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RESEARCH ON THE EFFECTIVENESS OF THE INNOVATIVE PROTECTIVE STRUCTURE FOR VEHICLES

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Abstract

This article presents results of the research on developed innovative protective structure for vehicles. The fundamental objective of executed work was to check the correctness of assumed assumptions, shape and geometry of the solution and configuration of components that affect the protective effectiveness during the impact of the explosive. In order to reach that goal, both model tests and experimental tests were carried out.

The experimental tests were carried out on the real object. Significant information about the level, directions and nature of affecting dynamic loads were obtained as well as information about their impact on particular structure elements. The MES numerical model of the research object has been developed in LS-Dyna system. Special emphasis was placed on the mapping of complex geometry, configuration of components and their interactions. Test calculations were carried out and then the resistance calculations were made. As a load, generating post-explosion impact wave, the load imposed by normative requirements concerning the way of explosive arrangement as well as the shape and weight. The analysis of obtained results of the experimental and numerical tests allows for high evaluation of effectiveness of proposed solution.

Keywords: *structure, dynamical loads, experimental research, numerical research*

1. Introduction

The explosives, in a form of mines or improvised explosive devices, placed in the ground make a high risk for light armoured vehicles (LAV). Compared to armoured vehicles of higher weight like tanks or supporting vehicles, the light armoured vehicles are particularly susceptible to that form of attack. Especially during operations carried out within a scope of peace missions and stabilization actions. Installation of the add-armour on the LAV vehicles is not always a good solution due to their limited load capacity. In order to meet the requirements of assumed level of protection, numerous studies on the use of composite and metal materials are being carried out as well as their configuration in the structure in order to provide the most efficient energy-absorbing shield for a vehicle [1]. The research on the susceptible energy-absorbing elements were presented, among others, in the papers [2-5, 10], where authors describe the results of analyses performed on the effects induced in the model energy-absorbing systems, made of metal spatial structures, by a detonated explosive. These tests were carried out at small scale on the laboratory samples using small energy equivalents. According to quoted literature, the purpose of applied spatial structures located between two metal plates is to convert the explosion energy into the energy of deformation of spatial structures. However, it is a right solution for low detonation energy and it can be applied where a low-weight shield is required.

The shape of the shield has a high influence on dispersion of detonation energy. Currently, the V-shaped bottoms are widely used in the wheeled armoured vehicles. As presented, among others, in the paper [6] the shape has a significant influence on dispersion of the detonation wave generated under a vehicle. However, that type of chassis is usually applied in LAVs as they have high clearance. Caterpillar vehicles, due to their specific structure, low clearance and drive transmission method, have limited abilities to use V-shaped deflectors. Besides, these vehicles are characterized with higher resistance to kinetic means of destruction and have a higher weight at minimized unit pressure on the ground at the same time [7]. Due to that, the weight added to a vehicle has a lower impact on its mobility. It allows for the use of shields made of composite materials of higher weight and rigidity but of sufficient plastic and springy susceptibility, using the structures of composite materials placed between the vehicle bottom and the crew cabin. The literature review indicates that vehicles equipped with properly designed, heavier energy-absorbing shields made of properly selected materials are more resistant to higher levels of exposure [15-16]. It results from the fact that they reduce the impact forces affecting the main part of a vehicle body and it directly affects the level of injury of the vehicle crew.

Irrespective of the military aspects, the energy-absorbing shields used in the civil industry are also tested, where there is a risk of gas detonation often with discharge of solids. It refers to e.g. coalmines, where deposits are characterized with occurrence of methane, oilrigs or protection of the government buildings against the acts of terrorism [8, 9].

2. Experimental Tests

2.1. Test Objects, Test Station

The test object included a model of a flat deflector, protecting the vehicle cabin bottom against the effects of the impact wave resulting from a detonation of the explosive. Deflector area amounted to 1 m^2. It consists of two sheets made of the Armox 500T armour steel, separated with an element, which damps the explosion energy. The bottom part of deflector is made of the 6mm sheet and the upper part of deflector is made of the 8 mm sheet. The damping element is located inside a rectangular steel frame made of an 80x80x3 mm closed profile and spot-welded to the armour sheet. Internal dimensions of the frame are 830x830x80 mm. Complete deflector was installed on the test station, modelling the vehicle cabin between two ”double T” profiles. After installation, it made the floor of the cabin model (Fig. 1a). Additionally, the ”double T” profiles were fastened with two steel flat elements. The cabin model was made of ”double T” profiles of increased resistance, that were cased with steel sheets and fixed with screws to the main frame structure of the test station in a way the lower sheet of the floor of the cabin model was located at the height of 450mm over the detonation plate (Fig. 1b).

a) *b)*

Fig. 1. Test station: a) 3D model; b) position on the training area

The detonation plate was made in accordance with recommendations of the standard document AEP-55 vol. 2. It has a cylindrical cavity where the explosive was detonated. Application of the detonation plate of that shape allows for repeating the experiment using the explosive of the same weight. Moreover, it directs the whole explosion energy to the tested object.

The cabin model was enclosed with a thin metal sheet in order to avoid entering of reflected post-explosion wave inside the cabin and to avoid the impact of the overpressure on the tested deflector from the top and interfere with the measurement result. The tests were carried out for 4 different deflectors with different ability to suppress the energy of the explosion wave. Deflectors were marked with the following symbols: P1; P2; P3; P4.

2.2. Test Methodology

The tests were carried out at two independent stages. Stage 1 included the tests on the military training area. The purpose of these tests was, apart from stating whether the tested deflector was physically pierced, to measure the maximum metal sheet deflection caused by detonation of the 1.5 kg TNT explosive and to measure the permanent deflection of the metal sheets after the end of the process. For that purpose, the measurement method, described in the American Test Operations Procedure TOP 2-1-007:2008 was applied [9]. The procedure makes use of the template of defined dimensions, made of a soft inelastic metal. The template is in a trapezoid shape with notched rectangular rods of various heights, fig. 2.

a) b) c)

Fig. 2. Template for deflection measurements: a) in accordance with TOP 2-1-007:2008; b) installed in the test station, c) test result

The longest rod touches the surface. The surface deflection causes bending of rectangular rods. Due to the fact that each rod has a defined size, the value of the biggest deflection can be calculated on that basis. At the stage 1 of the subject tests, a template made of a thin 0.5 mm aluminium sheet was used to measure deflection of the upper deflector sheet. The highest deflection value indicated by a bending of particular (dimensioned) rod informs about the maximum deformation of the upper deflector sheet. Read dimension of that dynamic deflection of the sheet is a sum of elastic and plastic deformations. In the next test step, after the end of the explosion process, the measurements of permanent (plastic) deflections of the lower and the upper sheets were carried out. Their maximum bending in relation to the reference line running on the opposite corners of the sheets was measured.

The essence of the performed tests was to obtain, by means of a measureable parameter, information on the abilities to absorb the energy coming from the impact wave by tested deflectors. For the purpose of comparison, the deflector without a damping element, composed of steel armour sheets only, was also tested. At stage 2, structures of the subject deflectors were modelled and analysed numerically.

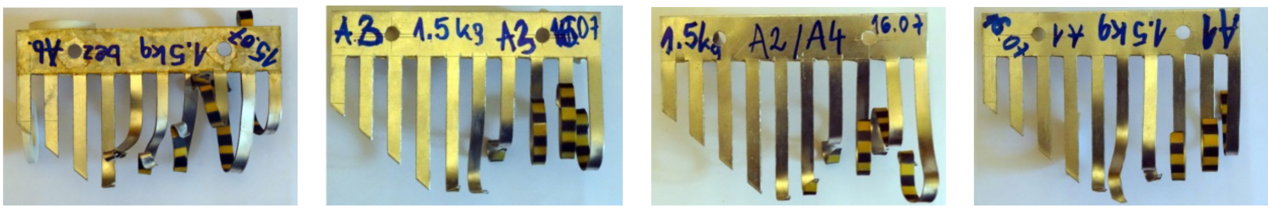
2.3. Results of the tests performed on the military training area

The results of deformation measurements for tested deflector solutions as a result of stage 1 of the tests are shown in table 1 and on fig. 3.

Tab 1. Specification of the experimental test results

No.	System	Explosive weight [kg]	Damping element	Total system deformation [mm]	Permanent deformation [mm]	
					Upper sheet 8 mm	Lower sheet 6 mm
1	P1	1.5	Without element	101.3	22	80.5
2	P2	1.5	A1	79.1	9	0
3	P3	1.5	A3	86.9	17,3	0
4	P4	1.5	A2/A4	82.3	15	0

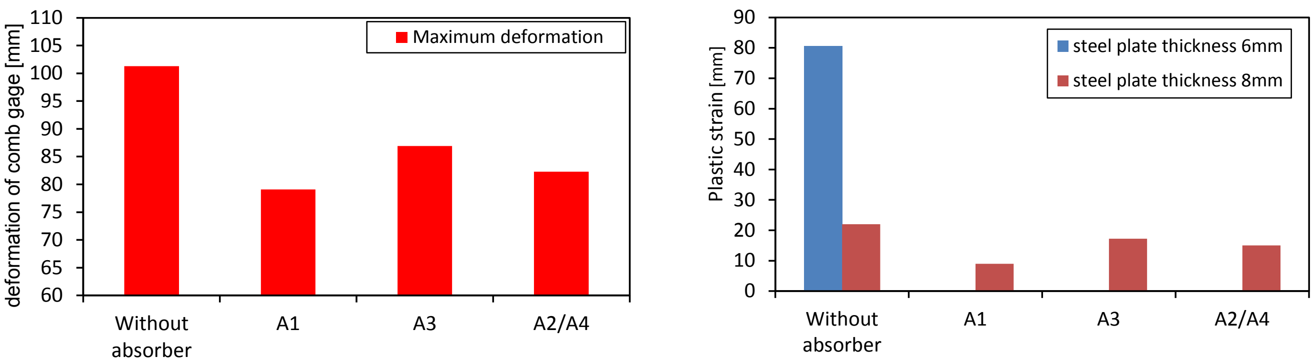
In the tested systems with damping elements A1, A3 and A2/A4 the maximum deformation values amounted to 79.1 mm, 86.9 mm and 82.3 mm respectively. The measurement results indicate that the deflector with a damping element A1 has a better ability to damp the energy than other solutions. Confirmation of that statement was reflected in measurements of plastic deformations of the upper 8 mm sheet (Fig. 3b) and amounted to 9 mm.



a) b) c) d)

Fig. 3. Appearance of measuring combs after performed tests: a) without a damping element; b) with a damping element A1; c) with an element A3; d) with an element A2/A4

Regarding the reference deflector P1, where its value of the plastic deformation of the upper 8 mm sheet amounted to 22 mm, a 60% decrease of the deformation value (Fig. 4a) was obtained. In case of damping elements A3 and A2/A4, deformation of the upper sheet amounted to 17.3 mm and 15 mm. While in all solutions of deflectors with damping elements, the lower 6 mm sheet has not shown any deformations within a plastic scope (Fig. 4b).



a) b)

Fig. 4. Experimental results of deformations: a) Total and b) permanent, of the energy-absorbing partitions without and with absorbers A1, A3, A2/A4

3. Model tests

The method using the description of the gas movement in the Euler's space and its interaction with the structure (FSI – Fluid-Structure Interaction) was used for the analysis of the phenomena of the influence of the explosive detonation pressure on the structure. The JWL condition equation was used for description of the pressure of the explosive detonation products. It considers the value of the pressure from the relative capacity and internal energy of the explosive. It has the following form [12]:

$$p = A \cdot \left(1 - \frac{\omega}{R_1 \cdot V}\right) \cdot e^{-R_1 V} + B \cdot \left(1 - \frac{\omega}{R_2 \cdot V}\right) \cdot e^{-R_2 V} + \frac{\omega \cdot E_o}{V}, \quad (1)$$

where: E_o – the internal energy of the explosive per capacity unit; V – relative capacity of the explosive, A, B, C, R_1, R_2, ω – equation coefficients defined experimentally.

3.1. Test object model

The test object model was based on the flat deflector, being a prototype innovative protective structure. Fig. 5 shows a basic flat deflector model, while fig. 6 presents an example of the absorbing insert.

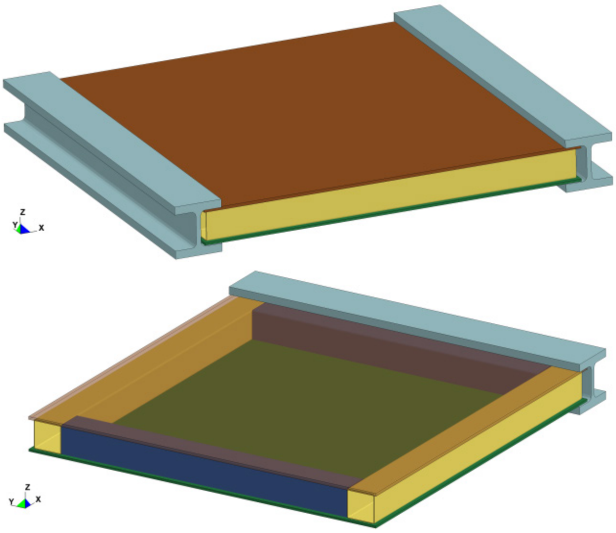


Fig. 5. MES model of the base innovative protective structure – flat deflector

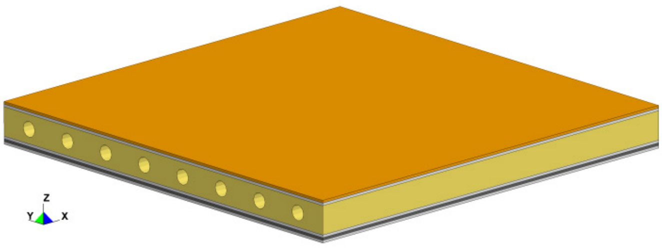


Fig. 6. Model of one of the deflector absorbing inserts

3.2. Model test results

Fig. 7 presents phases of the pressure wave propagation in the air elements. Contrary to the explosives detonated on the flat ground, in case of placing the explosive in the cylinder, vertical orientation of the pressure wave is visible. As a result of such detonation, the values of the pressure affecting the elements placed directly over the explosive can reach the values 2-3 times higher than for the hemispheric explosive.

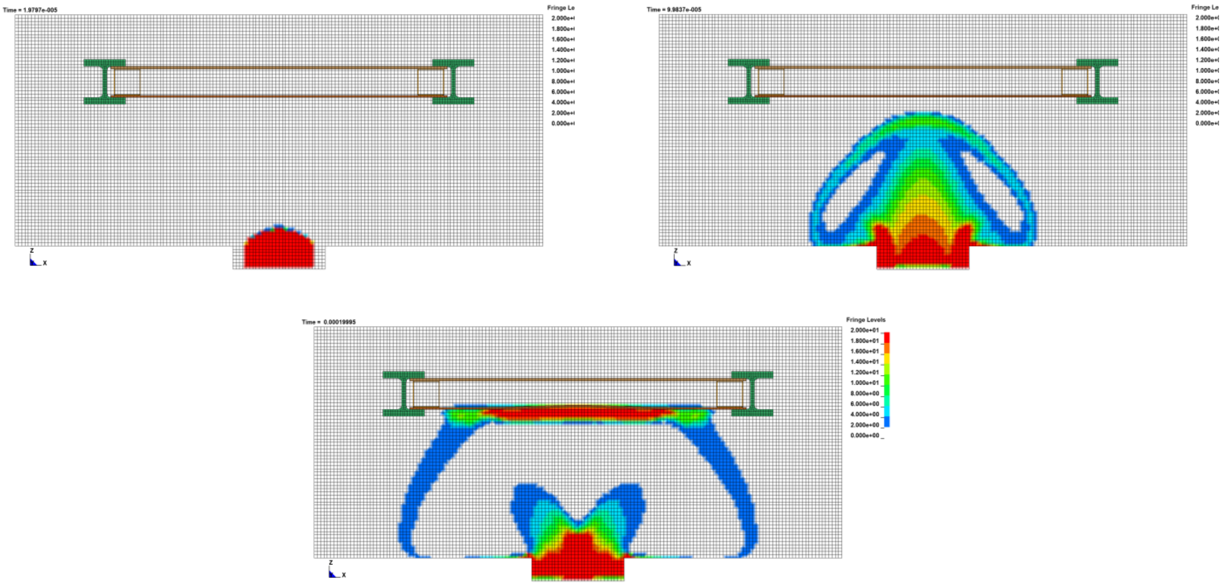


Fig. 7. Pressure propagation phases (t = 0.02; 0.1; 0.2 ms)

Fig. 8 presents phases of deformation of the basic deflector. After about 0.2 ms the lower plate touches the upper plate. As a consequence of the energy transfer, the upper plate starts to deform. For the time of about 2.5 ms, the upper plate undergoes the maximum deflection. The centre of the lower plate goes up by app. 162 mm, while the centre of the upper plates moves by 90 mm (Fig. 6.6). After the disappearance of the pressure wave, the panel plates vibrate freely. High deflection of the lower plate causes breaking of the joints that connect profiles with the bottom. As a result, a partially deformed profiles located on the sides of the panels are pushed outside.

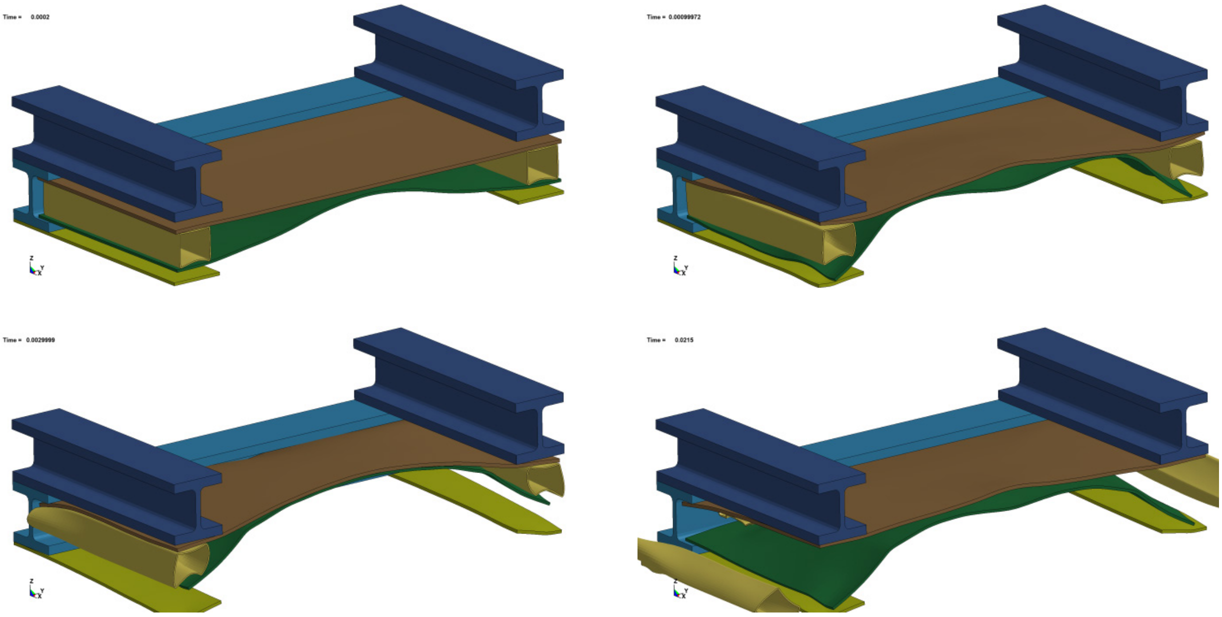


Fig. 8. Base deflector deformation phases (t = 0.2; 1; 3; 21.5 ms)

Fig. 9 presents deformation of the panel with the absorber **B (P2)**, while fig. 10 shows the panel with the absorber **C (P3)**. Introduction of the absorber significantly affected the course of deformation of the armour plates. The essential transfer of the explosion energy takes place through the absorber insert. At the initial stage, the insert bends accumulating the energy. Due to small damping, this energy is then transferred to the upper plate. However, contrary to the base panel, it takes place on much bigger area. The plate bends evenly and there is no local creasing of the metal sheet. After the end of the process, the plates with the filling vibrate freely until complete cessation of the movement.

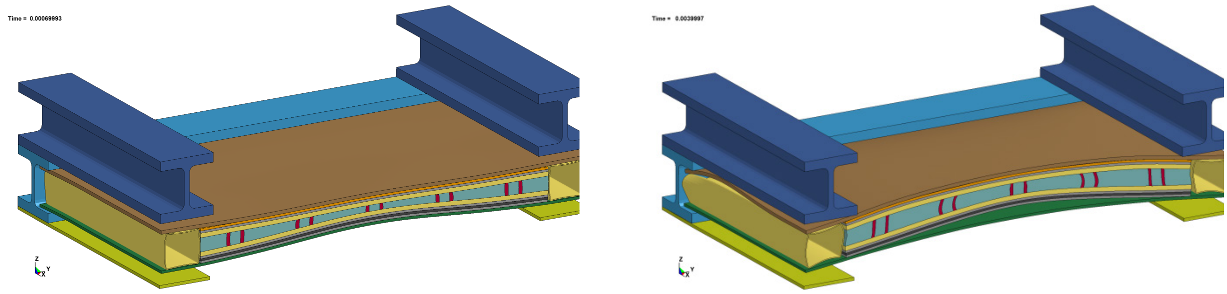


*Fig. 9. Deformations of the deflector with the absorber **B (P2)** (t = 0.7 and 4 ms)*

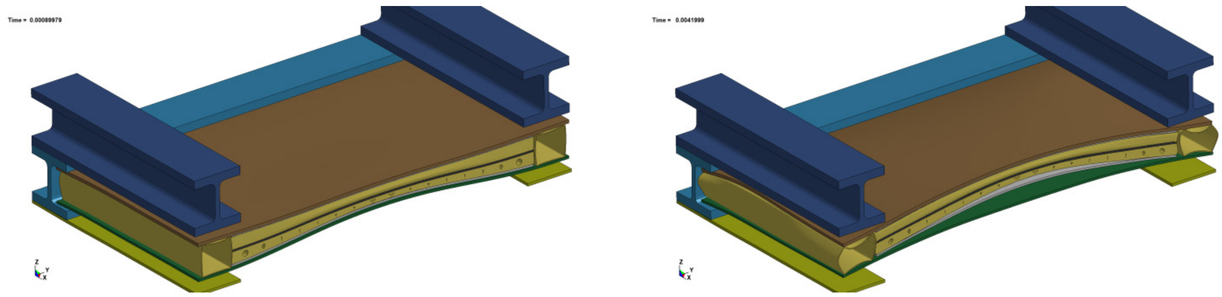


*Fig. 10. Deformations of the deflector with the absorber **C (P3)** (t = 0.9 and 4.2 ms)*

Different process of the armour plate deformation affects the distribution of stress in the plates and the form of plastic deformations. The maximum stress values for the plates with absorbers are about 600 MPa lower than the stress in the plates of the base deflector. During calculations, the limit of plasticity for the lower plate material was practically not exceeded. Therefore, it does not undergo permanent deformations. The upper plate slightly bends alongside edges – permanent bend amounted from 7 to 11 mm depending on a type of applied absorber. However, it should be underlined that the middle part of the plate remained flat contrary to the base model.

4. Summary and final conclusions

The comparative analysis of obtained results from performed experimental and numerical tests indicates their good compatibility. Differences of dynamic bends and permanent deformations for analysed variants usually do not exceed 10%. Moreover, similar forms of deformations of the upper and the lower plates were obtained.

Considering obtained results it should be stated that introduction of additional reinforcement of the bottom filled with absorber panels favourably affected the level of the bottom deformation. Dynamic bend and the distribution of permanent deformations decreased. The absorber inserts break the force into a bigger surface and therefore the whole bottom deforms evenly. Therefore, there is no local bending of the metal sheet, as in case of structures without the inserts, resulting from the effect of the impact of the lower and the upper plates. Moreover, the introduction of absorbers causes the reduction of the structure straining level.

Obtained results of the experimental and numerical tests on the protective panels make a basis for carrying out the tests on the full-size object models equipped with proposed protective structures.

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