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Environmental influences on propagation of explosive wave on the dynamic response of plate

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Abstract. The purpose of this article is to present the influence of the environment on the propagation of a shock wave and the dynamic response of the plate load by a shock wave. In the course of research in this field an experimental study was performed. An experimental study concerns the test plate loaded by a shock wave, formed after the detonation of an explosive device with equivalent weighing of TNT equal to 1 kg. During numerical investigations environmental impacts have been tested on the dynamic response disc. The considered environments of explosions were air water and soil. A model of the phenomenon has been prepared using commercial software MSC DYTRAN.

Key words: improvised explosive device, numerical model, validation.

1. Introduction

All kinds of numerical studies about structures which are loaded by the blast wave, are burdened with many errors. In the case of loss of dynamic stability protective structures distinguish global loss of stability of the structure and the local (in certain areas) one. This loss is due to the short pulse pressure with a high value. In the case of numerical analysis, there are a few approaches to the dynamic phenomenon. The first approach is related to the vibration of the structure. This issue was developed by many scholars [1, 2]. Modern science considers the approach to numerical analysis of implicit and explicit types. These approaches are associated with the duration of impulse and, with the frequency of the vibrations of object [3, 4].

When the pulse duration is shorter than the period of natural vibrations of object the problem is solved by explicit method.

The main problem in numerical analysis is the appropriate choice of material properties and load parameters. In the case, where load parameters are considered, often analytical methods are used [5]. These methods are based on many complex formulas and experiments [6].

2. Object of research

During research were carried out one experiment and three numerical analysis. Summary of the tested objects shown in Table 1.

All experimental studies were carried out during the realization of the research work, which the author was the head of [7]. The test ground consisted of a frame and a steel plate with a thickness of 5 [mm]. Elements of test ground were made of steel S235JR2 (according to the European standard EN 10025:1990).

Table 1
Summary of the tested objects

Test	Charge [kg]	Distance [m]	Environment	Density of medium [kg/m^3]	Experiment	Numerical analysis
1	1	0.4	air	1,2829	yes	yes
2			water	1000	no	yes
3			rare soil	2300	no	yes

The tensile test for steel S235JR2 were carried out by the Department of Applied Mechanics MUT. Exemplary test results are shown in Fig. 1.

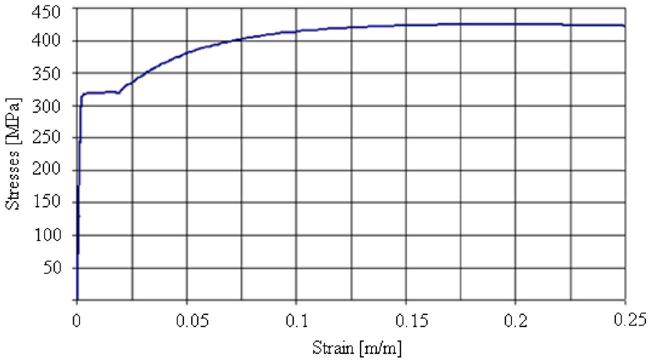

Fig. 1. The plot of the stress-strain tensile tests obtained from the plate material S235JR2 (according to the European standard EN 10025:1990)

Based on the analysis of the test results, the following material parameters are adopted for the numerical model:

- Young's modulus E = 215 [GPa];
- Yield strength R_e = 320 [MPa];
- Tangent modulus H = 700 [MPa];
- Tensile strength R_m = 430 [MPa];
- Poisson ratio ν = 0.31.

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Welding a test plate to a frame allowed to avoid the local loss of stability. Besides the strong bending, there also appeared the state of tension.

The base frame was made of steel profiles. Profiles were made of steel S235JR2 and they had square shape 120 × 120 [mm] and a wall thickness of 5 [mm] (Fig. 2). Profiles were respectively cut and welded at the corners.

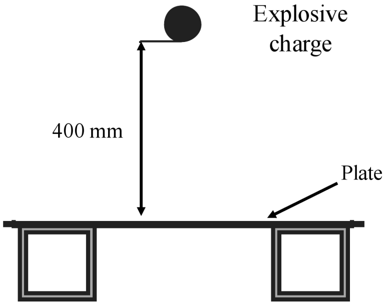

Fig. 2. The scheme of the test zone

The entire test plate had dimensions 0.76 × 0.76 [m]. An open test zone had dimensions 0.5 × 0.5 [m] (after excluding a test frame). An open test zone can be deformed freely.

The test-plates (Fig. 2) were loaded by a pressure wave (impulse) which came from detonations of explosive charges. A charge had equivalent of 1 kg of TNT. The load was placed centrally above the plate at a distance of 0.4 [m] from the top surface of the plate.

3. The results of experimental studies

Experimental studies performed in conditions of testing ground. The following test zone was made based on numerical simulation and analysis of the available literature. The results for the alone plate were presented in the work which author participated [8].

During development and implementation of the test ground the ability to change some of initial parameters of the experiment to carry out tests for different sizes of explosives was taken into account. A general view of the position is shown in Fig. 3. In additional studies, an additional steel plate was used as a non-deformable base to the leveling land effect on permanent deformation of a test plate. Additional studies have shown superfluity of the abovementioned plate – there was no difference in the final deformation of the tested systems.

The source of the pressure pulse was a big load of TNT placed at a distance of 0.4 [m] from the object. The explosive was freely placed on the test object. An induced detonation pulse load was characterized by the short duration and high amplitude. The duration of this pulse pressure is an order of magnitude or even two orders shorter than the time of impact, and is a few tens of milliseconds.

Fig. 3. A general view of the position of test panels loaded by large explosives

A result of the experiment was the obtained permanent deformation of a test plate. A size of deformation was initially measured using the straight edge and caliper. The deformed base plate is shown in Fig. 4. Figure 4a shows a photograph of a test plate after the experimental study and Fig. 4b shows a map of permanent deformation obtained using a 3D scanner. As a result of scanner measurements, it was found that the permanent deformation of the plate was 16.5 [mm]. This value was measured in the symmetry center of a plate, at the site of the largest deformation.

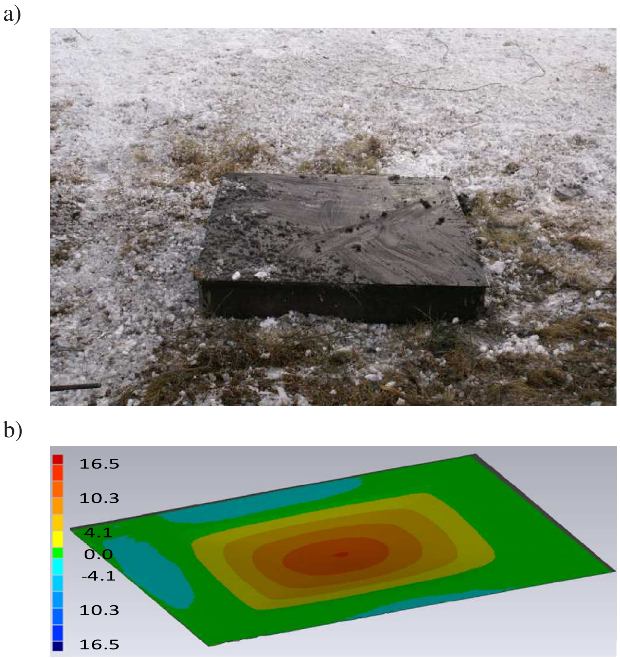

Fig. 4. Appearance of an experimental position after the experiment – Test 1: a) the system after the explosion, b) deformation map obtained by measuring with the use 3D scanner

4. Numerical research

4.1. The formulation of the physical model. Analysis of the impact of a pulse pressure on the structure was carried out by the finite element method (FEM) with the explicit scheme of integration of equations of motion implemented in the MSC DYTRAN [3]. In those algorithms the equilibrium equation of discrete model (4.1) is solved by direct integration of the time. These equations occur in the conjugate form, which binds with high numerical cost of their solutions and high demand for memory in calculation.

The basic equation in explicit approach, omitted damping due to the short duration of the phenomenon, is as follows:

$$[M]\{\ddot{x}\}_n = \{F\}_n - \{F_{int}\}_n\,, \tag{1}$$

where $[M]$ – mass matrix, $\{F\}$ – matrix of the external forces, $\{F_{int}\}$ – matrix of internal forces, n – step.

Assuming that the mass matrix occurs in a diagonal form, the equation of motion can be solved by the explicit Euler method. In this case, the nodal acceleration vector $\{\ddot{x}\}$ can be determined from the formula [8]:

$$\{\ddot{x}\}_n = [M]^{-1}\left(\{F\}_n - \{F_{int}\}\right)_n. \tag{2}$$

In Eq. (2) the damping can also be taken into account, just as a diagonal matrix. An additional advantage of this approach, is the uncoupling of differential equations of motion, which makes them a separate resolution.

Velocity $\{\dot{x}\}_{n+1/2}$ and displacement $\{x\}_{n+1}$ vectors in successive time steps are obtained by integrating over time with the use of the central finite difference method [3]:

$$\begin{aligned} \{\dot{x}\}_{n+1/2} &= \{\dot{x}\}_{n-1/2} + \{x\}_n \Delta t_n, \\ \{x\}_{n+1} &= \{x\}_n + \{\dot{x}\}_{n+1/2}\Delta t_{n+1/2}. \end{aligned} \tag{3}$$

Unfortunately, this method is conditionally stable. In order to ensure the stability, there the length of an integration step should be reduced:

$$\Delta T \leq 2/\omega_{\max}, \tag{4}$$

where $\omega_{\max}$ is the first and the highest frequency of a not-damped vibration discrete model. It means that the time step must be shorter than the propagation time of the wave through the smallest element occurring in the calculation model. The consequence of this is that the more accurate is the model (small elements), the integration step is shorter and computation time is longer. At the same time the problem of a length selection vanishes.

Mechanical issues solved by computer modeling and simulations require the adoption of an adequate description of the behavior of the materials which were used. This description must take into account their specific characteristics, such as physical state, plasticity, brittleness, hardness.

4.2. Description of the numerical model. Numerical analysis was carried out for the structure which was loaded by a pressure wave created by explosion of an explosive charge, which was placed centrally above the test object (according to Table 1). The pressure wave caused by detonation (an approximately simulated detonation in a point) was spread in an area of a cube shape with assigned appropriate boundary conditions. The theoretical solution of propagation of strong discontinuities with a spherical shape initiated from a point source exists in the form of analytical similarity equations formulated by Taylor which after transformation can be written as (5):

$$p(r) = 0.155Eor - 3, \tag{5}$$

where E_0 – initial internal energy, r – current radius of the sphere.

This allows for the computer simulation of a shock wave propagation process by giving appropriate initial conditions (density, energy, pressure) to some selected elements of the Euler domain and solution laws of conservation of mass, momentum and energy. Typical values for the explosive substances are: density – 1600 [kg/m^3], and a specific internal energy – 4.2 [MJ/kg]. The space in which the shock wave spread, was modeled with the use of Euler type elements Hex 8 characterized by the ideal gas properties of γ = 1.4 and density corresponding to the density of atmospheric air at standard conditions ($\rho = 1.2829$ [kg/m^3]). The calculations take into account the changes caused by deformation of the structure, because of that the structure was modeled by using elements of the Lagrange type Shell Quad 4. Those elements have been given the following mechanical properties: E = 2.15·10^9 [MPa], $\nu = 0.31$. To describe the behavior of the steel, piecewise linear plastic material model DYMAT 24 was used. The maximum strain failure criterion was adopted [3].

Developing a model of the structure was preceded by additional laboratory testing of mechanical properties of a steel armor. Laboratory research was carried out in the Department of Mechanics and Applied Computation Science on Military University of Technology.

A general view of the numerical model of the test structure is shown in Fig. 5. Ground was described by the material model Mie-Gruneisena with the following parameters: $\gamma = 2$ and a density of 2300 [kg/m^3]. The main parameter describing water was density equal to 1000 [kg/m^3].

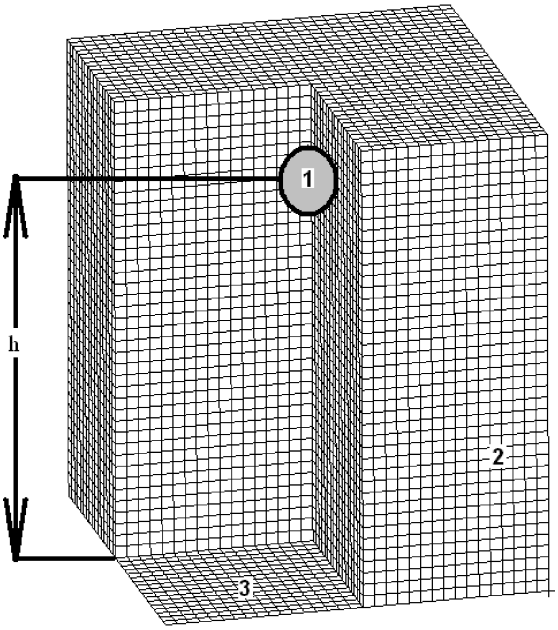

Fig. 5. Diagram of numerical model tested structure: 1 – an explosive, 2 – Eulerian domain, 3 – tested structure

4.3. The results of numerical analysis. The numerical model was loaded in the same way as it was done in an experiment. Among others pressure maps and displacements charts, accelerations and speeds for characteristic points on structure, especially for a center test plate, were the result of numerical analyzes. Additionally, values of strain energy and hourglass energy (responsible for the numerical errors) were studied. It is known that, in theory increase the medium increases the pressure incident on the barrier. This phenomenon is caused by the treatment a medium as a continuous. This results in the pressure pulse acting on the medium in front of him causing compaction of the medium. Figure 6 shows the change of medium density in the central point of the plate. In the case of air by the action of the pressure pulse a density value of the medium increased nine fold. In the case of water and soil the value has increased twice. Treatment of dense medium (water and soil) as a continuous medium resulted in behaviour of concentrated medium as a stamp. This phenomenon is widely known and used for explosives embossing with metal [9].

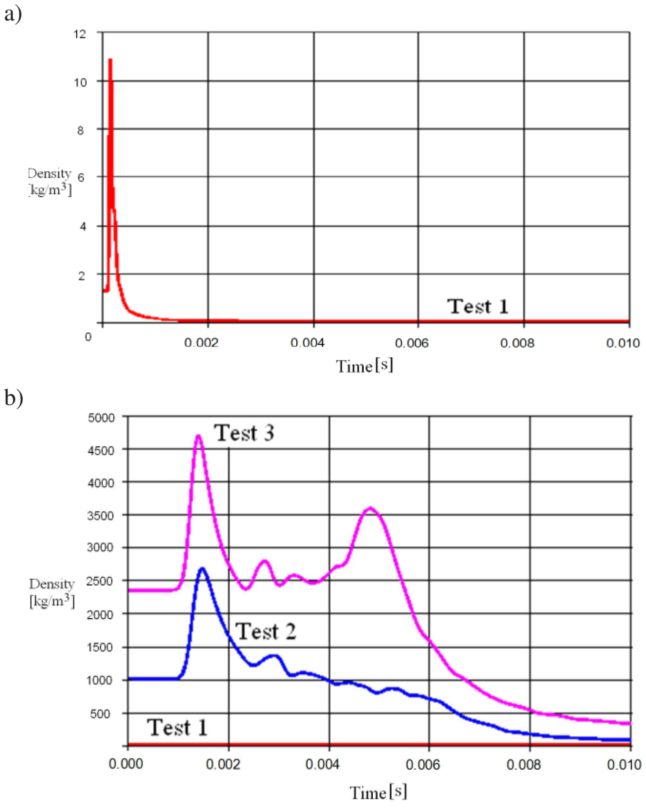

Fig. 6. Change the value of medium density at a central point of the plate a) air, b) summary air (Test 1), water (Test 2) and soil (Test 3)

Graphs obtained in a numerical way for individual tests are interesting. In the case of displacement the largest sustained displacement (Fig. 7) was observed for the central node for test 3 (soil), and it was equal to 0.061 [m]. The smallest permanent displacements was observed for test 1 (air) and it was equal to 0.017 [m]. Summary of the results obtained were shown in Table 2. In addition, this table presents a comparison between results obtained in the experimental and numerical methods.

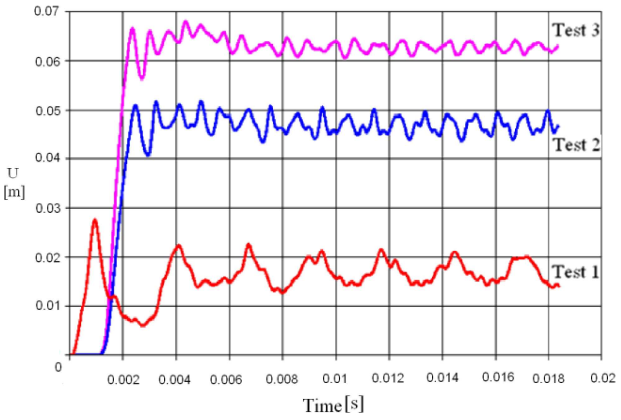

Fig. 7. The middle node displacement plots for individual tests

Table 2
Summary of displacement for each test

Test	Numerical results – maximal displacement [m]	Numerical results – permanent displacement [m]	Experimental results [m]	Difference [%]
1	0.0275	0.017	0.0165	2.9
2	0.051	0.047		
3	0.065	0.061		

The values of permanent displacement of a middle node, represent the results for acceleration, velocity and energy. Characteristics of graphs, above mentioned, are shown in Figs. 8–10.

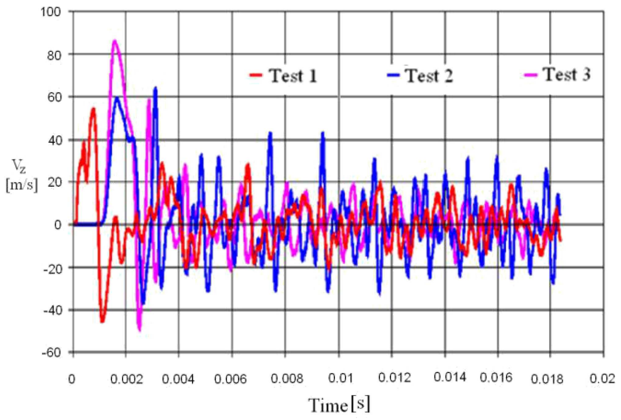

Fig. 8. Chart of speed for the node located on the upper wall of the object (in the plains of symmetry)

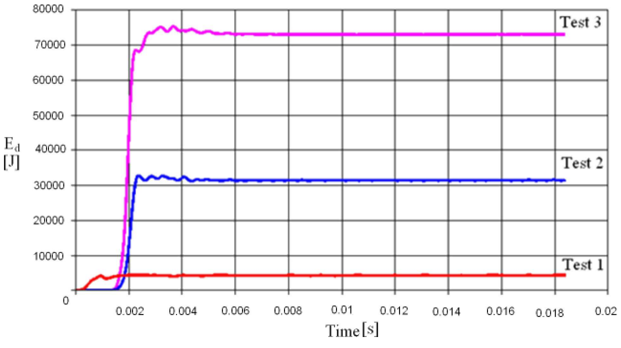

Fig. 9. The strain energy for each test

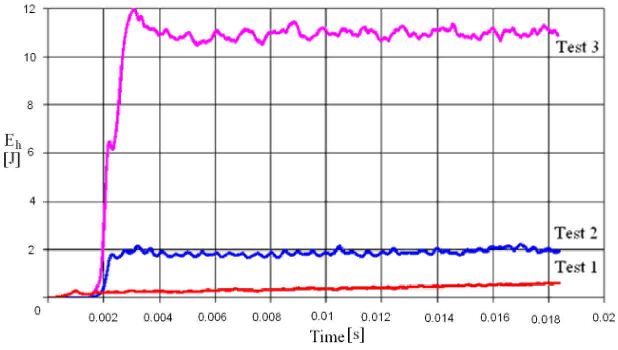

Fig. 10. Chart of hourglass energy for each test

The greatest value of the speed for a middle node is noted for test 3–84 [m/s]. For tests 2 and 1 speed values were respectively 63 and 53.7 [m/s].

The greatest values of the strain energy and the hourglass were read for test 3 and amounted to 73 [kJ]. The comparison of all additional physical quantities are shown in Table 3.

Similarly as in the case of graphs additional physical quantities obtained from the numerical analysis such as maps: displacement, strain and equivalent tensile stress were shown in Figs. 11–13. All maps were characterized by symmetry (which proves the correctness of modeling issue).

Table 3

Summary of values: speed, strain energy and hourglass energy for each test

Test	Speed [m/s]	Acceleration [m/s2]	Strain energy [J]	Hourglass energy [J]
1	53.7	347 000	5000	1
2	63	600 000	30 100	2
3	84	664 000	73 000	11

The values of permanent displacement have been described previously. Interesting strains of a test plate are shown in Fig. 12. As in the case of displacement, the maximum values of permanent deformation for each test are equal to, respectively: $2.28 \cdot 10^{-2}$, $1.05 \cdot 10^{-1}$, $1.24 \cdot 10^{-1}$ i $9.63 \cdot 10^{-2}$ (the biggest for test 3).

As in the case of displacements and permanent strain, maximum stress values for each test are respectively equal to: $6.9 \cdot 10^8$ [Pa], $7.35 \cdot 10^8$ [Pa], and $5.04 \cdot 10^8$ [Pa] (the biggest for test 1). The values of equivalent tensile stress for each test are shown in Fig. 13. They point to the correctness of physical quantities ??previously obtained for test plates. Such high values of equivalent tensile stresses for steel were due to dynamic reinforcement of the material.

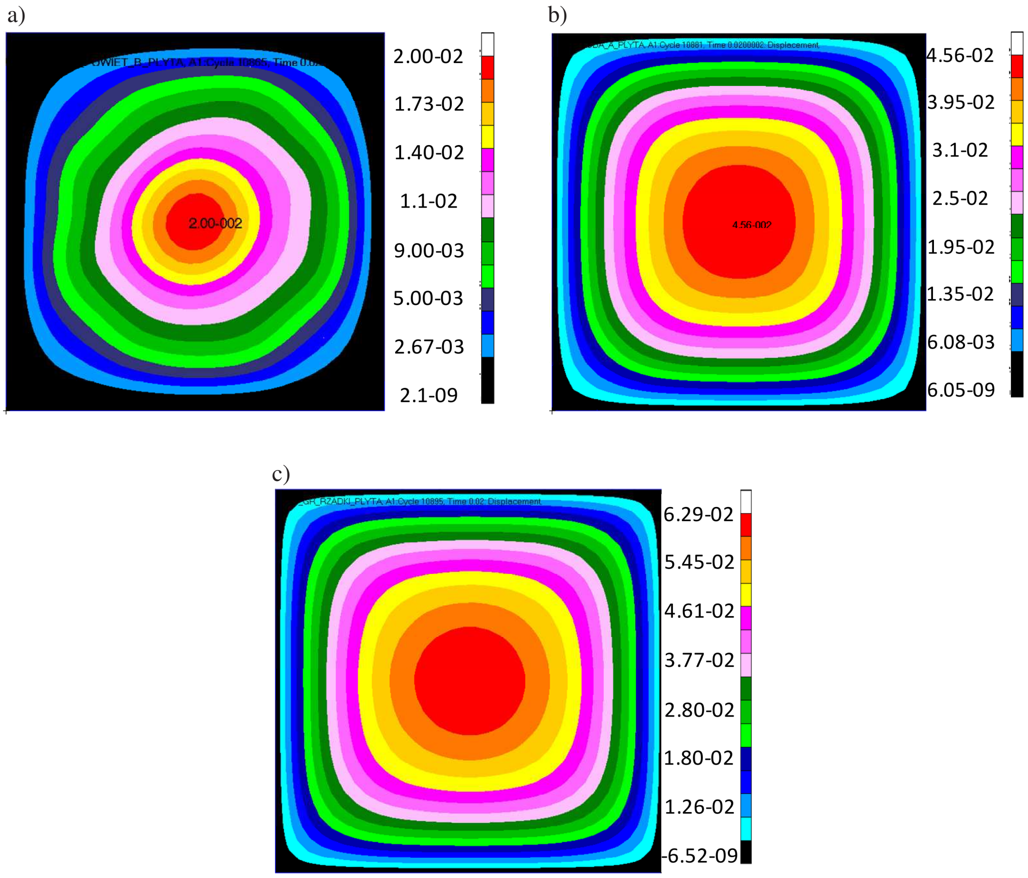

Fig. 11. Displacement map: a) Test 1 – air, b) Test 2 – water, c) Test 3 – soil

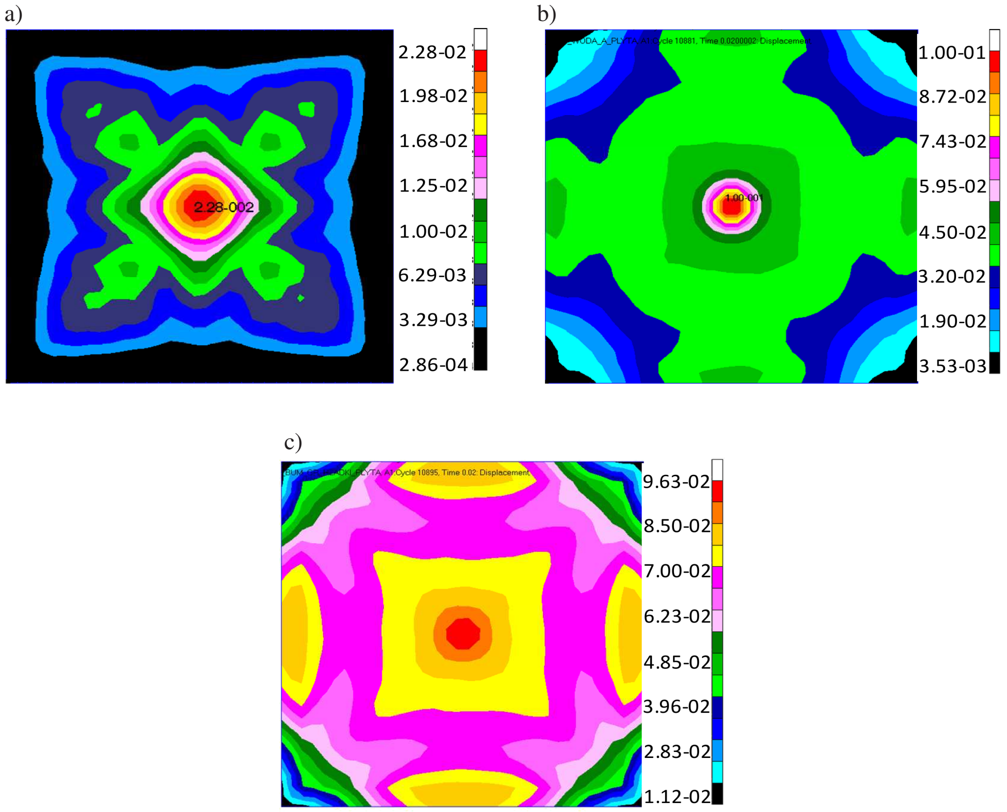

Fig. 12. Strain map: a) Test 1 – air, b) Test 2 – water, c) Test 3 – soil

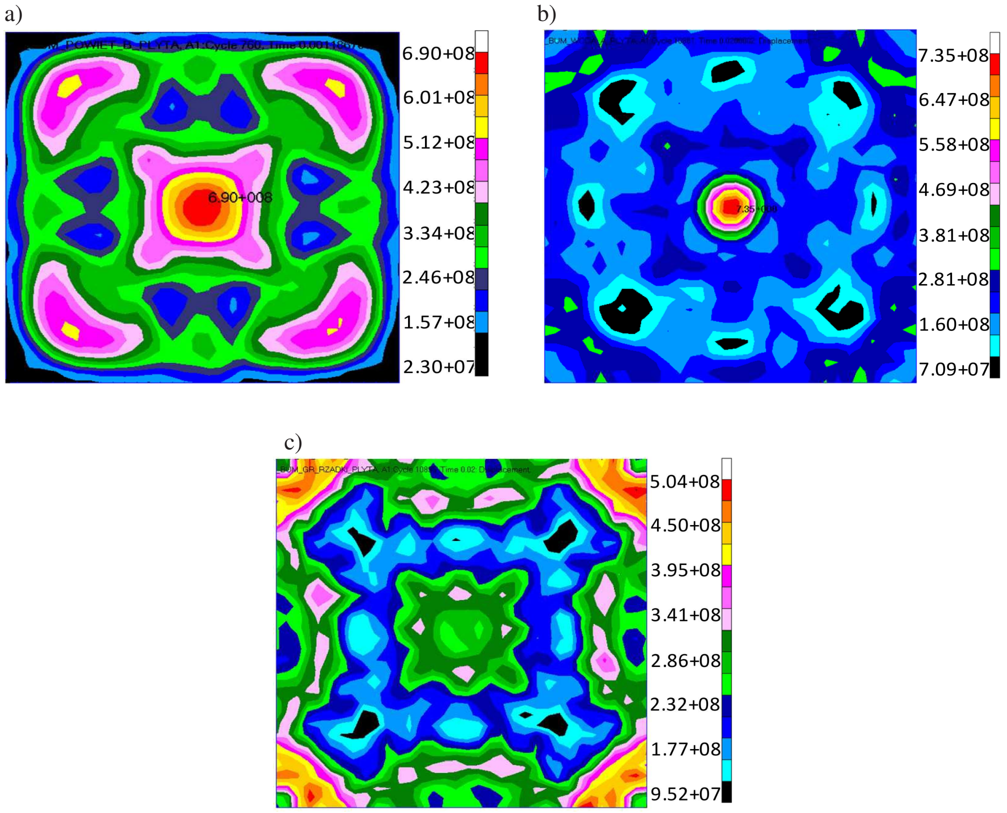

Fig. 13. Map of equivalent tensile stresses: a) Test 1 – air, b) Test 2 – water, c) Test 3 – soil

5. Summary

This paper presents the results of experimental and numerical analysis of the dynamic response of plate load by a pressure pulse.

Comparing the results with the numerical analysis allows to state an opinion that the charts are the most reliable. In the case of read values, especially mechanical quantities, from maps there is a concern of poor approximation of results.

Research especially experimental of test plates are extremely important because of the correctness of the results. The above example can be used to validate numerical models in the context of the explosive and the constitutive model describing the barrier.

This issue is quite important from the point of view of the protection of vehicles and military facilities. In the numerical analyzes coupling ALE to join the Euler domain (describing an air) and the Lagrangian domain (describing structures) were used.

In the case of numerical analysis the gas had parameters of air, water and soil.

All kinds of material data have been selected on the basis of experimental studies and available literature. Plates were described using a piecewise linear plastic material model with dynamic strengthening.

During the tests of the test plate response for a variety size of charges an innovative test stand was used. The aim of the study was to validate numerical models in an aspect of constitutive equations describing the model material and the choice model of explosion and medium in which pressure pulse was spread.

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