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Research paper / Praca doświadczalna

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Determining the degree of pulse absorption of air blast wave by spaced material systems *Określenie stopnia tłumienia impulsu fali uderzeniowej materiału wybuchowego w przestrzennych układach materiałowych*

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Abstract: *The paper presents the results of a study to determine the degree of attenuation of a detonation wave pulse generated by a spherical ceresin-phlegmatized hexogen charge, by spaced material systems. The systems were mounted on a ballistic pendulum and the amount of energy absorbed was determined based on the change in pendulum swing. The spaced panels with absorbing elements, simulated the flat bottom of a vehicle exposed to a single blast.*

Streszczenie: *Praca przedstawia wyniki badań nad określeniem stopnia tłumienia impulsu fali podmuchowej, generowanej wybuchem cylindrycznego ładunku heksogenu flegmatyzowanego cerezyną, przez przestrzenne układy materiałowe. Badane układy montowano na wahadle balistycznym a miarą stopnia absorpcji energii był stopień wychylenia się wahadła. Zastosowane panele przestrzenne z elementami absorbującymi, symulowały konstrukcję płaskiego dna pojazdu poddanego jednokrotnemu udarowi siły.*

Keywords: *overpressure wave, detonation, explosive material, spaced material system*

Słowa kluczowe: *fala nadciśnienia, detonacja, materiał wybuchowy, przestrzenny układ materiałowy*

1. Foreword

Spaced panels with absorbing elements were used to determine an optimum material solution for the design of a blast energy absorber. This system is used to reduce the impact of the detonation wave energy pulse on the tested structure, in the first phase, and reduce the baffle deformation as a result of the overpressure wave, in the second stage. The experimental tests were carried out following the analysis of material properties of elastoplastics and testing on the test stand, carried out to determine material response to static and dynamic constraints. The experiment also included the testing of selected systems at the ranges using an overpressure wave generated by different masses of explosive.

2. Test methods

2.1. Instron testing machine with a measuring range up to 200 kN and on-line data logging

To select the optimum materials for a spaced structure, the selected elements were tested on static testing machines. The results were used to estimate the material behaviour under load. The tests enabled material susceptibility to bending, maximum compression at constant strain and loss of strength properties, to be determined. The first stage involved material testing under compression along a single axis. The tests were aimed at eliminating those with a limited ability to return to the initial state or materials subjected to plastic strain.

2.2. Instron Ceast 9340 400 J drop weight impact system

The dynamic tests were carried out using a dropweight impact system with a 400 J measuring range, determined as sufficient for the test. The impact energy was altered by changing the impact height and adding extra weights. The testing included a series of tests using the same test configurations as those in the compression test. Two series of tests with varying weights were carried out for each test configuration. Based on the measured values: weight, impact height and impact speed, the absorbed impact energy at multiple loads without significant changes to structural properties, were determined, from which the materials for a spaced system were selected. The strain characteristics of the loaded elements were determined by measuring the maximum material deflection and the maximum impact force.

2.3. Ballistic pendulum

Testing of spaced material systems was carried out on a ballistic pendulum [1] at IPO, Krupski Młyn [2]. A series of tests using high-energy materials (HEM) was planned. The explosive charges were detonated remotely from the bunker at a distance of 20 m from the pendulum. To determine the overpressure generated by the detonation, a measuring station comprising a HIOKI multi-channel digital recorder, four pencil type pressure sensors and a single three-axial acceleration sensor attached to the pendulum mortar, were used. Piezoelectric pressure sensors and acceleration sensors by PCB PIEZOTRONICS were used. The pressure sensors enable a very high overpressure wave to be recorded. Tables 1 and 2 include specifications of the sensors used. The three-axial acceleration sensor by PCB PIEZOTRONICS was attached to the back of the mortar with a mechanical vibration filter. The filter was supplied with the sensor by the manufacturer.

Table 1. Specification of piezoelectric pressure sensors – 137A23 type

Parameter	Unit	137A23 sensor Sn:6803	137A23 sensor Sn:6843	137A23 sensor Sn:7282	137A23 sensor Sn:7283
Measuring range	kPa	0-345	0-345	0-345	0-345
Resolution	kPa	0.069	0.069	0.069	0.069
Nominal sensitivity	mV/kPa	14.5	14.5	14.32	13.88
Maximum measured value	kPa	6895	6895	6895	6895

Table 2. Specification of piezoelectric acceleration sensor

356B20 sensor Sn:66405				
Parameter	Unit	X-axis	Y-axis	Z-axis
Nominal sensitivity	mV/g	1.06	1.11	1.11
Maximum measured value	V	9,7	9,7	9,7

The charges for the tests were prepared by mould pressing hexogen (RDX)-based explosives with 3% ceresin content: 350, 500, 750 and 1000 g. The average density was 1.6 g/cm³. The charges were suspended on the arm at a height of 1.0 m above the ground and 1.0 m from the absorber plate and initiated centrally from the top.

The tested systems (Fig. 1) included steel panels with energy absorbing elements installed between those panels. The tested panels were mounted from the side of the mortar seat of the ballistic pendulum. The panels with absorbing elements were also filled with polyurethane foam to protect the sleeve against displacement during multiple tests using the blast wave.



Figure 1. The tested material systems installed from the side of the mortar seat of the ballistic pendulum

Before the test, pencil type sensors were calibrated on lower-weight explosives: 100 and 200 g. The tested systems were exposed to a blast wave generated by spherical explosive charges. The parameters of the blast wave were determined experimentally to determine the force used to load the tested energy absorbing systems. The average wave propagation velocity was determined for each test, based on the time recorded by the sensors. For a 100 g charge (Fig. 2) in the section between sensor 1 and 2 (1.0 and 1.5 ms) – 674 m/s, between sensor 1 and 3 (1.0 and 2.0 ms) – 454 m/s. For a 200 g charge (Fig. 3), in the section between sensor 1 and 2 the velocity is 974 m/s, and in the section between sensor 1 and 3, the velocity was 500 m/s.

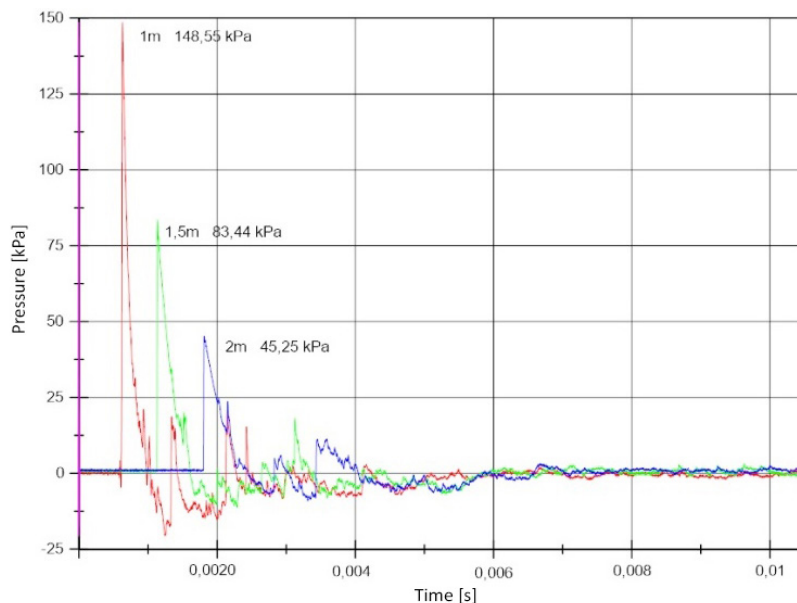


Figure 2. Pressure curve for the 100 g charge

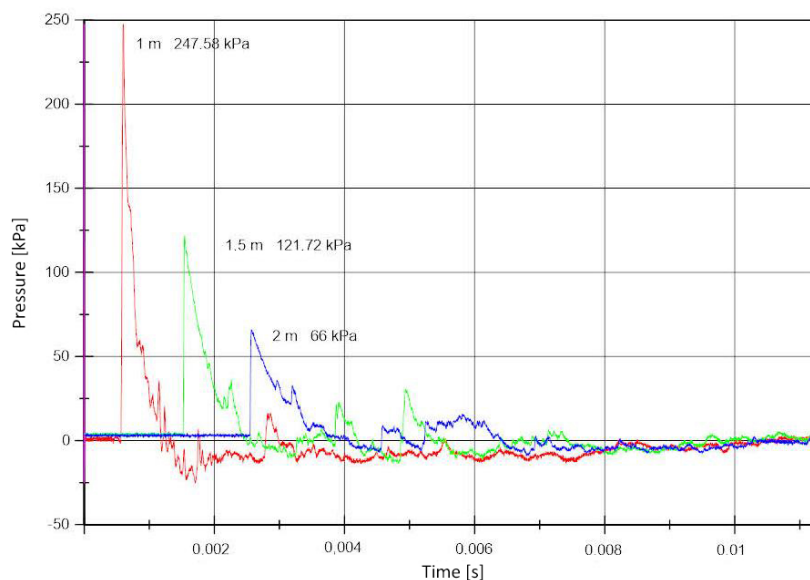


Figure 3. Pressure curve for the 200 g charge

3. Testing the elastoplastic elements

3.1. Uniaxial compression testing on the Instron testing machine

The materials intended as energy-absorbing elements (Fig. 4) were subjected to uniaxial compression at constant displacement. The materials had identical wall thickness and were available in two diameters: 42

and 62 mm. Two tests were carried out on each sample to verify the loss of material properties. Due to plastic strain, a single test was carried out for a glass composite sample (Fig. 5). The polyurethane (PU) energy-absorbing sleeves are resistant to weather, oils and greases and show low wear.

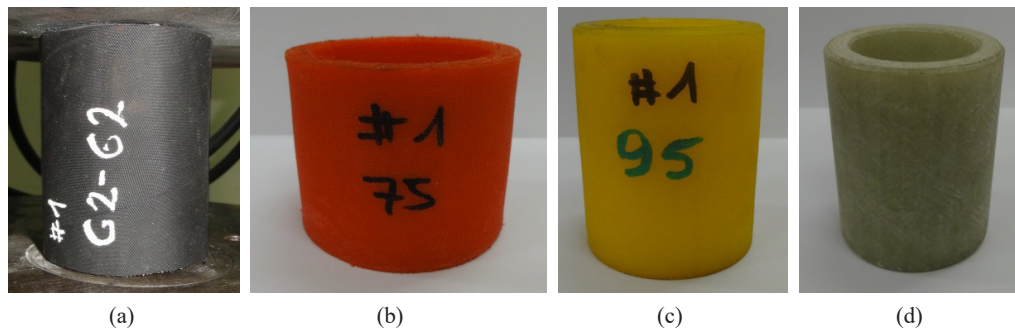
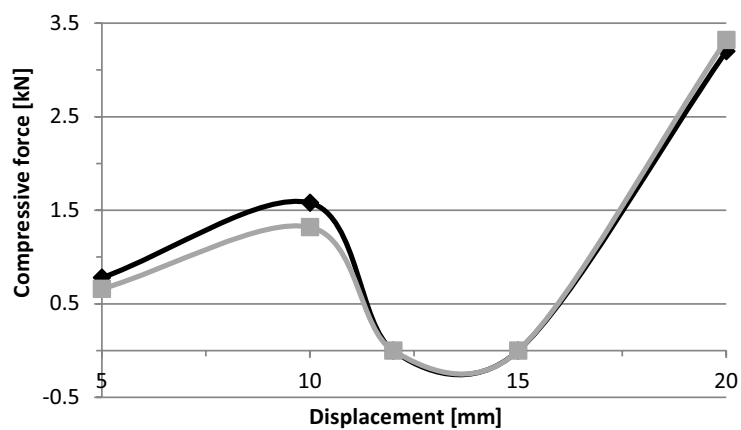
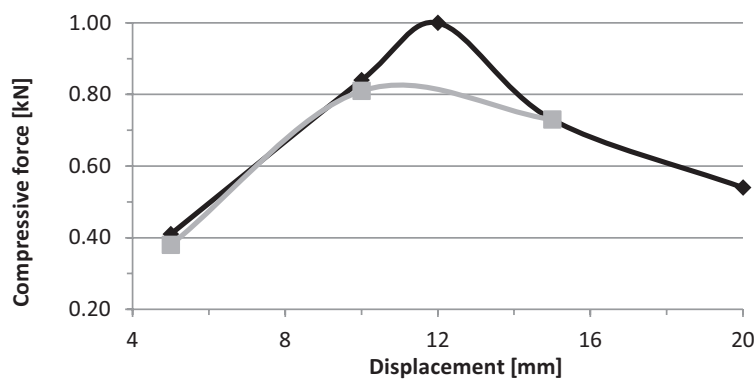


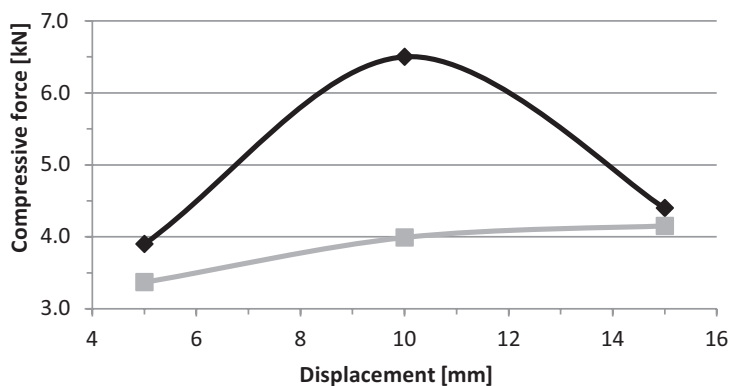
Figure 4. Structural material samples before the test: (a) reinforced rubber; (b) PU with 75SHA hardness; (c) PU with 95SHA hardness; (d) glass composite



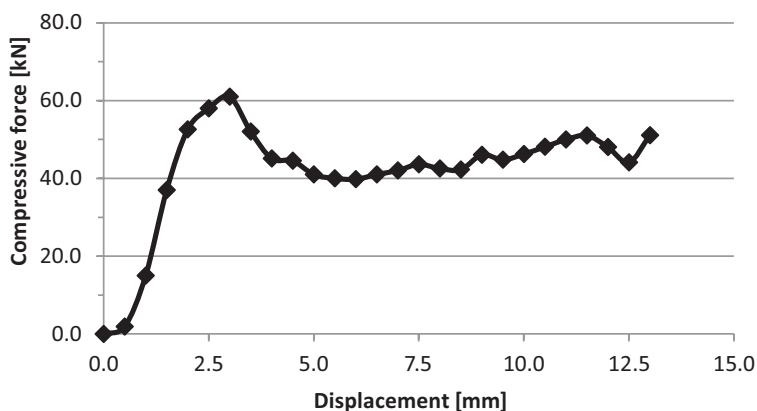
(a)



(b)



(c)



(d)

Figure 5. The S-N curves for the tested structural elements: (a) reinforced rubber; (b) PU 75SHA62; (c) PU 95SHA42; (d) glass composite

3.2. Dynamic testing using 400 J drop weight impact system

The tests carried out enabled the strength response of the tested materials within a relatively low loading force range to be determined. It determines material susceptibility to deflection (converting the impact energy into the internal work of the material). The assumption was verified and validated by dynamic testing using a 400 J drop weight impact system.

The tests were not carried out for the glass laminate samples, based on analysis of compression tests data where, for the majority of materials, the maximum compressive force was between 0.8-7 kN. For the glass composite, the first strain was observed at 60 kN and varied between 40-50 kN. Similar forces would have exceeded the measuring range of the drop weight impact system. Figure 6 shows the recorded changes in properties of the tested elastoplastic elements.

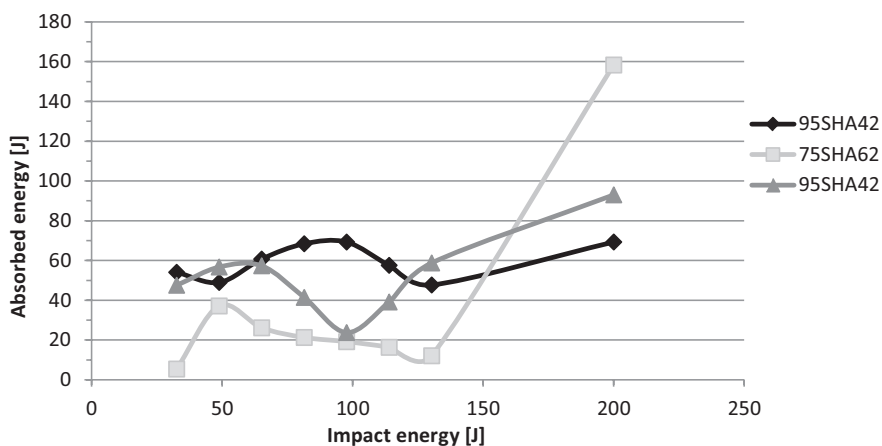


Figure 6. Changes in energy absorbed as a function of impact energy

The tests (Fig. 6) show that the best results were recorded for PU samples:

- 95SHA42, 42 mm high – with respect to energy absorption. For this material, at the value close to 60 J, the energy absorbed is a limit value which in further tests, allowed the behaviour of the entire system to be estimated and predicted. Other materials show lower or uneven energy absorption capabilities.
- 75SHA62, 62 mm high – for changes in the compression force, the material shows the ability to increase its internal work with an increase in impact force.

The analysis showed that both materials were used to design spaced material structures in experiments involving loading with the explosion force, on the ballistic pendulum.

3.3. Experimental tests of energy-absorbing panels using a ballistic pendulum

The energy absorption capabilities were verified by determining the mechanical mode of action of the shock wave. The shock wave reaching the object results in a sudden increase in pressure [3] exerted on the surface of the obstacle. The obstacle is subject to an overpressure pulse shown in Figure 7 [4].

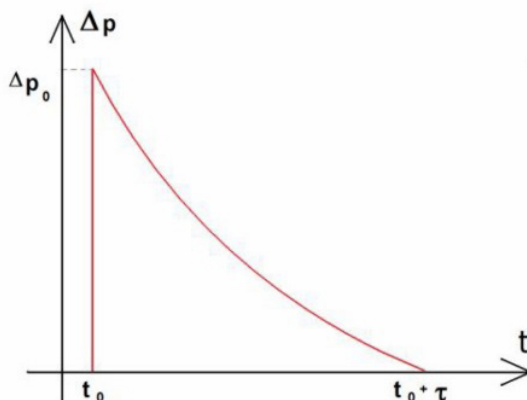


Figure 7. The pressure impulse on the surface of the object subjected to the shock wave load, where Δp_0 is the maximum overpressure peak, t_0 is the time in which the shock front reaches the obstacle; τ is the positive phase duration in which the pressure exceeds the ambient pressure

A series of dynamic tests was carried out on the ballistic pendulum using remotely-detonated plastic explosives. The explosive charges (Fig. 8) for the tests were moulded from RDX with 3% ceresin content: 350, 500, 750 and 1000 g. The average material density was 1.6 g/cm^3 . The moulding was carried out by adding the explosive material composition to a specially shaped mould under uniaxial compression to obtain a compact, uniform structure (Fig. 9).

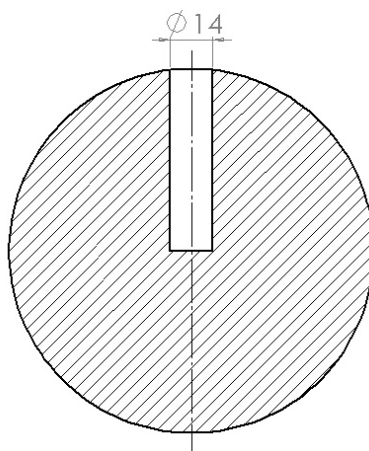


Figure 8. The diagram of a variable weight spherical explosive charge initiated from the top



Figure 9. Assembling the tested material systems: 1 – aligning sleeve

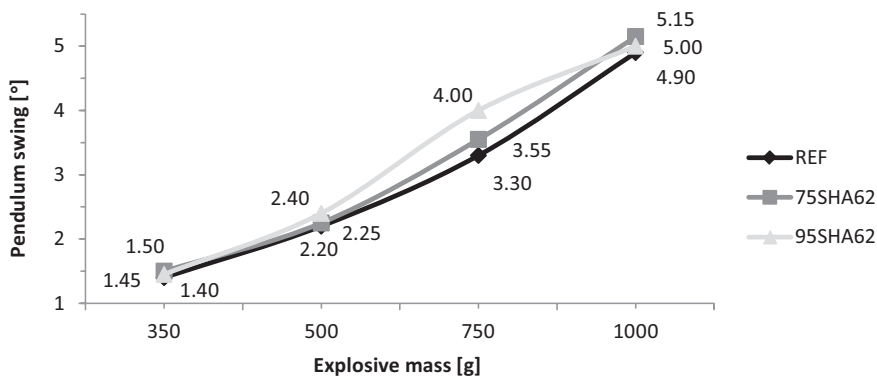
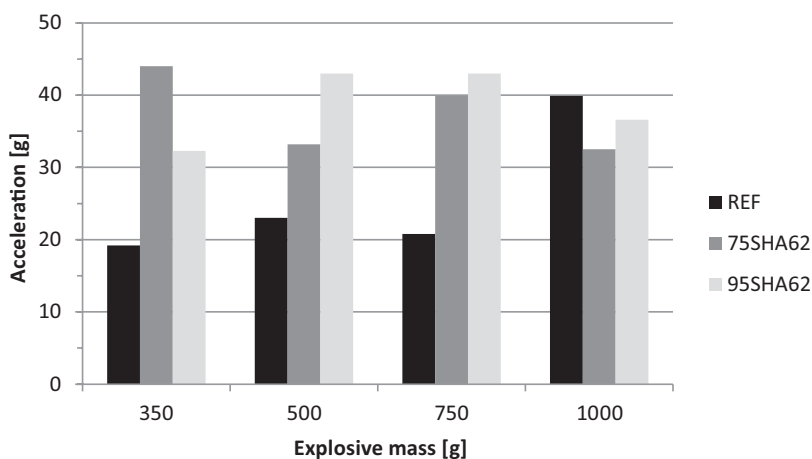
The tests involved evaluating the effect of the blast wave on an empty steel plate system (two steel plates without any intermediate layers) and two steel plate systems filled with: 75SHA62 and 95SHA42. The test involved determining the work of those systems by calculating the swing of the ballistic pendulum as a result of the blast wave pressure [3]. Table 3 and Figures 10 and 11 show the data collected during the tests for all tested absorber types. The energy of the ballistic pendulum was determined in accordance with [1] using Equation 1:

$$W = M \cdot g \cdot L \cdot (1 - \cos\varphi) \quad (1)$$

where: M – weight of the pendulum with panel = 390 kg, g – gravitational acceleration = 9.81 m/s^2 , φ – pendulum swing angle [°], L – pendulum arm length from the axis of rotation to the centre of mass = 2.985 m.

Table 3. Measurement results – ballistic pendulum

System	Explosive charge weight [g]	Pendulum swing [°]	Maximum pressure P_{\max} [kPa] at [m]				Pendulum energy [J]	Maximum pressure impulse [Pa·s]
			1.0	1.5	2.0	2.5		
REF	350	1.40	304.82	181.03	94.27	–	274.09	241.80
	500	2.20	406.20	214.48	122.20	–	433.97	324.00
	750	3.30	375.86	271.00	148.00	–	650.96	452.70
	1000	4.90	482.00	390.40	–	129.90	970.73	552.10
75SHA62	350	1.50	383.45	170.34	101.60	71.00	296.93	278.30
	500	2.25	378.62	205.51	122.90	85.40	445.39	426.30
	750	3.55	462.10	291.72	168.29	118.80	708.06	489.00
	1000	5.15	486.21	352.41	201.11	135.87	1016.41	654.20
95SHA42	350	1.45	318.96	169.65	99.16	67.36	285.51	259.10
	500	2.40	420.68	216.55	90.08	77.08	468.23	323.30
	750	4.00	395.86	294.48	168.29	102.30	788.00	489.40
	1000	5.00	492.41	327.58	181.56	126.08	993.57	624.50


Figure 10. Ballistic pendulum mortar swing as a function of explosive charge weight

Figure 11. Ballistic pendulum mortar acceleration during the experimental tests

The tests to determine the explosion energy absorption of the tested systems allowed an estimation of their effectiveness to be made. The plots of the shock wave (pulse, pressure) generated by the different weight explosives were determined experimentally. The recorded overpressure waves 1.0, 1.5, 2.0 and 2.5 m from the detonation point, were used to determine the relation between the maximum overpressure wave (P_{\max}) and the location of the piezoelectric pressure sensor.

The systems filled with polyurethane of different hardness, showed effective and repeatable energy absorption capabilities and the materials used for the design did not degrade as a result of the test loads. In those solutions, the explosion energy is dissipated by the change in shape and height of the element under load.

The design of the impact energy absorber allowed the energy to dissipate and reduce its impact on the ballistic pendulum. The degree and scope of energy dissipation was controlled by using materials with different strength properties. The overpressure, as a result of detonation, generated pressure on the system surface resulting in compression. This was converted into strain and temperature inside the system. After multiple loading of the tested absorber with a blast wave, no changes in the shape of PU sleeve (height, crowning) were observed. This was not the case under static sample compression, where change in sleeve diameter was observed. Time is a key factor in those two cases. For the static tests, the compression lasted for 30 s, whereas for the dynamic tests of the blast wave, the loading lasted for 0.0015 s.

4. Summary and conclusions

The aim of the tests was to determine the differences in tested material systems and included material hardness and explosive charge size. The static tests enabled the determination of the optimum solutions for the testing carried out at the testing grounds. The aim was to obtain information on the ability of the tested absorbing elements to absorb energy generated by the shock wave, based on measurable parameters. The ballistic tests showed several design faults:

- a) filling the systems with polyurethane foam to provide rigidity,
- b) insufficient spacing of the sleeves.

The energy absorbing properties of the materials were determined using the acceleration recorded for each system. The 75SHA62 and 95SHA62 polyurethane sleeves showed the highest work recorded for a 1000 g explosive charge detonation. Compared to the system without intermediate layers, the attenuation of the blast wave was 18.55% (75SHA62) and 8.27% (95SHA62), proving that the materials with a lower rigidity and a lower number of energy-absorbing elements per surface area, are more effective.

The results of multi-variant explosive tests enabled the identification of two hazard sources: shock wave and acceleration. The results will be used to optimize armour design and the carrying out of further validation tests.

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