

Review of methods for prediction of internal blast loading

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ABSTRACT

A review of internal blast loads on structures modeling methods is presented in the paper. Also, numerical simulations of the internal explosion were done in numerical software Ansys Autodyn. Critical areas of confined spaces were identified for this type of explosion event.

Recommendations were given regarding the use of numerical simulations in blast wave parameter prediction, as well as suggestions for further research.

Keywords: Interior explosion, Blast overpressure, Structures, Simulation

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1. Introduction

Explosions inside structures can happen for various reasons, their parameters are usually difficult to estimate, and they can lead to the collapse of the buildings and other structures.

Internal blast loading of structures by high explosives is generally described in [1,2,3]. Reference [1] contains also topics as flame propagation in gas-air mixtures, the effect of flame area and turbulence increase, as well as internal loading by dust and gas explosions. Particular methods and analytic expressions from [1,2] will be described in more detail in Section 2.

Recently Feldgun et al. [4] included numerical simulations of the internal loading (room with rigid walls) and analytical derivations. They investigated the influence of the charge size and its location in the structure. They also introduced the analytical model to estimate the residual internal pressure.

Fedorova et al. [5] presented 3D numerical simulations of a shock wave in urban areas, modeled using prismatic bodies on a flat plate and inside a closed structure.

Wei-zheng Xu et al. [6] presented different numerical and experimental results for blast waves generated by cylindrical TNT charges in a partially confined chamber. They also developed codes for predicting the evolution of shock waves using fifth-order weighted nonoscillatory finite difference schemes, with which they investigated shock tube problem, interacting blast waves, shock entropy wave interaction, and double Mach reflection.

Anthistle et al. [7] describe the design and results of experiments performed using a test cell to measure the pressures created when structures were placed inside to alter the propagation of shock waves, using quarter symmetry to reduce the required test cell the size and charge.

Feldgun et al. [8] also presented different models for the prediction of the gas pressure, where the sensitivity of the gas pressure to the heat capacity ratio and explosion internal energy is studied.

The analysis of the shock wave interactions with the structure can also be found in [9], and some aspects of the problem in technical manuals [10,11].

Many authors presented various reports on shock wave - structure interaction by using external explosion in the vicinity of some obstacles, but the problem of a confined explosion is very complicated and considerably less investigated.

2. Internal loading of structures by high explosives

The structure can, generally, behave as unvented or vented when an explosive device detonates within the structure. Compared to a vented, an unvented building has to be harder to withstand an explosion since some pressure relief can be expected in vented structures (ie windows shattering). For detonation inside a structure, two loading types can occur. The first is reflected loading, where, because of reverberation from repeated wave reflections, the original reflected shock wave is accompanied by multiple reflected pulses. This blast wave train typically decreases in amplitude, and as the reverberating shock waves are decaying, because of the expansion, the second loading occurs, creating a gas pressure loading. Venting can be helpful for structures, for the defense against dangerous gas pressures, but protective venting is of no use for people since accidents are likely to be triggered by the initial blast wave [1,2].

Prediction is more difficult in the case of oblique reflections inducing Mach stem waves and the complex pressure enhancements that occur at internal corners in box-like enclosures. Programs such as the BLASTIN code allow estimation of the multiple shock wave reflections from the floor, walls, and roof produced by high explosive detonations in closed rectangular box-shaped rooms together with the subsequent gas pressure phase [1]. The initial reflected shock wave parameters (P_r, i_r) can be determined using the curves shown in empirical diagrams (i.e. incident and reflected shockwave parameters after the detonation in free air and at surface level [10]). However, estimation of the re-reflected shockwaves is somewhat harder, especially where Mach stem waves are present. A first-order estimation pressure inside the structures can be made by idealizing the pressure pulses with a triangular form. For the following reflections, Baker et al. [3] assumed that the maximum pressure and impulse can be halved on each re-reflection. After several (i.e. three) reflections, the remaining (reflected) wave pressure is approximated to have zero values (Fig. 1) [2]:

$$P_{r_2} = \frac{1}{2} P_{r_1} \quad P_{r_3} = \frac{1}{2} P_{r_2} = \frac{1}{4} P_{r_1} \quad P_{r_4} = 0 \tag{1}$$

$$i_{r_2} = \frac{1}{2} i_{r_1} \quad i_{r_3} = \frac{1}{2} i_{r_2} = \frac{1}{4} i_{r_1} \quad i_{r_4} = 0 \tag{2}$$

The reverberation time (Fig. 1) can be defined as the delay between individual blast wave hitting the internal side of the structure. It is approximated as constant (equal to $2t_a$; t_a is first blast wave time of arrival). Fig. 2 shows blast waves inside a structure, such as can be expected by penetration of a high explosive projectile.

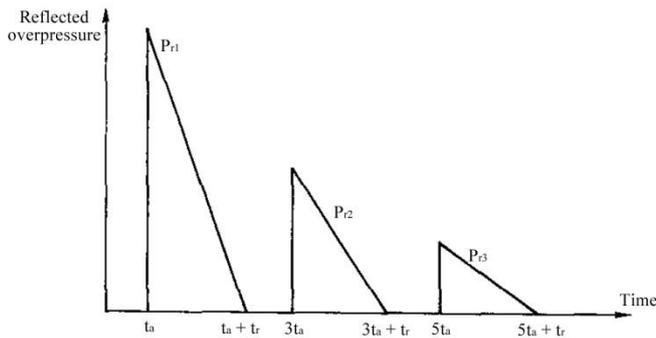


Figure 1. Simplified internal blast wave reflections (adapted from [1])

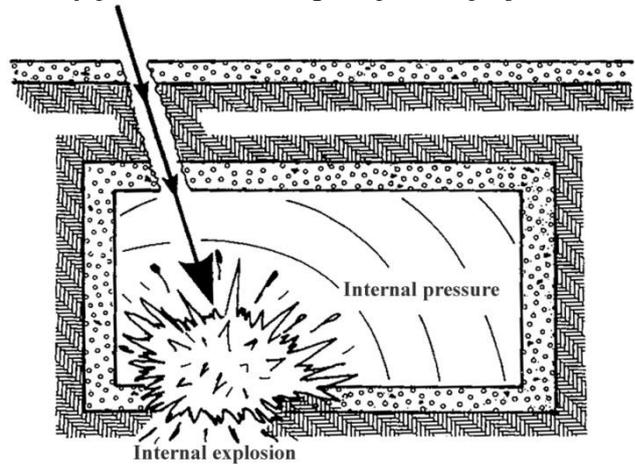


Figure 2. Blast waves generated inside a structure by penetration of a HE projectile (adapted from [1])

The next approximation is suggested in reference [3]. Namely, if the time of the response for the loaded building is much longer than the combined load duration ($5t_a + t_r$) then all three shockwave pulses can be approximated as one pulse with total maximum pressure p_{rT} , and a total specific impulse i_{rT} [1]:

$$P_{rT} = P_{r_1} + P_{r_2} + P_{r_3} = 1,75P_{r_1} \tag{3}$$

$$i_{rT} = i_{r_1} + i_{r_2} + i_{r_3} = 1,75i_{r_1} \tag{4}$$

An example of an unvented containment structure capable of withstanding the loading from a 5 kg TNT charge is given in Figure 3, where the massive, heavily reinforced form of the structure should be noted. Here, the quasi-static load of gas pressure is forming, and the reverberating blast waves decrease in strength (decaying). At any given moment, the magnitude of this load depends on the structure's volume, vents area in the structure, and the explosive's characteristics.

Figure 4 shows an example of $P(t)$ curve for a protective structure with gas venting. Figure 4 also indicates several reverberating blast waves (three in this case, supporting the approach highlighted in the equation 1) and a formation of gas pressure load with its maximum and which then decays at point B [2].

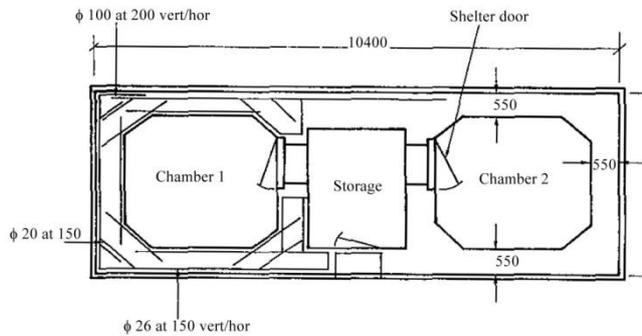


Figure 3. Structure to contain detonation of up to 5 kg TNT (adapted from: [1])

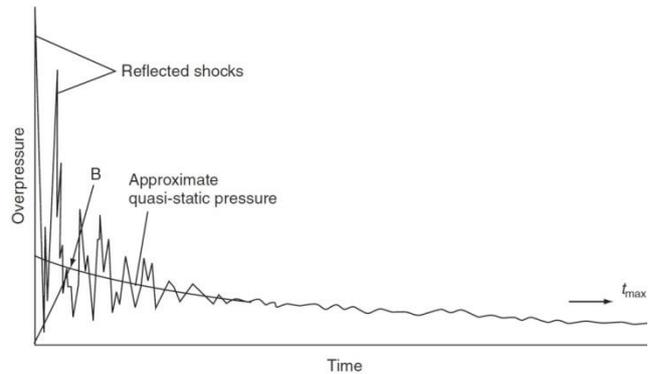


Figure 4. Pressure - time profile for internal blast loading for vented structure (adapted from [2])

Reference [3] presents overview of an approach for prediction of the pressure-time history by using approximated form of the gas pressure load, as shown in Fig. 5.

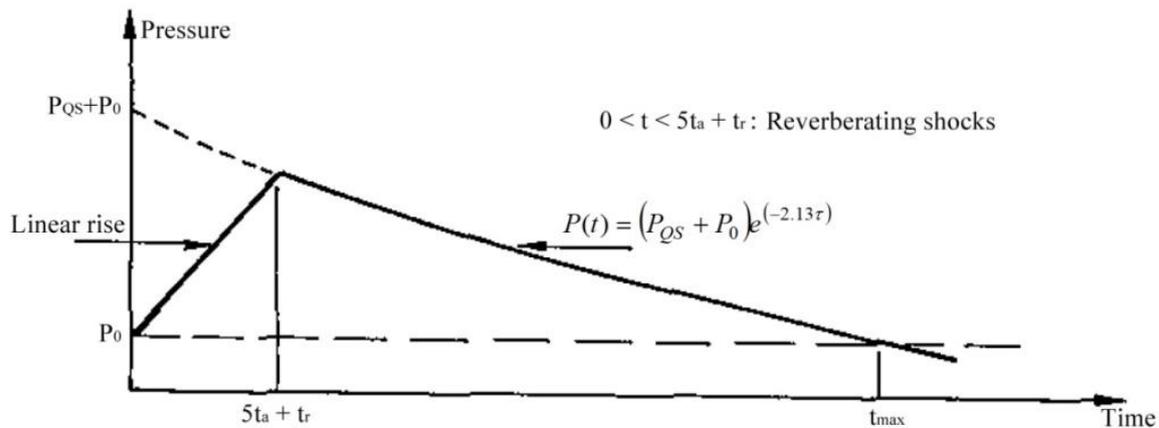


Figure 5. Simplification of development of gas pressure phase inside a structure (adapted from [1])

The equation for estimation of the gas pressure decay can be presented in following form [1,2]:

$$P(t) = (P_{QS} + P_0) e^{(-2.13t)} \tag{12}$$

Here parameter P_{QS} is maximum quasi-static pressure, and P_0 is environmental pressure. Also [1,2]:

$$\tau = \frac{\alpha_e A_s t a_0}{V} \tag{13}$$

Here α_e is ratio of vent to wall area, V is the building volume, a_0 is the sound speed, A_s is the area of inside roof and wall. The gas pressure rise is approximated using a linear function and it has a maximum at the end of the reverberation ($5t_a + t_r$). The gas pressure curve in Figure 5 is shown with the solid line.

The blowdown time (when the gas pressure falls to ambient pressure) corresponding to τ_{\max} can be determined as [1]:

$$\tau_{\max} = \frac{1}{2,13} \ln \left(\frac{P_{QS} + P_0}{P_0} \right) \quad (14)$$

The impulse i_g of gas pressure can be approximated with the area under the curve (we can ignore initial linear rise), and can be determined as [2]:

$$i_g = \int_0^{\tau_{\max}} (P(t) - P_0) dt = \frac{P_1}{C} (1 - e^{-C\tau_{\max}}) - P_0 \tau_{\max} \quad (15)$$

Here $P_1 (= P_{QS} + P_0)$ is the peak internal pressure and:

$$C = \frac{2,13\alpha_e A_s a_0}{V} \quad (16)$$

There are several ways of venting a structure, including openings in the building, frangible panels that break at some predetermined pressure, and buildings constructed to fail in such a way as to provide safer venting of an explosion [1].

Figure 6 shows such a structure that is designed to fail-safe during the explosion.

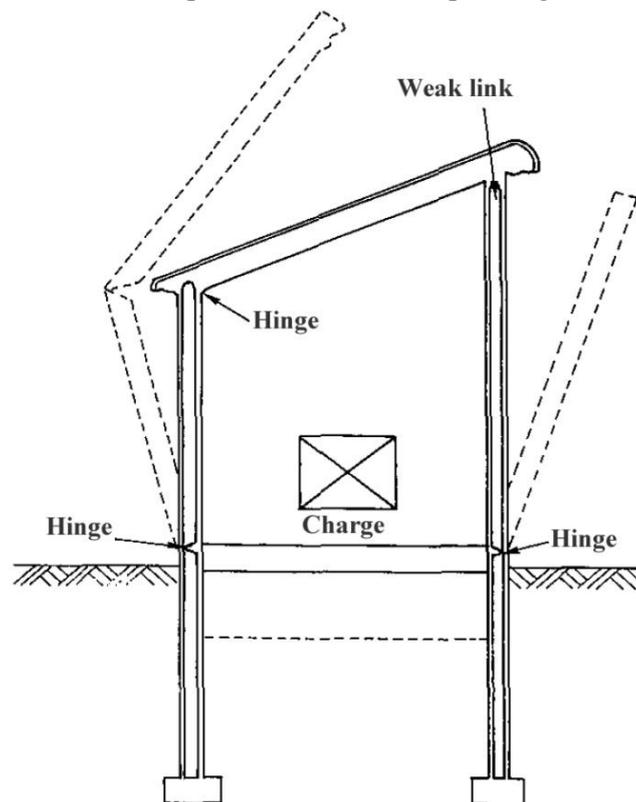


Figure 6. Example of a structure designed to fail safe and vent harmlessly (adapted from [12])

When an explosive detonates inside the structure, the initial maximum pressures will be very high and are usually intensified by several reflections inside. The consequences of the large temperatures and gaseous materials created by the explosion can create additional pressures depending on the containment configuration and can increase the load duration inside the building. The structure can be weakened by the cumulative forces of these pressures unless it is built to withstand the internal pressures. Venting these pressures can minimize

their duration and intensity. Usage of structures of the cubicle type (Fig. 7) or other barriers (with more surfaces or frangible ones), can lead to venting.

Calculation procedures for different cubicle structure designs, with appropriate diagrams, can be found in [10]. The estimation of the shock loads is usually done using computer programs because of a large number of parameters at play.

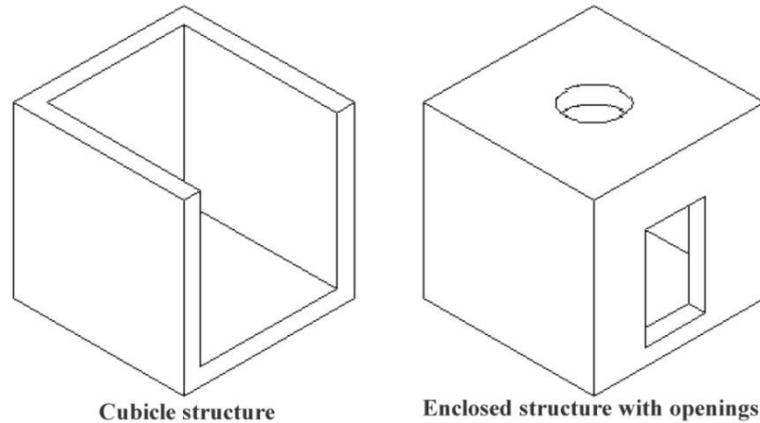


Figure 7. Confined explosion structures (adapted from: [6])

The blast pressure loading in internal parts of structures can be very complex. Gregory [13] shows the loading for a vented (cylindrical) structure. Fig. 8 indicates schematically a moment when the incident wave is reflected from internal surfaces obliquely, and parts of the cylindrical surfaces are loaded with a reflected wave. If the angle of incidence is large, this oblique reflection can also create Mach waves. Pressures can be also increased when waves hit corners or reflect near the axis of a central part of the cylindrical structure. In a structures shaped like a box, the reflection process can be even more complex (as will be shown in numerical simulations later).

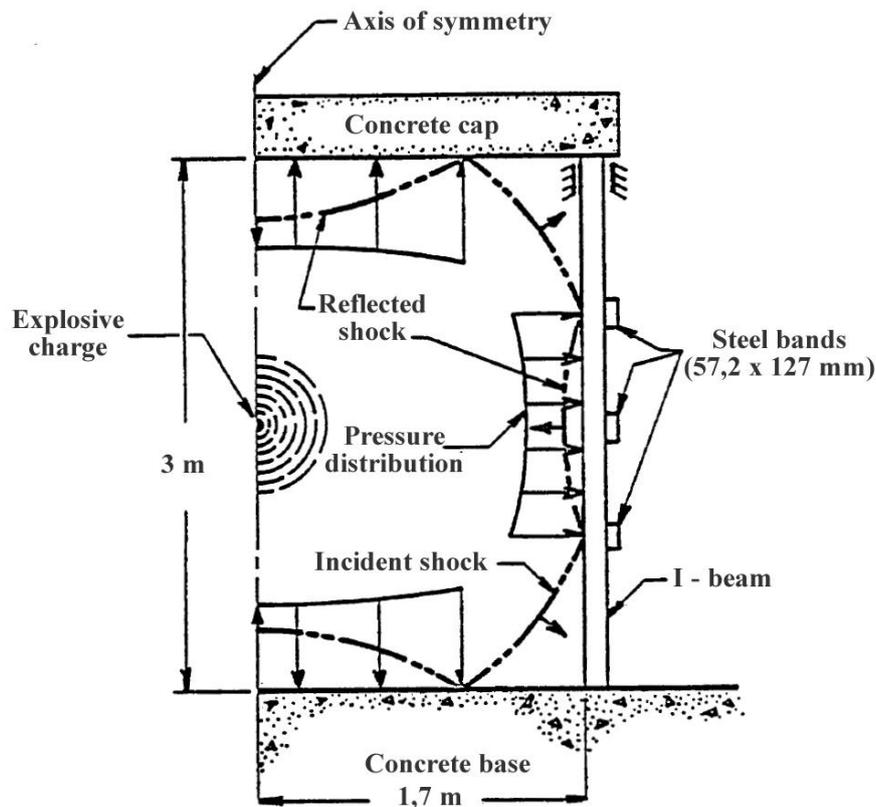


Figure 8. Shock reflections inside cylindrical (suppressive) structure (adapted from: [3])

In the process of estimation of internal blast loads, the first stage is the estimation of the pressures on the inside part of the structure (floor, inside walls, roof, etc.). This depends on the location/characteristics of the explosive charge, the geometry of the structure, as well as the presence, size and location of openings. A confined space can be generally defined with narrow spaces, with a comparatively long duration of the pressure and a number of follow-up peak pressures [14].

With sufficiently capable blast measurement devices, shock wave loading can be determined, or it can be calculated for symmetrical structures. The loading can be reasonably accurately estimated for centrally positioned or eccentric blasts in a spherical containment system. Current (but complex) computer 2D programs can be used in a cylindrical system to predict specific pressure-time loads on the cylinder axis for blast sources. The estimation of precise pressure-time loads is much more difficult for complex geometries typically used in real systems, so approximate solutions can be used here or experiments can be made. Kingery et al. [15], and Schumacher et al. [14], contain the data for measurements of internal blast on vented structures (for different shapes).

Example analytical calculation of basic parameters of internal loadings of structures can be found in [3].

In our earlier paper [16] we made comparison of analytical models for blast wave overpressure estimation after the explosion and introduced numerical simulation method for this purpose. Also, in [17] we reviewed estimation methods for external blast loads on structures, together with numerical simulation methods used in dealing with external blasts.

3. Numerical simulations

When employed in an urban environment problem, computational fluid dynamics (CFD) models take into consideration not only the conservation equations, materials, equations of state and boundary conditions, but accounts for the interaction of the blast wave and geometry in the domain, thus predicting complex reflections of the blast wave after the explosion. For complex geometries, this cannot be done using empirical methods.

In this paper, numerical 3D modeling of the internal explosion was performed in Ansys AUTODYN for 16,65 kg TNT charge (to compare the results with reference [4]), with a density of 1630 kg/m^3 , located in the centre of the fully confined rigid space with internal dimensions $3 \times 3 \times 3 \text{ m}$ (structure, shown in Fig. 9). Material parameters (default values) for air and TNT were chosen from the AUTODYN.

The computational grid for interior space contained 343 000 cells, and Euler solver was used. Mesh in Euler solver is fixed, and material flows through faces of numerical cells. It is mostly used for fluid modeling, as well as for gases and solids deformation.

This multiple material solver uses Godunov method, where material is transported across cells, and algorithms estimate the state of cells with multiple materials. Advantages of Euler solver are: no grid distortions, large deformations possible, rezoning and erosion not required, and higher time step in general. Disadvantages are usually: more computations, need finer zoning and additional cells for potential flow regions, shocks are diffused more than using Lagrange solver, less flexible for strength modeling and thin sections need smaller time steps [18].

During the calculation, the pressure history was recorded at the corner of the room, since this is the location with the highest recorded values of overpressures after the explosion in confined space, and also in the centre of the structure side, as well as in the middle of the structure edge (Fig. 9).

We started the analysis with a free airburst explosion simulation (1D detonation wave [18]), with an explosive mass of 16,65 kg (charge radius 134,6 mm; numerical cells 1 mm size). Results of this 2D numerical simulation were saved (.fill file) and remapped later into the center of a 3D closed space environment (Fig. 9).

Fig. 9 presents an initial setup of a rigid closed space 3D model after a remapping solution from 2D numerical simulation. The detonation point was located in the center of the room. Velocity vectors of the initial shockwave are also visible in Fig. 9, as well as different gauge points in the room.

Figure 10 presents computed pressure histories at gauges (measuring points) 1, 2, and 3, located in different parts of the room. It can be seen that, because of a relatively large mass of the charge (16,65 kg), quite high overpressure levels were present at the point in the corner of the room (about 41,1 MPa, a result closely matching the one from reference [4]).

Maximum overpressure at gauge 2 is around 12 MPa, and at gauge 3 is around 5,4 MPa. We can also see additional pressure peaks developing over time (confirming the theory mentioned in the previous section), increasing the total blast wave impulse delivered.

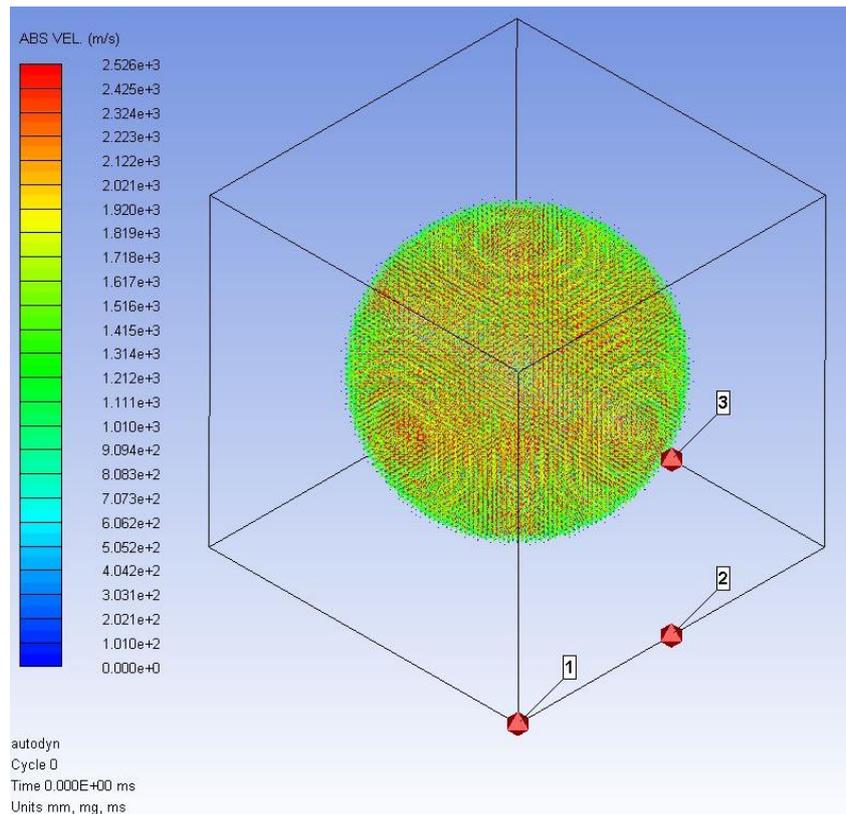


Figure 9. Initial setup of interior explosion (3D model) after remapping solution from 2D simulation

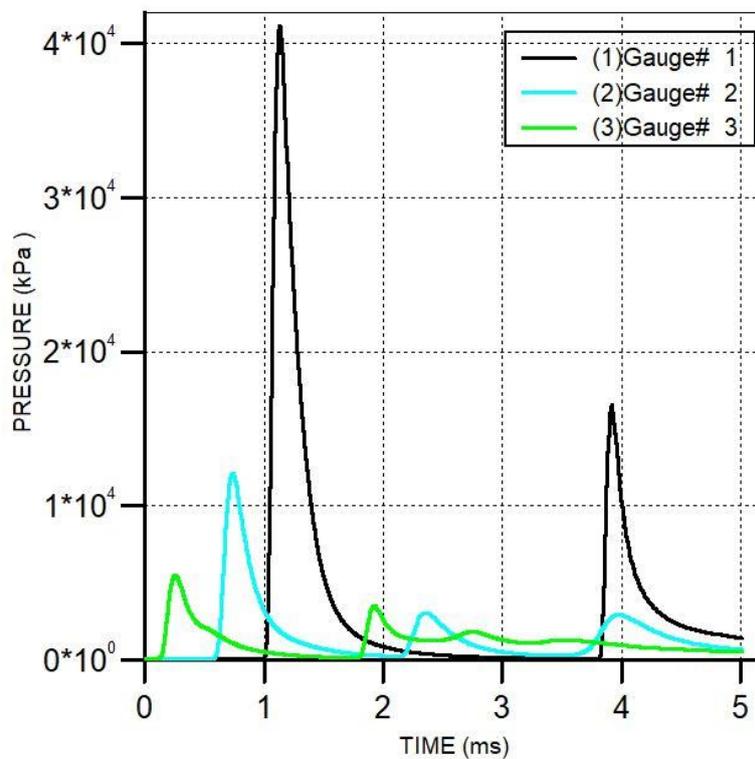


Figure 10. Computed pressure history at gauges 1, 2 and 3, located in the room

Fig. 11 presents shockwave velocity vectors for different numerical simulation times. From Fig. 11 we can see the movement of the shockwave and its velocity at different times. Also, symmetrical wave reflections can be seen as a wave develops away from the detonation point and bounces off the inner surface of the structure.

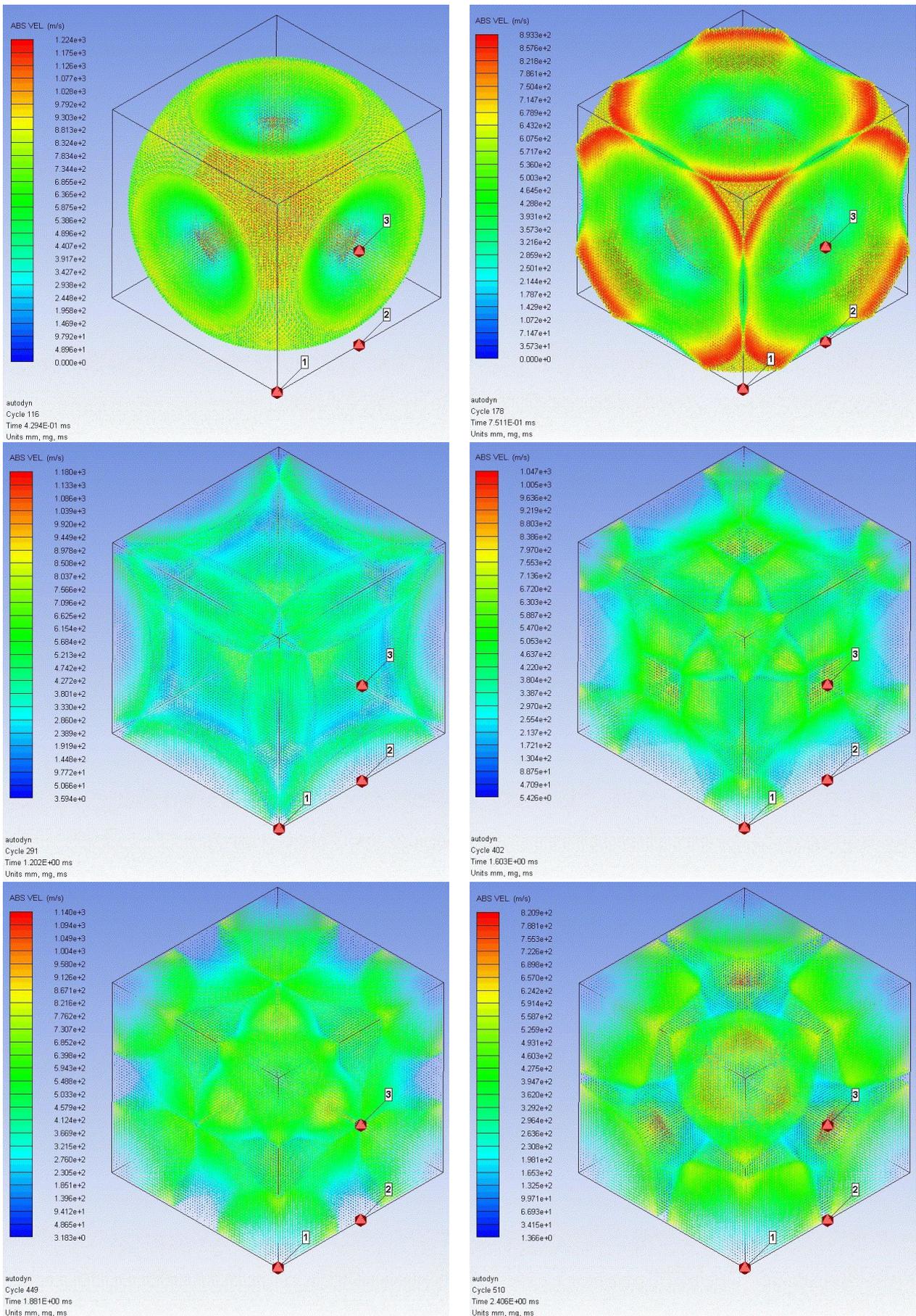


Figure 11. Shockwave velocity vectors for different times in a rigid closed space environment

Figure 12 presents the pressure contours on the plane through the centre of the room (cubicle) for different simulation times, showing the shock wave propagation and reflection. After reflection from the wall, the shock front moves toward the room centre, and after symmetrical reflection, the whole process is repeated, with the additional pressure peaks of lower intensities.

In the second image to the right in Fig. 12 ($t = 0,251$ ms) we can see the pressure values over 5 MPa, as indicated in Fig. 10 for gauge 3. The third image, to the left in Fig. 12 ($t = 1,88$ ms), is also interesting showing complex reflections pattern taking place after the blast wave bounces inside the structure.

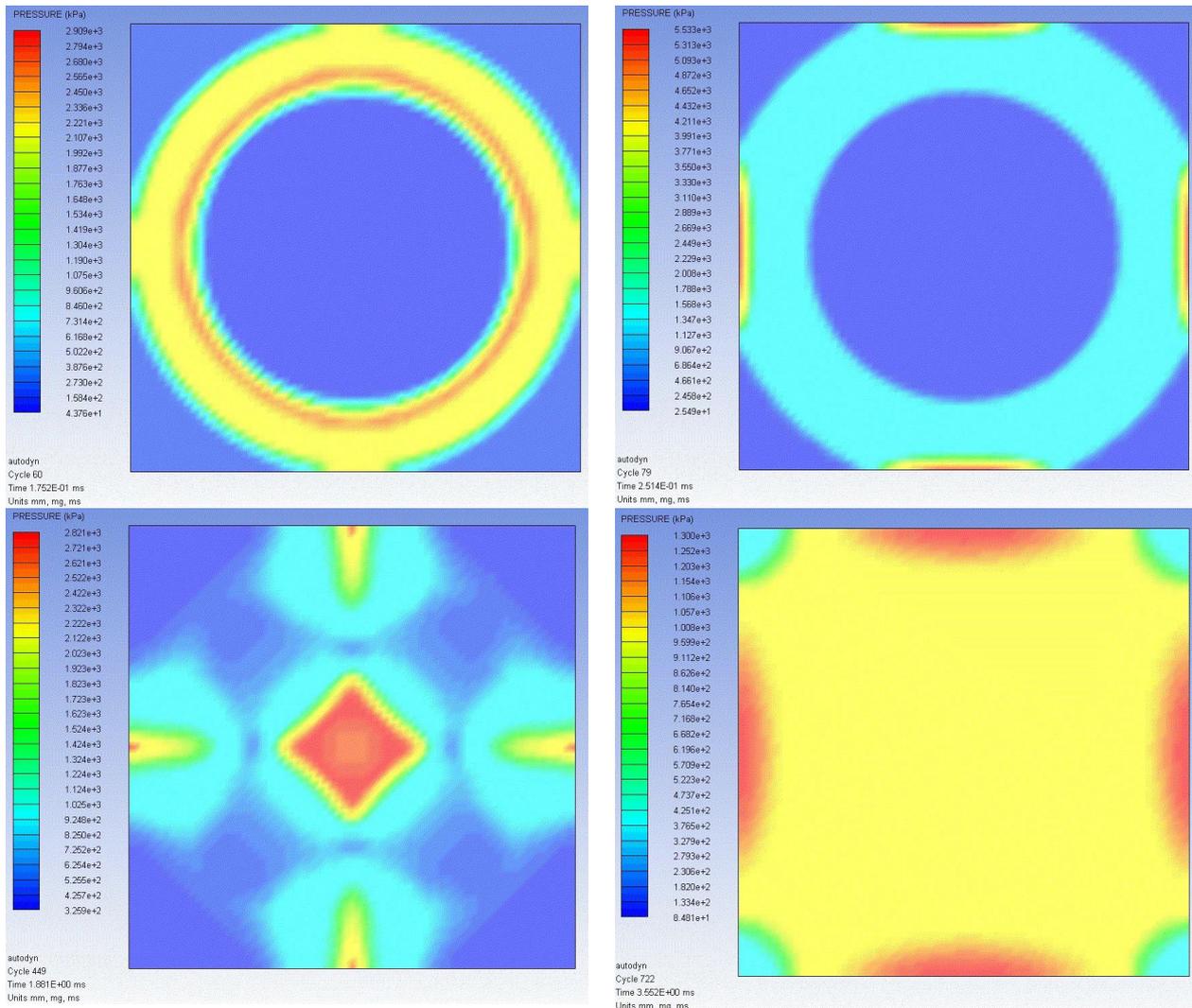


Figure 12 Pressure contours on the plane through the centre of the room for different simulation times

Figure 13 presents the pressure contours, this time on the plane representing the floor of the room (confined cubicle) for different simulation times. The total simulation time was 5 ms, the same as in previous cases.

Here, it can be seen from the blast wave pressure contours that overpressure values are significantly higher, with values reaching over 40 MPa for $t = 1,126$ ms. This pressure value corresponds to the location of a gauge point 1 in the corner of the confined room (pressure history shown in Fig. 10). These contours confirm an earlier statement (also mentioned in [4]) that the highest blast wave pressure is usually achieved in the corner of the confined space due to symmetrical wave reflections.

Generally, as we can see, at the beginning of the process the peak pressure is developed at the wall centre (Fig. 12, second to third image), and then it moves further, to the edge's direction (Fig. 13, third image), where the values of peak pressures noticeably increase. These kinds of numerical simulations, using CFD methods, can give us valuable insight into the complexity of shockwave propagation in closed spaces and the inherent danger of an explosion in such an environment. Together with experiments and theoretical models, they can be an efficient tool in the estimation of blast parameters in an urban scenario.

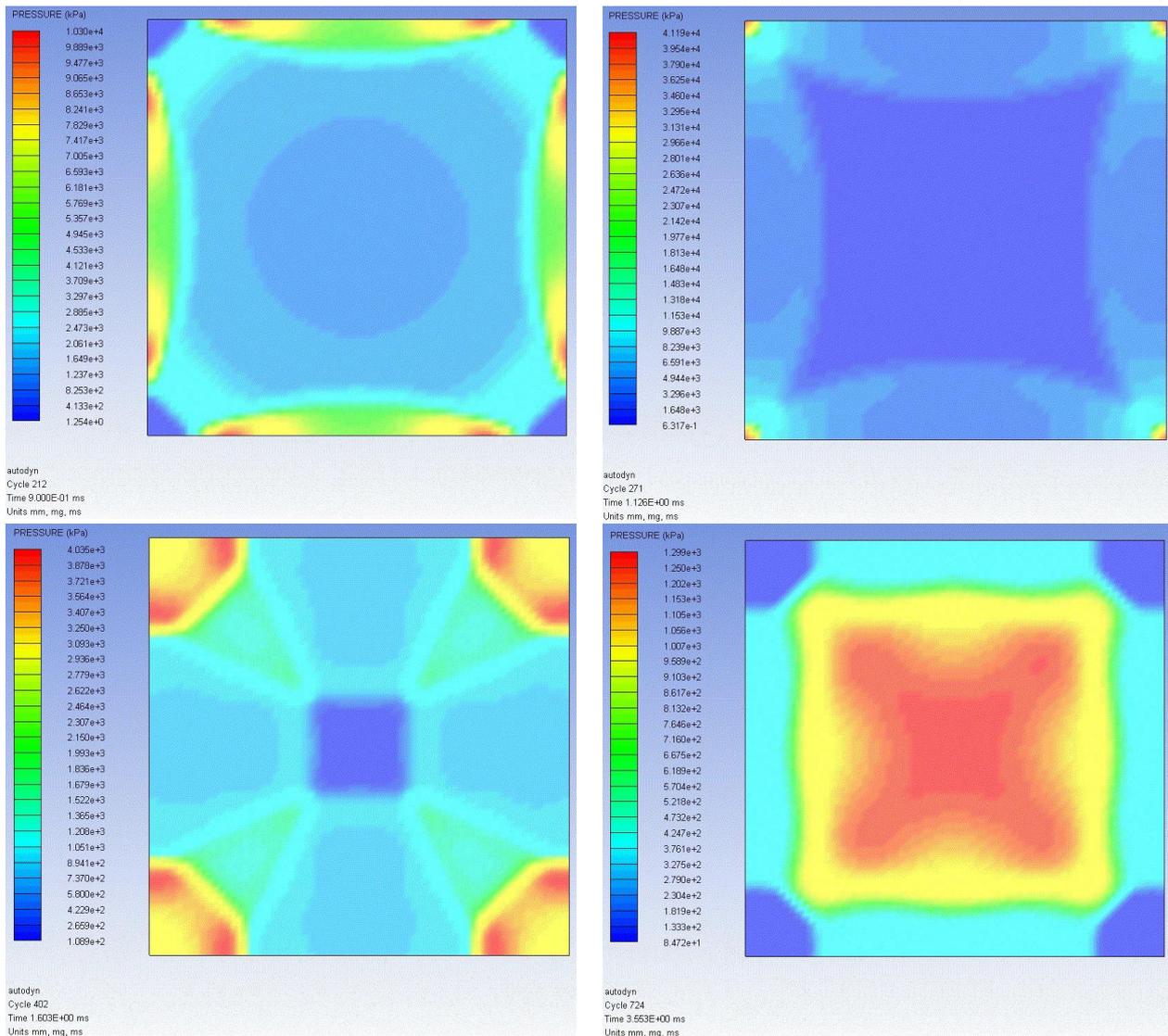


Figure 13. Pressure contours on the plane representing the floor of the room for different simulation times

4. Conclusions

A review of internal blast loads on structures modeling methods is presented in the paper.

Numerical simulations of an explosion in a confined environment scenario were done in software Ansys AUTODYN and compared with available data [4]. It was confirmed that the highest blast wave pressure is usually achieved in the corner of the confined space.

Recommendations were given regarding the use of numerical simulations in blast wave parameter estimations for the confined space environment.

Further research in this field could be directed to simulations of structural response to loading. Methods for reinforcing the structures to the blast load and human protection techniques could also be pursued in future research.

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