the complete mitigation of HPBT bullets, the thickness of the steel slag layer must be at least 4 cm.

Characteristic Diameter of the ball	Theoretical velocity [1] [m/s]	Experimental velocity [m/s]		Atenuation, %
		impact	final	
Φ8 mm	710	726	529	27.13
Φ10 mm	571	526	294	44.11

[1] Theoretical velocity determined according to equation (1).

Table 2
CPK VELOCITY ATTENUATION

Blast attenuation
Mechanisms of blast attenuation

The blast attenuation of CPK and CPD is due in particular to the polyurea mitigation features. The main mechanisms underlying the attenuation of the shock wave by the polyurea are considered as follows [18]: a) Shock-wave-induced hard domain ordering; b) Shock-wave-induced hard domain crystallization/densification; c) Shock wave induced hydrogen bond cleavage and formation; d) Viscoelastic stress relaxation within the hard-domains/soft matrix interfacial regions; e) Shock wave capture and neutralization. Of all these mechanisms, the latter is one that can easily be highlighted. In a layered heterogeneous material system, e.g. multi-layered composite panel made of polyurea and Kevlar or Dyneema, a leading shock front is followed by a release wave which reportedly catches up with and attenuates the leading shockwave thereby leading to shock attenuation [19]. This dual shock-wave pattern is attributed to the material architecture through which shock wave propagates, i.e. the shock characteristics. To illustrate the importance of the shock characteristics on the shock wave attenuation, the shock polars of the materials used to make the composite panels (polyurethane, Kevlar or Dyneema) and also of three different materials such as polystyrene, polyethylene and steel were plotted and compared, figure 7. To plot the shock polars of the materials, the follow equation was used:

$$p - p_0 = \rho_0 \left(c_0 \cdot u + s \cdot u^2 \right) \qquad (2)$$

where: p_0 is the atmospheric reference pressure, c_0 is bulk sound speed and s is a constant of material. The shock characteristics of these materials are shown in table 3.

Table 3
SHOCK CHARACTERISTICS OF MATERIALS

Material	ρ_0 [g/cm³]	c_0 [km/s]	s	Ref.
Polyureea 1000	1.098	2.901	2.13	[21]
Kevlar filled EPDM	0.923	1.660	2.03	[22]
Dyneema	0.950	1.770	3.45	[20]
Iron	7.850	4.722	1.44	[15]
Polyethylene	0.915	2.901	1.48	[15]
Polystyrene	1.044	2.746	1.32	[15]

The characteristics of the induced shock (shock wave velocity, material velocity and pressure) produced by the contact detonation of an explosive charge in different materials can be determined by intersecting the shock polars of the materials with the isentropic of detonation products (Fig. 7). It can be seen that the arrival of a shock-wave to an interface of polyurea, Kevlar or Dyneema material is associated with a slow rate of pressure transfer. Unlike these materials, in case of the steel the induced pressure is even higher than the Chapman - Jouguet (CJ) state values.

Attenuation of the shock wave by CPK and CPD

To determine the rate of attenuation produced by the CPK and CPD panels, the value of the reflected pressure recorded by the sensor S1 (this sensor was covered with a CPK or CPD panel) was compared with the reflected pressure measured by the S3 sensor. Firstly, there were recorded some reference values of overpressure. The recorded values of sensor S1 (face-on), sensor S2 (side-on) and sensor S3 (face-on) without application of any sample above sensor S1 are shown in figure 8. The measured values are the overpressures and zero value in the graphs of figure 8 corresponds to atmospheric pressure. The maximum overpressure values recorded by sensors
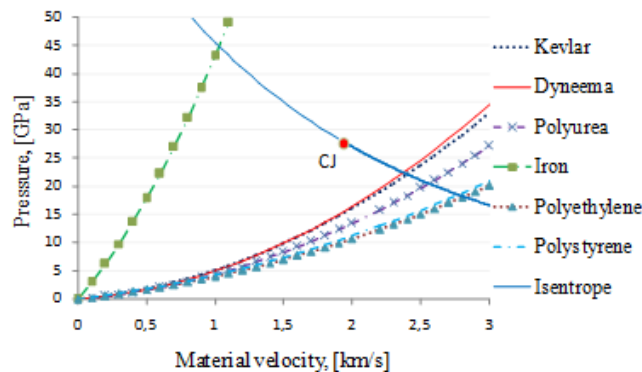

Fig. 7. Intersection between Hugoniot curves in p-u plane and isentrope of detonation products

S1 and S3 are similar, approximately 0.87 MPa, while the impulse associated with the overpressure variation curve for sensor S1 is 0.081 MPa·ms and 0.102 MPa·ms for sensor S3, respectively.
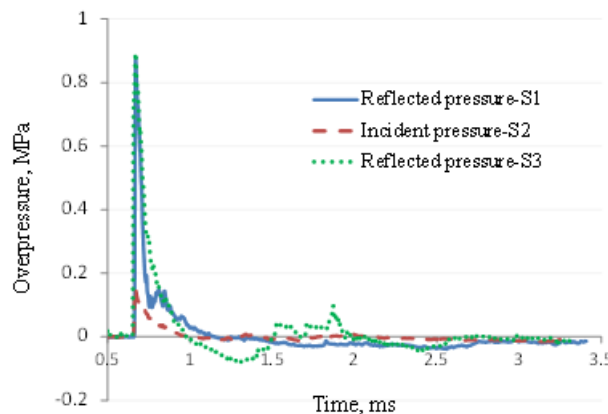

Fig. 8. Reference values of overpressures

After adding the CPK or CPD composite panel over the S1 sensor, it is observed an attenuation of the reflected pressure recorded by this sensor comparing with the value measured by sensor S3 (Fig. 9).
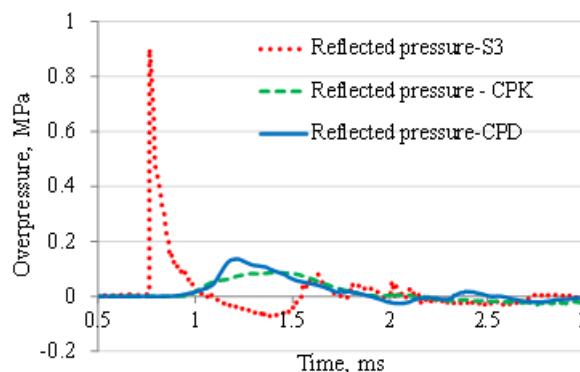

Fig. 9. Shock wave attenuation by CPK or CPD panels

The maximum reflected overpressure value recorded by the S1 sensor when the shock wave passes through the CPK or CPD composite panels is 0.12 MPa for CPD and 0.09 MPa for CPK, indicating a 90% pressure attenuation for CPK and 87% for CPD. It can also be noticed that in both cases of using composite panels, a shock wave delay occurs (there is an increase of the time of arrival at sensor S1). This delay is approximately equal to the duration of the positive phase for the pressure measured by S3, namely 0.259 ms. It should be noted that the positive phase duration for the reflected pressures measured by S1, after the shock wave passed through CPK or CPD panels (approximately 0.898 ms for each case), is greater than the positive phase duration of pressures recorded by the S3 sensor. By

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measuring the areas under the pressure-time curves, the impulses of positive phases were determined. By comparing these areas with the area under the pressure-time curve recorded by the S3 sensor, an impulse attenuation of 16.29% for CPK and 6.17% for CPD, respectively was determined.

Conclusions

The use of multi-layered ballistic panels to mitigate the effects of improvised explosive devices in large openings (airports) is in line with the current trend to increase the protection of soft targets. The advantages of such panels are mobility and high capacity to reduce the effects of shock waves and fragments. The panels were designed to consist of two layers of porous materials arranged externally, with the main purpose of attenuating the fragments, and a central composite panel with a primary role in the attenuation of the shock wave. The purpose of this paper was to present the results obtained from experimental tests performed on 24 mm thick composite panels obtained by spraying polyurea on Kevlar (CPK) or Dyneema (CPD) support layers. Tests were performed to determine the CPK and CPD attenuation of deformable (7.62 mm HPBT type ammunition) and non-deformable (steel balls of 8 and 10 mm diameter and 7.62 mm FMJ type ammunition). The results obtained show that the CPK and CPD panels have a mitigation capacity of less than 3% for FMJ type ammunition. In the case of HPBT ammunition, the attenuation is 7.13% for CPK and 7.79% for CPD panels. The attenuation rate of the non-deformable steel balls is higher than for 7.62 mm bullets, the attenuation percentage being 27.13% for 8 mm diameter balls and 44.11% for balls of 10 mm diameter. These data show that the speed and impact area, as well as the inner structure of the projectile, are important characteristics to be taken into account in determining the attenuation percentage. However, CPK and CPD panels are not suitable for use as protection systems under deformable or non-deformable projectile. The small number of layers of Kevlar and Dyneema used in the composite panel, as well as the fact that these layers have been dispersed in the composite and have not been able to move freely, are among the probable causes of the very low ability to attenuate the projectiles. Concerning the shock wave attenuation, the experimental tests have shown that the CPK composite panels had a percentage of attenuation of the reflected pressure and impulse by approximately 87% and 16.29%, respectively. In the case of the CPD panel, the pressure attenuation was of about 90% and the impulse mitigation was approximately of 6.2%. The plotting of the shock polars of the materials used to make the composite panel (Kevlar, Dyneema and polyurea) showed that the internal structure of the material, quantified by its shock characteristics, plays an important role in the way of the pressure in front of the shock wave is reflected on the interface or is transmitted in the material. For the polyurea, this transmitting capacity is lower than for Kevlar and Dyneema, and this shows that it is responsible for the high shock wave attenuation capacity of the composite panels.

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