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Numerical and experimental investigation on internal membrane pressure wave inside sealed structure

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Abstract. The article presents an approach to modeling the internal membrane pressure wave inside a sealed structure. During an explosion near a vehicle when a pressure wave reaches a hull, a pressure wave inside arises due to the hull's bottom and the deformation of sides. They act like the piston – membrane. This membrane transfers the pressure impulse into the vehicle's interior. A pressure increase causes the damage of internal organs or even death of occupants. In case of an armor penetration the pressure increase may be even larger. One of basic methods to protect a crew is to open hatches. However, such a method cannot be used in a contaminated area.

Key words: internal membrane wave, military vehicle, crew safety.

1. Introduction

The basis of requirements for vehicles ballistic protection is the NATO STANAG 4569 standardization. Designers and companies producing armored vehicles search for new high strength ballistic materials with better energy absorbing properties securing both vehicle and personnel inside in the case of a mine or the IED attack [1–4]. After the detonation, depending on the material size, type and potential additives, a blast wave arises and with potential fragments hit bottom or sides of a vehicle.

The main problem in the vehicles safety is the growing mass of an explosive. Existing Defense and NATO Standards do not take into account so big charges. Standard procedures are based on explosives that are of multiple standard anti-tank mine size 3 kg.

In the literature, there are many positions concerning the explosion of classic materials and a blast wave propagation in air [5, 6] and in metals or soil [7–9].

In case of loading the vehicle hull with the rapid and intensive pressure impulse from detonation of an explosive charge the main threat which is a vehicle elimination due to plastic deformation of the vehicle's hull sides and bottom. In extreme situations the vehicle can overturn which leads to serious crew injuries. As well as that, the overpressure inside a vehicle – internal membrane pressure wave – is another threat to the crew. In case of a high peak value it can be lethal or can lead to serious internal injuries as presented in Fig. 1.

An example of overpressure injury on a human body versus a distance is presented in Fig. 1. Both auditory and respiratory systems damages are indicated.

An internal membrane pressure wave arises from deformation of a hull surface (an obstacle) due to the incident pressure wave impact. A general scheme of the secondary membrane pressure wave initiation is presented in Fig. 2.

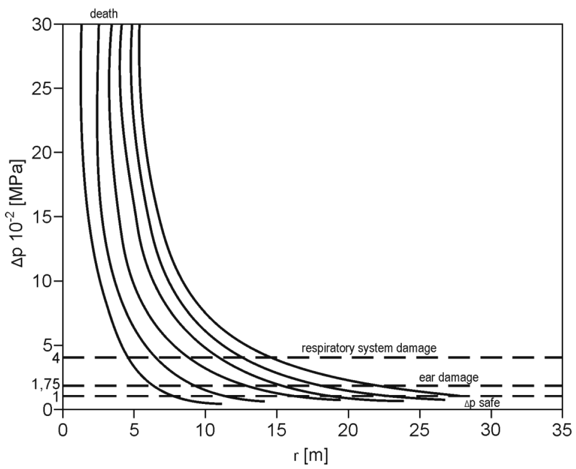

Fig. 1. Overpressure versus distance from explosive charge after Ref. 4

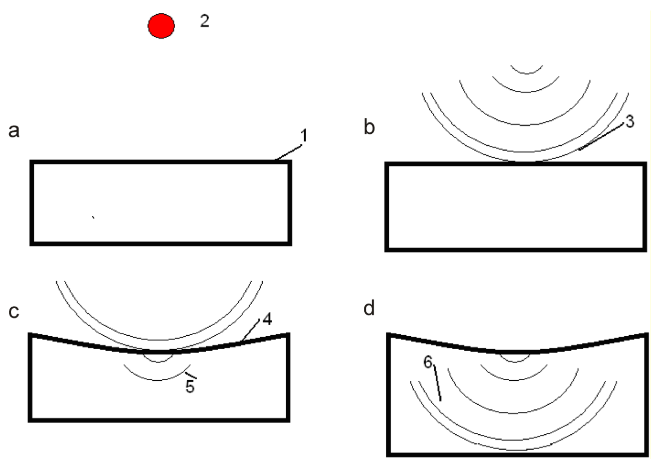

Fig. 2. Scheme of secondary membrane pressure wave initiation: 1 – surface on which incident wave impacts, 2 – explosive charge, 3 – incident pressure impulse on membrane, 4 – deformed membrane, 5 - initiation of internal pressure wave, 6 – internal pressure wave propagation

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In the beginning of the internal membrane pressure wave (Fig. 2b) the wave front (3) caused by the detonation of the explosive (2) reaches the surface 1 (Fig. 2a). Then, the obstacle (5) deforms which leads to initiation of the internal membrane pressure wave (5) (Fig. 2c) and its propagation (Fig. 2d).

2. Experimental trials

2.1. Test stand. For the purpose of conditioning and amplification of signals from an incident wave pressure the gauge transducers and the LTT 500 amplifier were used. It was made by Tasler GmbH and is designed to register rapid changing signals. The registration process was done using NIUSB 6833 measurement card with the 16 bit analog – digital transducer (sampling 2 MHz on every channel) made by National Instruments. Additionally, the Toshiba Satellite laptop was used to run the tests. All the equipment is shown in Fig. 3.

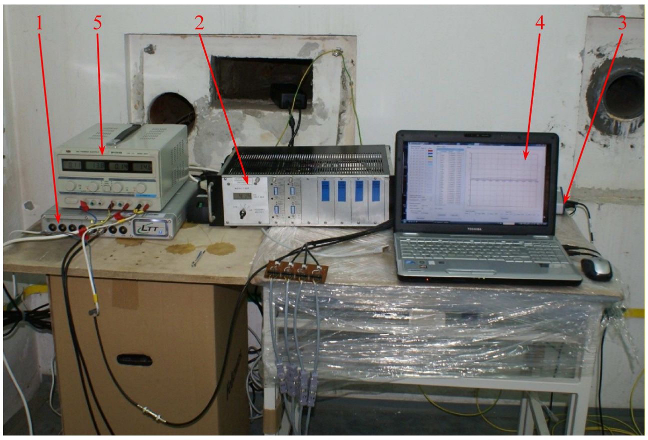

Fig. 3. Test apparatus for the purpose of experiment 1 – LTT 500 amplifier, 2 – tensometric amplifier MS1001, 3 – meassurment card NI-USB 6833, 4 – computer with proper software, 5 – power supply

The indicent wave pressure run was meassured using the special pressure gauge 137A21 made by PCB Piezoelectronics (fabric no. 9080) with sensitivity 143.3 mV/MPa of the range 6.894 MPa. The gauge was placed 400 mm from the explove axis in the middle of a test stand.

2.2. Experimental results. During the examination of the secondary pressure wave an unique test stand in form of a cube with the edge length 0.5 m was used. All walls were made of ARMOX steel plates 6 mm thick. In order to obtain a membrane the lid was made of a 2 mm plate. During the experiment the reflected wave pressure (affecting the lid) was measured as well as an internal membrane pressure. An internal pressure gauge was placed in a symmetry plane of the box. As well as pressure, also strains were measured using the electrical resistance method. In order to measure pressure inside a box, the bottom was bolted to the walls and sealed with a special tape. A general view is shown in Figs. 4–6.

Fig. 4. Scheme of test stand

Fig. 5. Mounting base of internal pressure gauge

Fig. 6. Incident pressure wave gauge and strain gauges

As a result the reflected wave pressure plot and the internal membrane wave pressure plot were obtained. They are presented in Fig. 7. The value -5 MPa refers to incident pressure wave. Therefore, it is important, to read pressure values properly.

As a result of cylindrical shape of the explosive and its mass – 200 g, large overpressure of a reflected wave was obtained with the peak value equal to 35 MPa. It is due to a shape and a mass of the explosive and the wave formulation. In case of an internal (reflected) wave, the peak overpressure reached 0.7 MPa. Basing on the plot presented in Fig. 1a serious auditory system injury of occupants will occur.

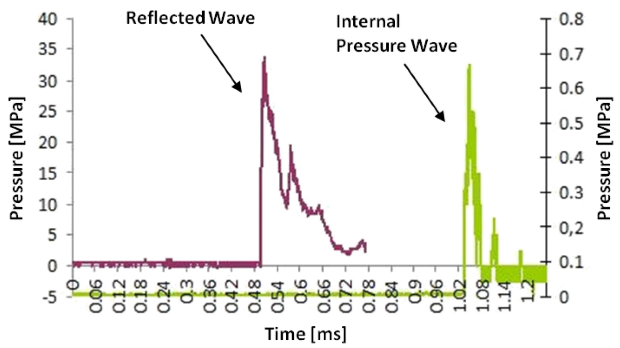

Fig. 7. Pressure values of reflected wave and internal pressure wave from 200 g of TNT

3. Numerical analysis

3.1. Physical model. The analysis of a pressure impulse impact on a structure was done using the finite element method with an explicit scheme of integration implemented in DYTRAN software [10]. In the algorithm the equilibrium equation of a discrete model (1) is solved by an explicit integration over time. Those equation are coupled so the computational cost is high and therefore, time required for computation is increased.

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

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

Supposing that mass matrix is diagonal, movement equations can be solved using the explicit Euler method. In that case, the acceleration vector $\{\ddot{x}\}$ can be obtained using Eq. [11]:

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

In Eq. (2) damping can also be taken into account, however, only in a diagonal matrix. Another advantage is uncoupling of differential movement equations which allows solving them separately. The velocity $\{\dot{x}\}_{n+1/2}$ and displacement $\{x\}_{n+1}$ vectors at subsequent time steps are obtained by integrating over time using the finite difference method [11]:

$$\{\dot{x}\}_{n+1/2} = \{\dot{x}\}_{n-1/2} + \{x\}_n \Delta t_n, \tag{3a}$$

$$\{x\}_{n+1} = \{x\}_n + \{\dot{x}\}_{n+1/2} \Delta t_{n+1/2}. \tag{3b}$$

However, the method is only stable under certain conditions. In order to ensure stability the time step of integration must be limited:

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

where $\omega_{\max}$ is the highest undamped frequency of a natural mode of a discrete model. It means that the time step has to be shorter than wave propagation through the smallest element in an entire computational model. As a consequence, the more precise model with smaller elements the shorter time step and longer computation time. Therefore, the problem of determining a proper time step disappears.

Mechanic problems are solved using modeling and numerical techniques which require an appropriate description of analyzed materials. It has to take into account specific features such as a physical state, ductility, brittleness or hardness. All the necessary data was obtained during experimental research held in the Department of Mechanics and Applied Computer Science of the Military University of Technology.

3.2. Numerical model. The numerical analysis was done for a structure loaded with a blast wave from an explosive charge placed above the reflected wave pressure gauge. The pressure wave caused by the detonation was modeled as a point source. The wave propagated in a cubic area with boundary conditions added. A theoretical solution of highly nonlinear spherical discontinuity comes in a form of analytical Taylor equations that can be presented as [10, 11]:

$$p(r) = 0.155E_o r^{-3} \tag{5}$$

where E_0 – initial internal energy, r – actual sphere radius.

It allows computer simulation of blast wave propagation by defining initial conditions (density, energy, pressure) to a certain element of the Euler domain and then solving mass, momentum and energy conservation equations. Typical values for TNT are density 1600 kg/m^3 an internal specific energy 4.2 MJ/kg.

The domain in which the blast wave propagated was modeled using Euler elements type Hex 8 with ideal gas properties at normal conditions ($\rho = 1.2829$ kg/m^3).

During computations, deformations of a structure were taken into consideration by modeling it using Shell elements type Quad 4. To describe the behavior of the steel, piecewise linear plastic material model DYMAT 24 was used. The maximum strain failure criterion was adopted [10, 11].

A numerical model of a structure was based on additional experimental research of armor steel properties made by the Department of Mechanics and Applied Computer Science [12].

A general view of a numerical model is shown in Fig. 8.

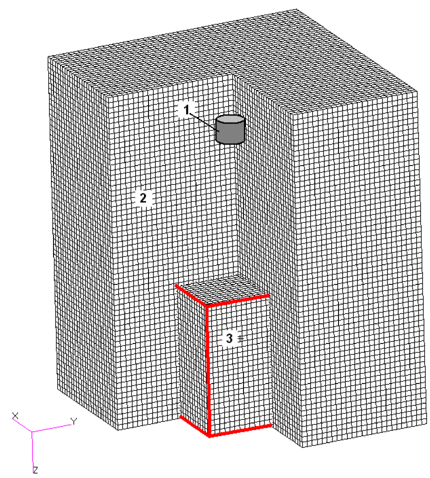

Fig. 8. Scheme of numerical model: 1 – explosive charge, 2 – Euler domain, 3 – analysied structure

3.3. Numerical results. The model was loaded with 0.2 kg TNT charge. As a result, pressure amps, displacement, accelerations and velocities plots were obtained for specific structure points. The analysis was based on the cubic, dense mesh Euler elements therefore, the influence on the detonation's front pressure is slight.

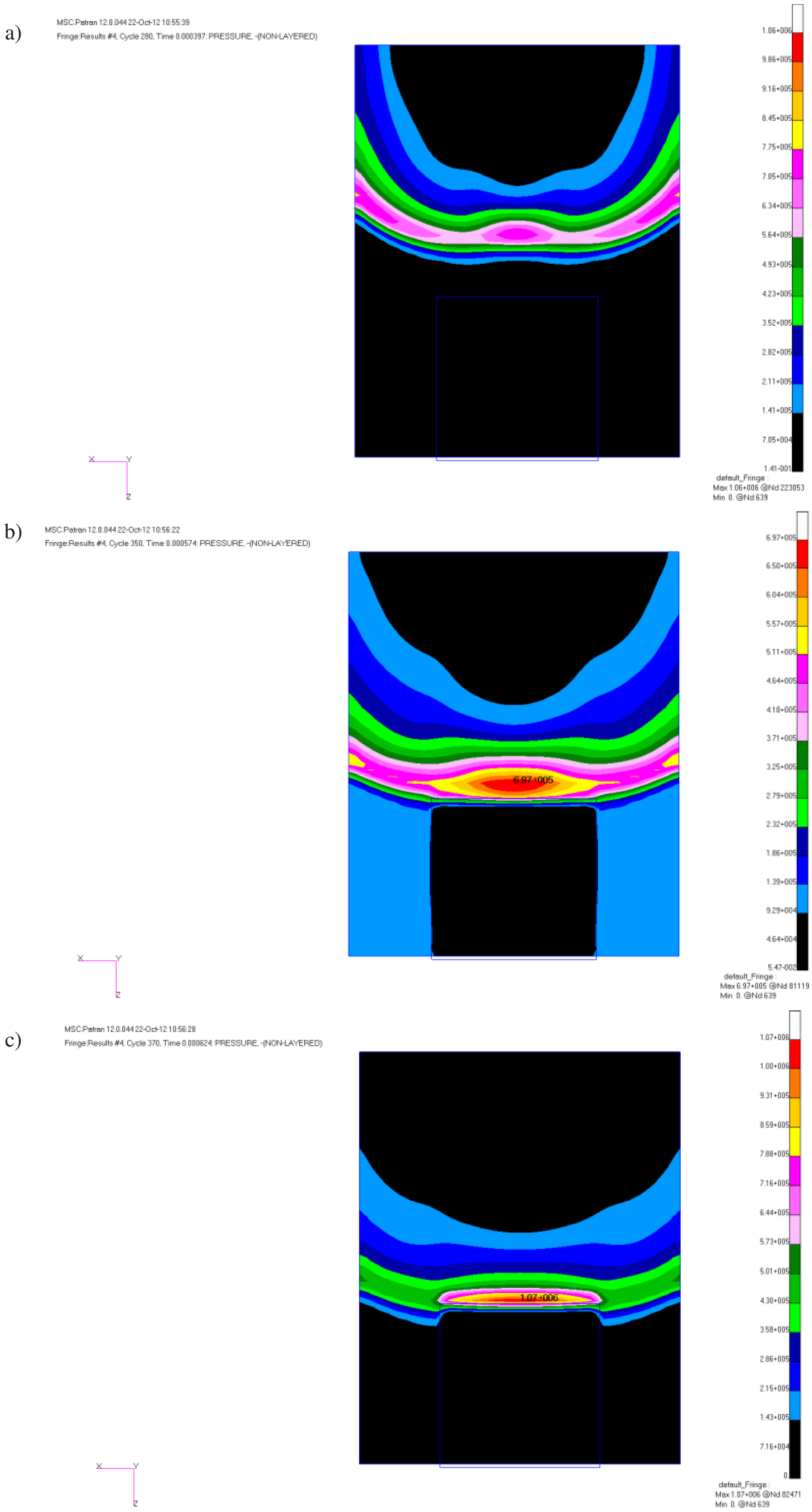

Fig. 9. Propagation of external pressure wave (affecting the structure) for subsequent time steps: a) 0.000397 s, b) 0.000574 s, c) 0.000624 s

Figure 9a presents a pressure distribution on the examined structure for the time 0.000397 s, when a pressure wave reaches a structure. Comparing to Fig. 13 (in which the beginning of interaction starts at 0.0002 s) the assumption can be made that pressure maps do not match a real situation due to discretization. Therefore, it is important to use plots when results are concerned.

Figures 11 and 12 show the propagation of the internal pressure wave inside the examined construction. The internal pressure plot is shown in Fig. 12.

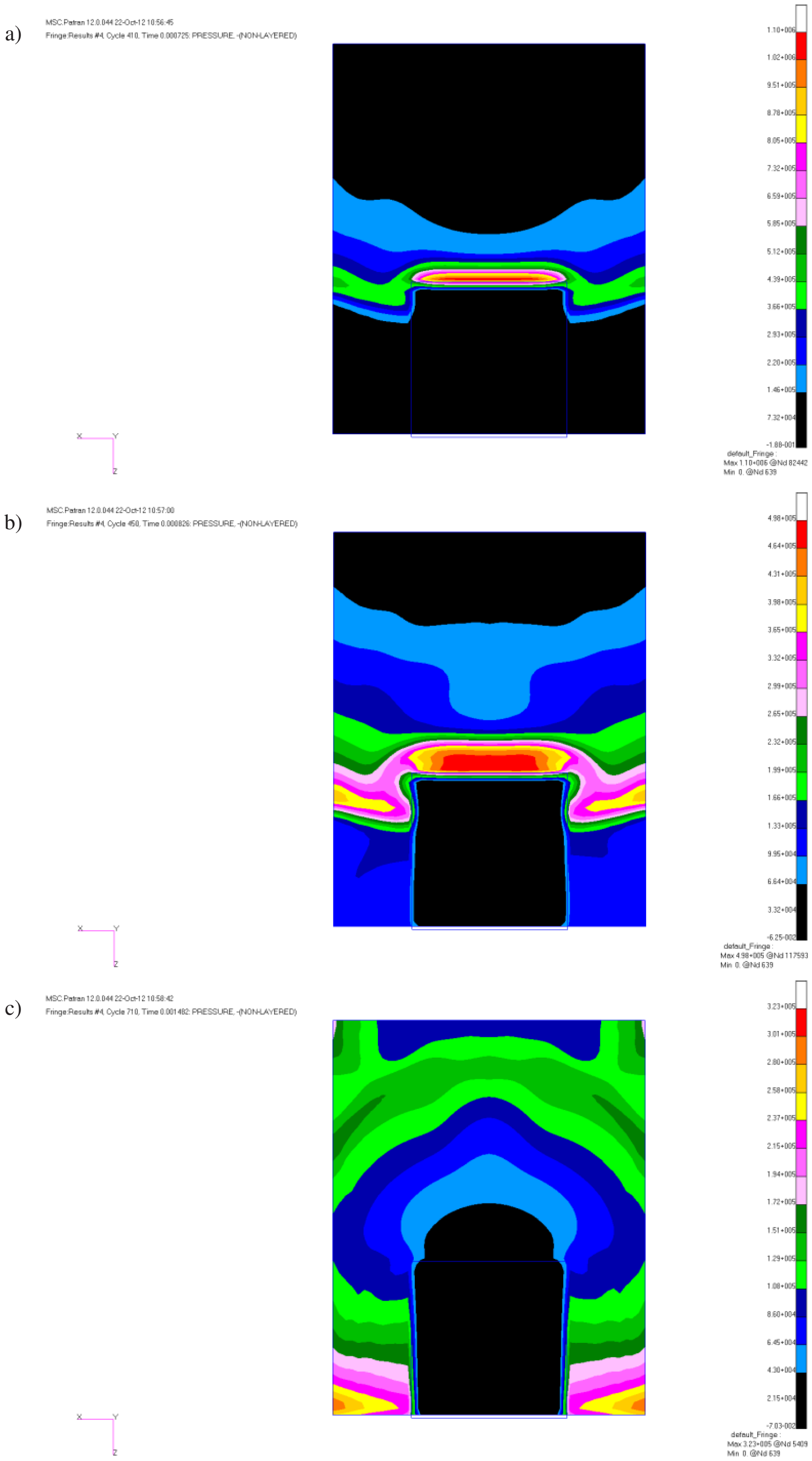

Fig. 10. Propagation of external pressure wave (affecting the structure) for subsequent time steps: a) 0.000725 s, b) 0.000826 s, c) 0.001482 s

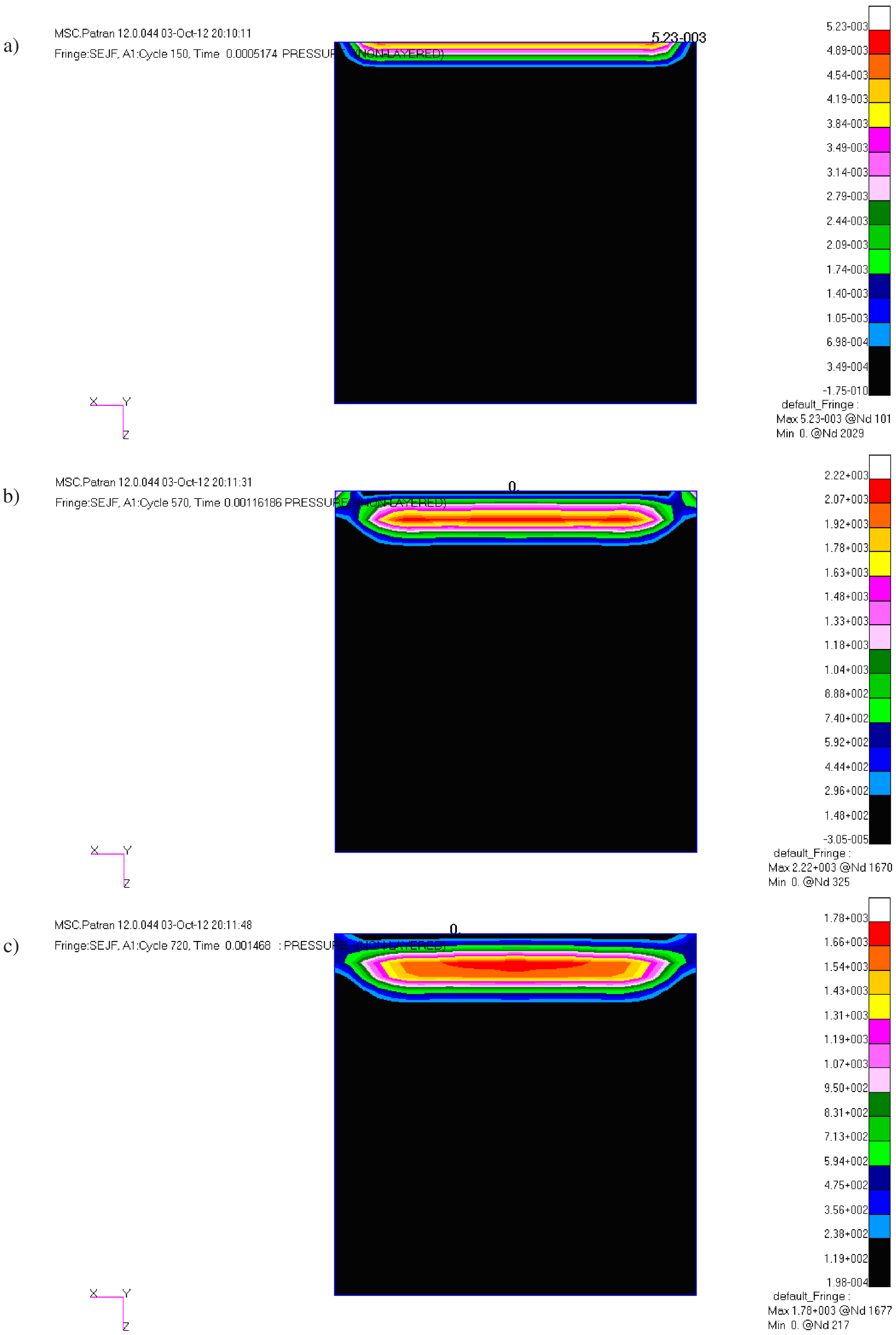

Fig. 11. Propagation of internal membrane pressure wave (caused by the incident pressure impact) for different time steps: a) 0.0005174 s, b) 0.00116186 s, c) 0.001468 s

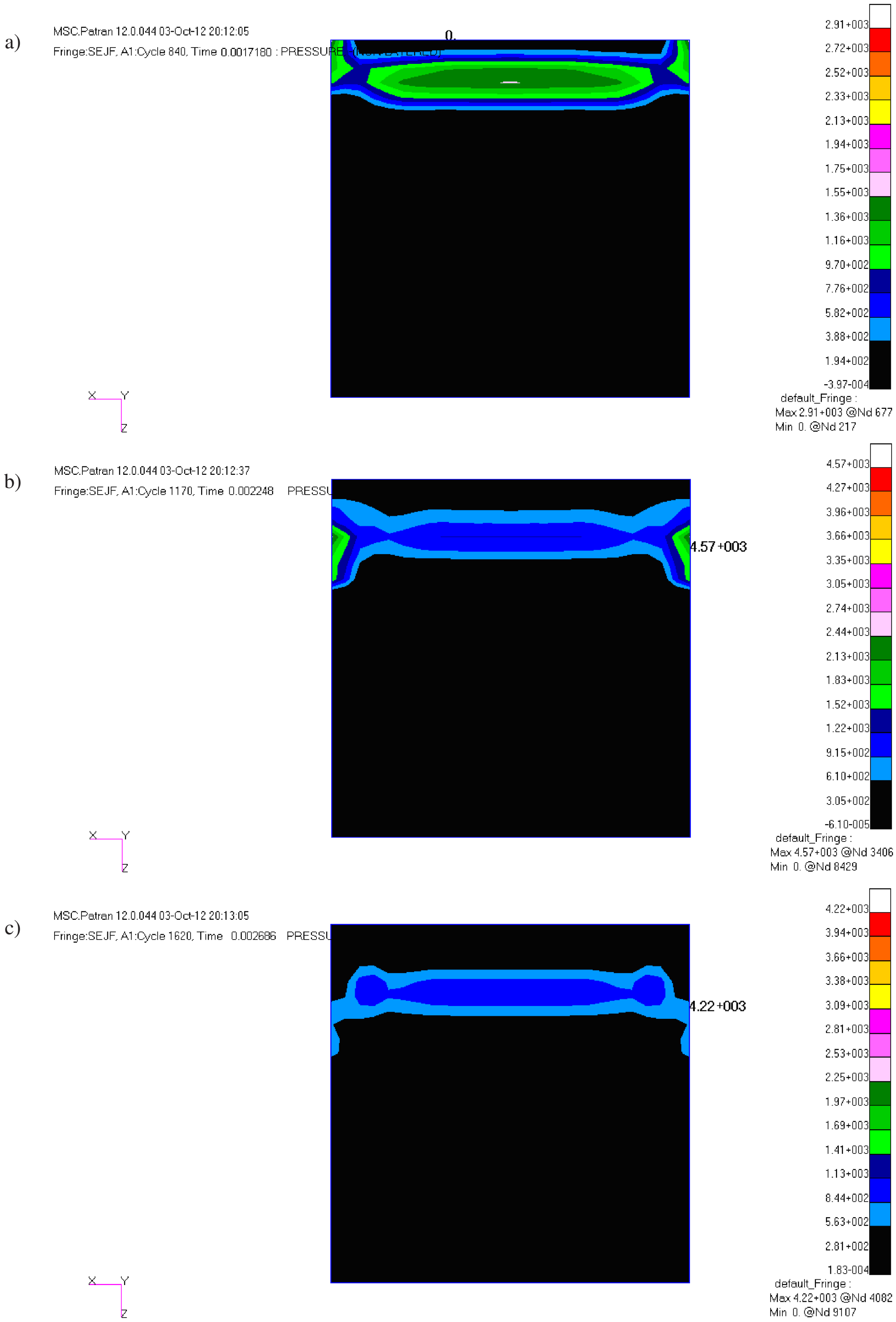

Fig. 12. Propagation of internal membrane pressure wave (caused by the incident pressure impact) for different time steps: a) 0.001718 s, b) 0.002248 s, c) 0.0026865 s

The peak value of the internal membrane pressure wave reached 0.6 MPa which is similar to experimental results.

The maximum acceleration value, shown in Fig. 14, reached above 350 000 m/s^2 in a node on a symmetry plane. The value is too big due to a position of the node.

The maximum velocity obtained during a study was 27 m/s for a node placed on a symmetry plane.

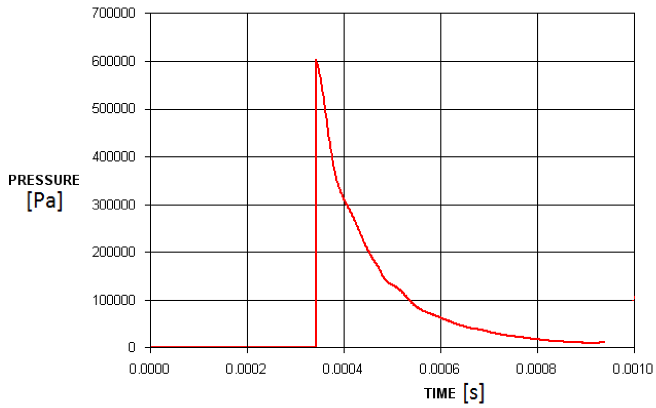

Fig. 13. Pressure versus time plot for internal membrane pressure wave

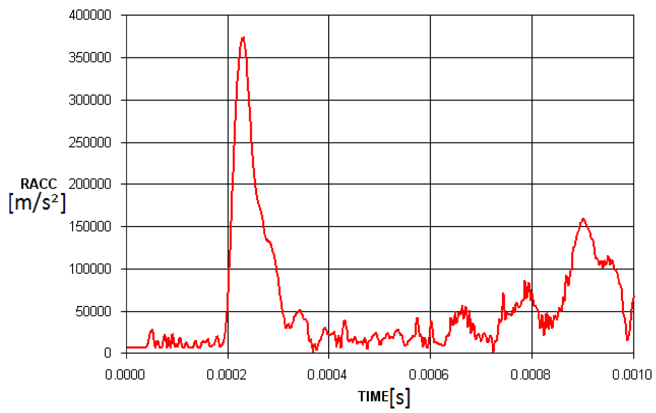

Fig. 14. Acceleration versus time plot for upper Wall node on structure symmetry axis

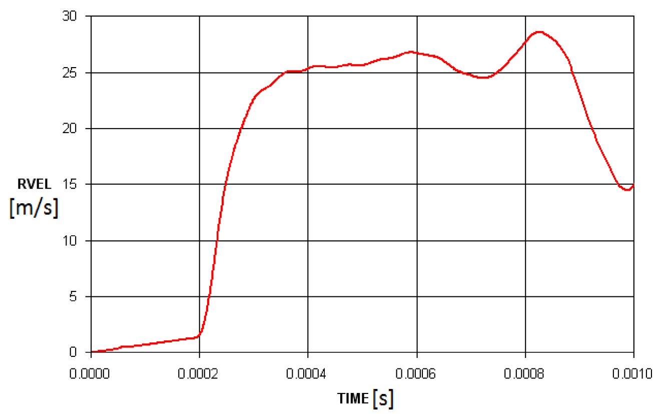

Fig. 15. Velocity versus time plot for upper wall node on structure symmetry axis

Comparing with other plots (acceleration and velocity) displacements are small. The situation is depicted in Fig. 16.

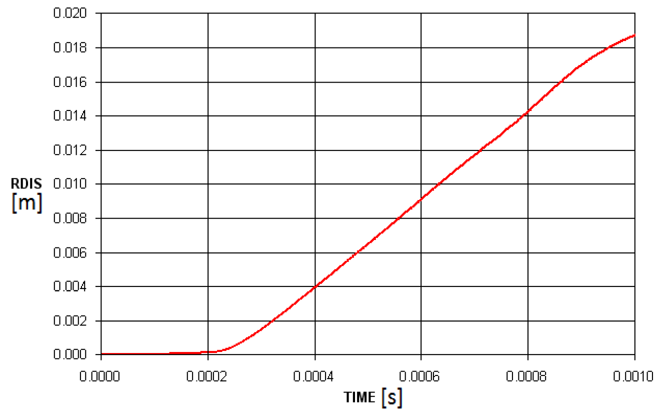

Fig. 16. Displacement versus time plot for node placed on upper wall on symmetry plane

4. Conclusions

The paper presents the results of experiments and the numerical analysis of an internal membrane pressure wave. The phenomenon is important when vehicle crew safety is concerned. The analysis included coupling between the Euler domain (describing air) and Lagrange elements (describing structure). In most cases researches of the nature of interactions between a pressure wave and susceptible parts of the vehicle, are often encrypted.

The paper discusses the last parts of a broader study on the above described phenomenon. It is important to obtain a construction method, without deflection of elastic walls, dealing with a response to the shock, coming from a strong explosive charge. The deflection will result in the phenomenon of the wave membrane (increase in pressure in an enclosed structure) caused by the above described deflection.

In case of the numerical analysis, gas had air parameters. Interactions between a vehicle and explosives were modeled using the general coupling algorithm. The model included the bilinear material model with dynamic strengthening. Such an approach fully describes all the phenomena in an entire system.

The numerical analysis was verified by the experimental tests. This verification is really important because of the fact of importance of the described phenomenon.

In case of experimental trials it was important to place all sensors properly.

The presented research is an introduction to further investigation on vehicles safety against terrorist attacks.

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