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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF ENERGY ABSORPTION ELASTOMER PANEL WITH HONEYCOMB STRUCTURE

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Abstract

The paper presents a prototype design of elastomer energy absorbing panel made in a shape of honeycomb structure. The proposed panel was installed in a protected plate and tested on a specially designed test stand, where a shock wave from a small explosive charge was applied. The elastomer honeycomb structure was compared with a version of the panel made of solid elastomer materials, the same as used in the honeycomb structure and also with a protected plate without any panels. During the research, acceleration in the middle part of each investigated protected plate was recorded. The protected plates were scanned after the tests in order to measure their maximum deformation. Acceleration graphs and maximum deflections of all three considered structures were compared.

The obtained results were used to validate numerical models of the designed structures and the test stand. A discreet model of the test stand and models of elastomer panels were developed with HyperMesh FEM software using shell and solid elements. The materials were described using a tabulated Johnson-Cook model and constitutive model for the rubber parts; all available in the material library of Ls-Dyna software. The blast loading was simulated using the CONWEP method. This model generates a boundary condition, based on the experimental data and TNT equivalent mass, which substitutes the wave propagation with a pressure.

Finally, the experimental results of acceleration and deformation of the plates were compared with the corresponding results of the numerical analyses carried out using finite element method. The numerical models can be utilised in the future research as a virtual range stand. The developed elastomer honeycomb structure can be modified to meet various requirements of ballistic protection levels, by applying elastomer of different stiffness or optimizing shape and dimensions of the honeycomb structure.

Keywords: *energy absorption structure, blast shock wave, numerical modelling, elastomer, validation*

1. Introduction

The paper presents the results of explosive tests and numerical analyses of energy absorption capabilities of protective panels, in which the main energy absorbing materials are elastomers. These materials have many advantages including high deformability while maintaining the elastic properties, high capabilities of energy absorption and dissipation, mechanical strength, constant hardness, high resistance to chemicals, a wide range of available elastomer products and the possibility to form any shape [1]. Such features qualify these materials as very good candidates for panel components.

The investigated panels were made in two variants: panel with layers made of solid elastomers and panel with layers made of elastomers in the shape of honeycomb. Both panels were installed on protective plates. Furthermore, they were compared with each other and with a protective plate tested without any panel.

The prototype panel with a honeycomb structure is characterized by a slightly weaker parameters relative to the solid counterpart. On the other hand, its main advantage is reduced mass, which is approximately two times lighter than in case of solid panel. This factor is very important for potential application in military vehicles. Moreover, empty spaces inside the panel can increase the buoyancy of the protected structure and the vehicle itself.

Two types of elastomers of medium hardness were used, each for one of two inner layers of protective panel construction. They were developed to minimize effects of an explosive charge with a mass of approx. 1.0 kg. On the market there are many elastomeric materials, with a wide range of properties (e.g. different hardness), which allow to design a panel for required level of ballistic protection [2]. Numerical simulations using finite element method presented by the authors in the paper can be very helpful during the designing process.

2. Object of investigation

The object of study is the energy absorbing multi-layer elastomer panel considered in two configurations. Both configurations of the panels are shown schematically in Fig. 1. In the first configuration (type A) the panel consists of four layers. Two internal layers are made of solid elastomers: Asmaprene Q (2) and Asmathane (3). The two outer layers (1) and (4) are aluminium alloy 2024 / T351 plates with the thickness of 3 mm. In the case of second configuration (type B), the arrangement of the layers and materials are the same as in type A panel, whereas the difference is an openwork structure in the shape of honeycomb, the same for both elastomeric layers. Both panels were installed on protected plates made of 41Cr4 steel with the thickness of 3 mm. In the Tab. 1. configuration of the panels and properties of materials of individual layers are presented. Thickness, weight per 1 m2 and hardness for each material were described.

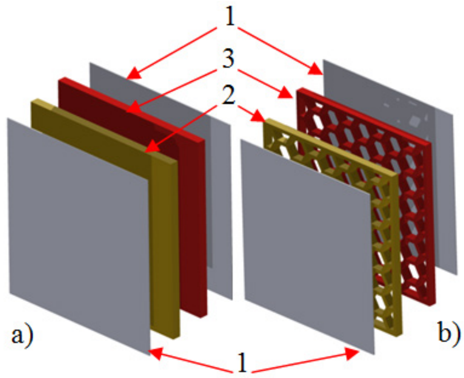

Fig. 1. Configuration of energy absorbing elastomer panels: a) without openwork structure, b) with openwork structure

Tab. 1. Configuration of energy absorbing panels and material properties of the layers

Layer number	Material	Thickness [mm]	Mass 1m^2 (type A) [kg]	Mass 1m^2 (type B) [kg]	Hardness
1	2024 - T351	3	8.13	8.13	124 [HB]
2	Asmaprene Q	20	27.50	10.40	55 [ShA]
3	Asmathane	20	25.96	9.82	65 [ShA]
Details of the complete panel		**50**	**69.72**	**36.48**	–

Dimensions of the honeycomb shape in the openwork structure were optimized based on preliminary numerical analyses. Selection of an optimal structure was made based on the criterion of maximum panel weight reduction with simultaneous acceptance of possible small deterioration of protective properties of the optimised panel. When working only for compression, the honeycomb structure absorbs maximum energy from the explosion.

Additionally, a developed during FEM simulations cross section of openwork walls guarantee the buckling of the structure not to occur during an initial loading from a blast wave (first cycle of load). It is known, that such a structure when operates only in compression load absorbs maximum blast energy.

Applied aluminium linings significantly do not effect on total mass of the panels, and they can be used for small explosives. When designing a panel for protection against a much larger explosive charge it may be necessary to strengthen the cladding layer, e.g., by increasing the thickness to avoid pinholing. It is very important for the panel having openwork structure, as any perforation of the cladding layer adversely affect the efficiency of energy absorption capabilities of the panel.

All layers of the panels were glued to each other and to the protected plate using elastomer Biresin 1419. It was decided to use this particular elastomer due to its very good adhesion to both metallic and rubber materials and resistance to weather conditions.

3. Test stand and conditions of the experimental research

Experimental studies were carried out on the test stand shown in Fig. 2. It consists of the support (1) on which the main frame is situated (2). To the main frame (3), the energy-absorbing panel (4) with the protected plate (5) are screwed with an overlay. On a specially profiled rod (6) fixed to the overlay, the explosive load is hung (7).

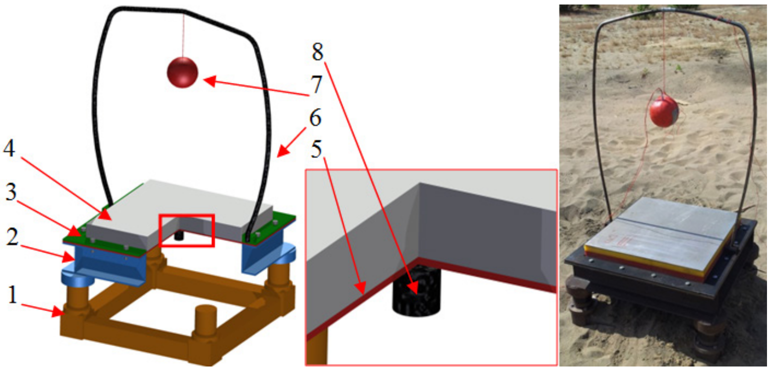

Fig. 2. Test stand: a) scheme, b) zoom of central area; c) picture from field tests

Tests of energy absorption panels as well as protected plate without a panel were carried out with the use of HE of mass 750 g (Semtex). Detonation of the HE was at a height of 430 mm from the plate.

During investigations of the HE detonation the signal of the piezoelectric acceleration sensor (8) (ICP PCB Piezotronics) was recorded. The sensor was installed on the middle of the plate on the opposite side of the panel relative to the load. The signal measurement was performed using the amplifier LTT500 connected to the recorder of fast measurements National Instruments (Fig. 3a). Recording device was connected to laptop (Fig. 3b) with the software for controlling devices and archiving test results. The signal was recorded with the sampling frequency of 0.5 Msamples/s. In graphs presented in the paper there are shown the results obtained for the first 10 ms of recorded data.

a)  b) 

Fig. 3. Fast waveform recorder National Instruments with connected measuring amplifier LTT500 (a) and a laptop computer recording results (b)

4. Numerical analyses of energy absorbing panels

Numerical models of tested variants of the panels and the protective plate were developed using modern CAE tools. Geometric models were made in Autodesk Inventor Professional. Discretizing process was carried out using HyperMesh software. Numerical simulations were performed using the computational code Ls-Dyna. LS-Prepost was adopted for pre- and postprocessing.

To develop discrete models eight-node brick elements and four-node shell elements were used. In all simulated scenarios (variants) interaction between parts was taken into consideration by adopting the contact procedure based on the penalty function method. Moreover, default values of friction in all contact definitions were used. The gluing of the panels in actual tests was simulated using tied-type contact. Due to bisymmetry of the test stand, a quarter of the model with adequate symmetry conditions was used in FE analyses. Three variants of the models are shown in the Fig. 4.

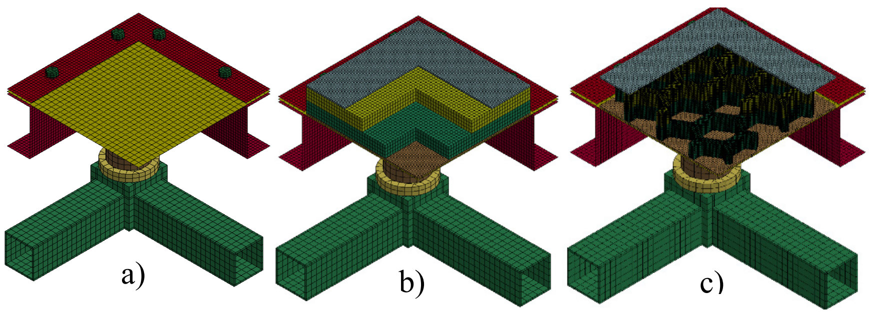

Fig. 4. Numerical models: a) test stand with protected plate, b) test stand with A type panel, b) test stand with B type panel

Tab. 2. Material constants of metal materials used in numerical analysis

Parameter	St3 steel	10.9 bolt steel	2024/T351	41Cr4
Mass density (RO)	7.85e-6	7.85e-6	2.6e-6	7.85e-6
Young's modulus, (E)	210	210	70	215
Poisson's ratio, (PR)	0.30	0.30	0.33	0.33
Yield stress, (SIGY)	0.33	0.90	-	-
Tangent modulus, (ETAN)	1.00	1.00	-	-
Plastic strain to failure, (FAIL)	0.50	0.50	-	-
Specific heat, (CP)	-	-	900	450
Room temperature, (TR)	-	-	300	293

In the numerical analysis, three types of materials model were used. To describe the elements of the test stand, which are working in the elastic, range applied (MAT_PIECEWISE_LINEAR_ PLASTICITY) material model. Elements of the test stand where this material was assigned are the supports, the main frame, the overlay, bolts and nuts (Fig. 2). The data used in that model are shown in Tab. 2.

To describe the panel linings made of aluminium 2024-T351 and the protected plate made of a material 41Cr4, tabulated Johnson-Cook (TABULATED_JOHNSON_COOK) material model was used. It allows describing behaviour of the material in the elasto-plastic range, taking into account its viscoplastic strengthening and thermal weakening (or strengthening). The flow stress is expressed as a function of plastic strain, plastic strain rate and temperature.

In the material model, it is possible to use a failure model based on a strain criterion. Plastic failure strain is defined as the result of several functions: stress parameters, scaling function of failure plastic strain by influence of strain rate, temperature and elements size [3].

The data for 2024 aluminium alloy were taken from the literature [4], while for the material 41Cr4, they were obtained base on own laboratory tests. The basic parameters are shown in Tab. 2.

In the case of aluminium alloy 2024 type, which was exposed directly to the explosion, there was applied full material model taking into account the influence of strain rate and temperature. In addition, there was used full failure model taking into account a state of stresses in the material. In the case of 41Cr4, material curves for the three strain rates were utilised. The effects of temperature and model of material failure were not taken into account, because after the research there was no damage (failure) of the protected plates.

The elastomer materials were modelled by material type (SIMPLIFIED_RUBBER / FOAM), which allows to describe the rubber materials and the foams through the introduction of hysteresis loop. The data used for the two types of elastomers Asmaprene Q and Asmathane, were determined because of performed compression and tensile tests. The material constants for elastomeric materials are presented in Tab. 3. The hysteresis loops shown in Fig. 5a) and b) present load-unload cycles for compression and tension describing Asmaprene Q and Asmathane respectively.

Tab. 3. Material constants for elastomeric materials

Parameter	Asmaprene Q	Asmathane
Mass density (RO)	1.250e-6	1.180e-6
Linear bulk modulus, (K)	0.23330	0.31329
(RP/BETA)	0.45	0.45

The blast loading was simulated using the CONWEP method. This model generates a boundary condition, based on the experimental data and TNT equivalent mass, which substitutes the wave propagation with a pressure. A type of blast source is spherical free-air burst (BLAST=2) [3].

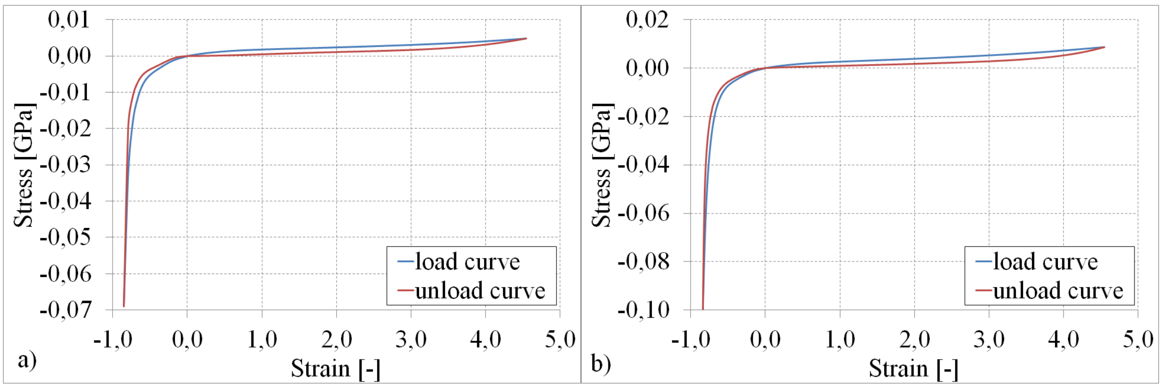

Fig. 5. Hysteresis loops of compression and tension for elastomeric materials: a) Asmaprene Q; b) Asmathane

5. Comparison of the numerical analyses and the experimental research

After the experimental investigations, it was shown that none of the tested panels (type A or B) was destroyed. The outer aluminium sheets of both panels were not perforated. Elastomer inserts did not show any signs of damage, and they potentially could have been used again. The protected plates of both types of panels were deflected. In the case of openwork structure of the panel B, local plastic deformations in the places corresponding to empty spaces in the elastomeric openwork structure were found. The adhesive bonds between the individual layers of the panels both A and B was crushed. The panels A and B after the explosive tests were shown in Fig. 6a and 6b respectively.

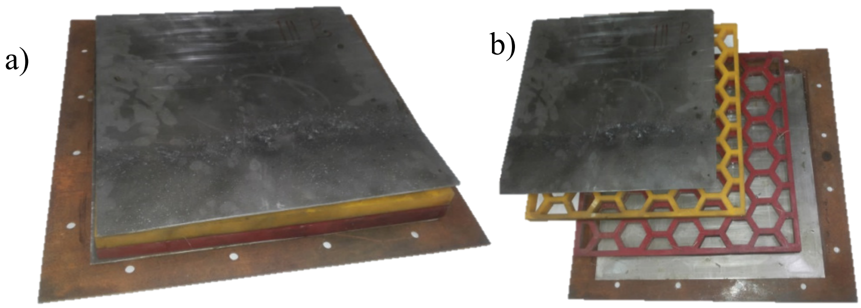

Fig. 6. Energy absorbing panels after experimental investigations: a) panel type A; b) panel type B

Tab. 4. Deformations of the protected plates received from experimental and numerical analysis

Panel type	P1 [mm]	P2 [mm]	P3 [mm]	P4 [mm]	Average from the experiment [mm]	Numerical analysis [mm]	Relative error δ [%]
Protected plate	31.1	31.6	31.2	30.8	31.2	33.5	0.53
Panel type A	3.4	3.3	3.3	3.4	3.3	5.3	0.47
Panel type B	20.7	21.0	20.7	20.5	20.7	24.5	0.88

To verify permanent deformation of the protected plates for each test, the maximum deflections were measurements in their central parts. The average from four performed measurements was calculated and presented in Tab. 4.

It is possible to estimate the relative error between experimental data and numerical investigations according to the formula below [5]:

$$\delta = \frac{|d_N - d_E|}{L} \cdot 100\%, \tag{1}$$

where:

dN – deflection of the protected plate calculated from the numerical analysis,

dE – deflection of the protected plate obtained from the experimental research,

L – reference distance equal to 430 mm. Tab. 4. presents the obtained results both from the experimental research and calculated numerically as well as the relative error obtained according to (1) [5].

The results of numerical investigations show good accordance with experimental research. Based on (1) relative errors were determined, which are as follows: the protected plate – 0.53%, the A panel configuration – 0.47%, and the panel B configuration – 0.88%.

Use of the panels reduced the maximum deflection of the protected plate. A much better panel in this case was a panel of the type A, because of the heavier weight, greater stiffness and elastic characteristics of the elastomers. However, deflection criterion cannot be conclusive.

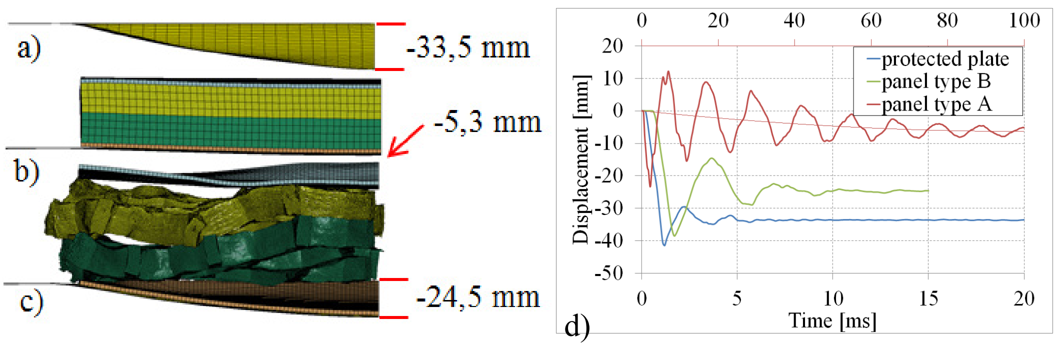

Fig. 7. Deflection of the protected plate based on the numerical analysis: a) protected plate; b) A type panel; c) B type panel; d) protected plate deflection waveforms in time

In the panel B local plastic deformations of the aluminium plate occurred. The deformations absorbed a significant part of the energy of the blast load. Furthermore, the acceleration is the most common cause of injuries of a crew of military vehicles and the obtained result of the permanent deformation of approximately 20 mm does not disqualify the considered openwork structure panel as an effective protection against explosions. The results of carried out numerical simulations of deflection in the centre of the plate presented in Fig. 7d, show that the maximum plastic deflection of more than 20 mm took place just after a blast wave reached the panel and was significantly higher than the value of the permanent deflection shown in Fig. 7a-c.

The accelerations recorded from the piezoelectric accelerometers installed in the middle of the protected plates of each panel were also analysed. The acceleration waveforms were filtered with low-pass Butterworth filter of 6 row, for a boundary frequency of 2560 Hz. The graphs shown in Fig 8. compare the experimental results with calculations from the numerical analyses, which were also treated with Butterworth filter with the same parameters. The graphs present the first 10 ms of the charts after the explosion.

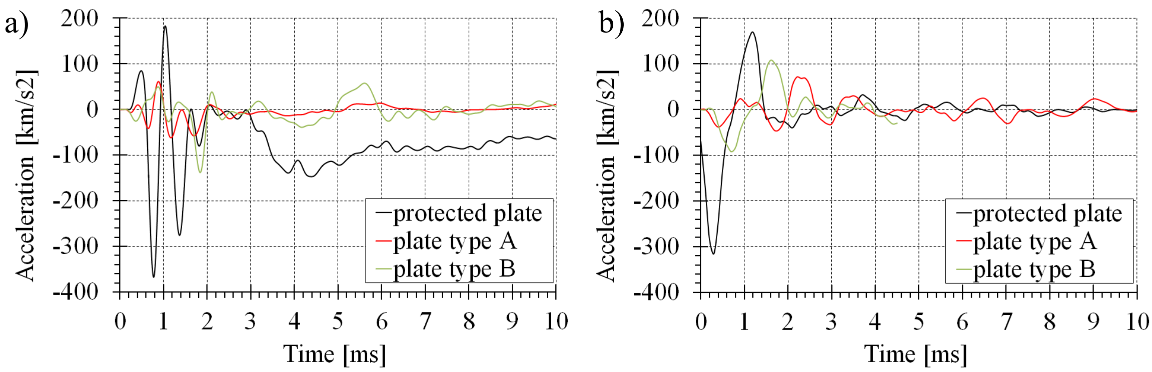

Fig. 8. Acceleration of the centre of the protected plate: a) experimental studies; b) numerical analysis

A good accordance was found between the numerical analyses and the experimental studies, both as to the general acceleration curve shapes as well as to the extreme values. Acceleration waveforms determined on the basis of numerical analyses showed slightly smaller values of the extremes than the extremes recorded from the experimental research. The middle and final part of the numerical acceleration course is flatter than the one obtained experimentally.

Comparing the configurations of the panels A and B with the uncovered protected plate; it was found that the panels significantly reduced the initial maximum acceleration peaks. The A panel reduced acceleration peaks to a greater extent than the panel B. (panel A – 62 km/s^2; panel B – 138 km/s^2; the uncovered protected plate – 362km/s^2).

In the Tab. 5. the balance of inner energy absorbed by the examined systems is presented. The calculations are based on the numerical analysis.

Tab. 5. Balance of energy absorbed by the panels based on the numerical calculations (– the energy of contact, friction, hourglass)*

	Protected plate	Panel type A	Panel type B
Total Energy [J]	**805**	**1100**	**2130**
Upper aluminum plate	-	0.5	2.26
Lower aluminum plate	-	4.5	251
Elastomer Asmathane	-	262	337
Elastomer Asmaprene Q	-	553	555
Protected plate	533	93.7	588
other*	272	187	350

In all considered cases, in the analyzed energy balance the energy resulting from contact, the energy of friction and the hourglass energy are present. The protected plate without any protection is able to absorb 553 J without destroying the plate.

The A type panel has absorbed 37% more energy (805 J vs. 1100 J) from the explosion than the uncovered protected plate. The largest amount of energy dissipated the panel B, double more than the panel A. This is due to very strong elastic deformation of the openwork structure of the panel B. In the case of A panel most of energy was dissipated in the elastomer layers.

The use of the openwork structure in the panel B increased the vulnerability of the elastomeric layers for elastic deformations, which increased the absorbed energy by the elastomers. Additionally, some part of the blast energy was absorbed by the first aluminium layer and by the protected plate. Using the criterion of an amount of absorbed energy (on the basis of the numerical research), it can be concluded that panel B is significantly more effective than the panel type A.

6. Conclusions

Based on the analysis of the results of the experimental studies and the numerical simulations the following conclusions can be drawn:

- based on the experimental research, the panel A reduced the extrema of acceleration and deflection values of the protected plate better in comparison with the panel B. However, this should not be the only criteria for best performing panel,
- the usage of the honeycomb structure in combination with suitably selected elastomeric materials can significantly reduce the total weight of an elastomeric panel, with possible only slightly efficiency drop,
- when comparing the acceleration curves and the maximum deflection of the protected plate, it was shown good accordance between experimental tests and numerical simulations. Finite element method can be an effective and relatively not expensive tool in the process of developing energy absorbing panels,
- based on numerical analysis, when taking into account the criterion of the energy absorption capability, it was found, that the panel B performed much better compared to the panel A. The usage of the openwork structure in the panel B increased susceptibility of the elastomers to elastic strains. In addition, considerable part of the blast energy was absorbed by the first aluminium layer and the protected plate.

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