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Influence of Foam Filling on Dynamic Response of Hemispherical Shell Subjected to Blast Pressure

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The paper aims to investigate the effect of aluminium foam filling of hemispherical steel shell on its dynamic response, accounting for the blast pressure modelling. The considered structures subjected to uniformly distributed pressure, rigidly connected with a steel plate, are considered. True material stress–strain curves for shell and foam filling are assumed in calculations. The problem is solved by FEM using ANSYS software. The time relations of strain energy and effective stresses for different simulations of blast pressure are determined and compared for steel shells and shells filled with aluminum foam.

Keywords: Blast pressure, shells, foam filling, strain energy, effective stress.

1. Introduction

Hemispherical shells due to their advantages are widely used in many constructions: e.g. roofing of large dimensions, pressure vessels, structures designated as explosion protections. Modeling of structures absorbing blast energy, resulted from industrial accident or terrorist attack, is the subject of interest of many engineers. The idea of applying thin shells as absorbers of the explosive energy brought the research which has been presented by authors in previous papers [4],[5]. It is well known that thin–walled plate and shell structures are good energy absorbers.

The assessment of blast loading effects is required for design of structures to withstand the explosion. The blast loading time relation, obtained empirically, is exponential and consists of two phases: positive (overpressure) of duration in range of milliseconds and negative one (subpressure) of duration in range of seconds. In the numerical analysis of explosion protection structures this relation is often represented by a right angle triangle and furthermore the important effects as multiple blast wave reflections, the Mach effect, and negative phase of the blast wave are usually neglected. Generally, it is assumed that explosions on surface or in air are free blast propagations without any contact with the ground or adjacent structures. Neglecting reflections of the blast wave could lead to overestimation or underestimation of structure effective stresses and its strain energy.

It should be mentioned that the characteristics of reflected blast pressure can never be achieved empirically but only by numerical simulations (see: [3],[6],[7]). In many cases the interaction of explosion wave and surrounding can result in magnification of the pressure impulse. The blast loading time relation may be of different character – it can be similar to the incident wave but of higher peak value or assuming perfect ground reflection and reflected wave overlaying the incident one, the blast loading time relation can be obtained by superimposing additional linearly varying loading. In authors previous works [4],[5] conical and hemisphere steel shells under blast pressure have been considered. This paper aims to analyze the response of hemispherical shell filled with aluminum foam under different courses of blast pressure and to find out the effect of foam filling on strain energy and effective stress values, comparing to the response of "empty" shell. The problem has been solved by finite element method using ANSYS software.

2. Assumed blast pressure relations

The exponential blast loading time relation, obtained empirically, consists of two phases: positive (overpressure) of duration in range of milliseconds and negative one (subpressure) of duration in range of seconds. In the numerical analysis of protection structures this relation is often represented by a triangle of the same duration T_p and peak value p_0. From numerical reasons it has been assumed that this peak value is reached at $t = kT_p$ where $k = 0.1$ (Fig. 1).

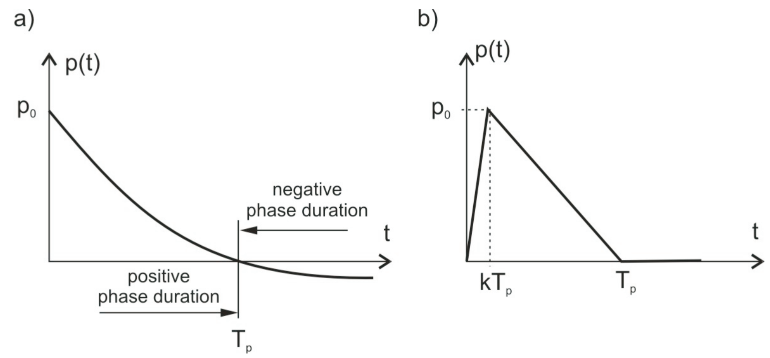

Figure 1 Blast pressure representation a) empirical b) triangular approximation

In aim to consider the effect of blast wave reflection three types of pressure characteristics are considered (Fig. 2). It has been assumed that in all cases pulse duration is the same and kept constant and equal to 0.5 ms. For all types the peak value of blast pressure equals p_0 and the impulses are equal each other. The pulse denoted by "I" is a triangle commonly used in calculations of structures subjected to blast pressure. The pulses denoted by "II" and "III"' represent the reflected blast waves in which the value of overpressure and impulse decreases linearly until certain limit when the pressure begins to increase due to the effects of reflections. For pulse "II" the maximum value of overpressure p_0 is reached at 0.05 ms and it decreases to $p = 0.2p_0$ at t = 0.2525 ms and next the pressure increases and equals $p = 0.8p_0$ at t = 0.2975 ms and finally it linearly decreases to zero at time $t = T_p = 0.5$ ms. For pulse "III" the first peak value equals 0.8 p_o and it decreases to $p = 0.2p_0$ at t = 0.2525 ms and next the pressure increases to the maximum value p_0 at t = 0.2975 ms and next linearly tends to zero at $t = T_p = 0.5$ ms.

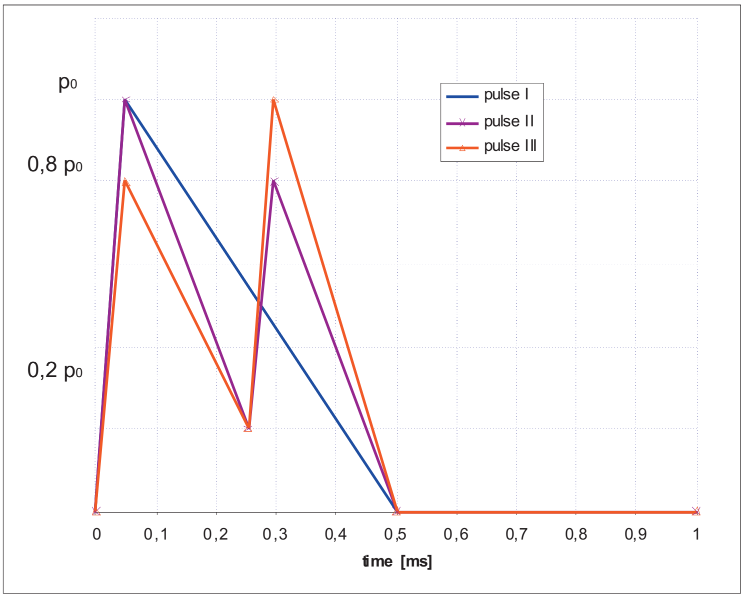

Figure 2 Assumed simulations of reflected blast pressure [4]

3. Shell geometrical model

The present paper deals with steel shells in shape of hemisphere (Fig. 3) that are filled with an aluminum foam. Considered shells are of the same thickness (h = 0.5 mm) and radius (40 mm) and are rigidly connected with a square plate of dimensions 80 × 80 mm. The boundary conditions are shown in Fig. 3. The plates have been used to model the boundary conditions for shells as close as possible to real ones. The displacements in three perpendicular directions and rotations about three perpendicular axes have been set to zero for all nodes lying along bottom plate edges. The structures are loaded by blast pressure (shown in Fig. 2 – pulses I, II, III) distributed uniformly over the whole surface.

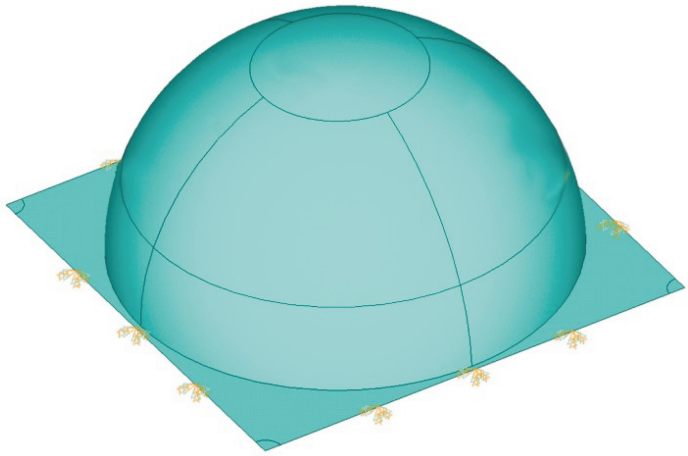

Figure 3 Boundary conditions of analysed hemispherical shell

4. Finite element modeling

To solve the problem of dynamic response of considered structures the ANSYS [8] software based on finite element method has been employed. Solid-shell elements have been applied in calculations. The outer surface (hemispherical steel shell) has been modeled by eight nodes shell elements of six degrees of freedom. These elements enable to take into account geometric nonlinearities (large deformations) and nonlinear material properties. The foam filling has been modeled by ten nodes solid elements (tetrahedrons) of three degrees of freedom in each node. The connection between aluminum foam filling and steel shell has been realized on the basis of deformation compatibility. No contact problem nor filling displacement versus steel shell has been accounted for. In the calculations the material stress-strain curves shown in Fig. 4 (for steel shell) and in Fig. 5 (for aluminum foam) has been implemented with following strength properties:

- for steel: Young's modulus E = 200 GPa, Poisson's ratio $\nu = 0.3$, density $\rho = 7850$ kg/m^3, initial yield stress $\sigma_0 = 200$ MPa.
- for aluminum foam [2]: E = 200 MPa, $\nu = 0.33$, $\rho = 500$ kg/m^3, $\sigma_0 = 0.92$ MPa.

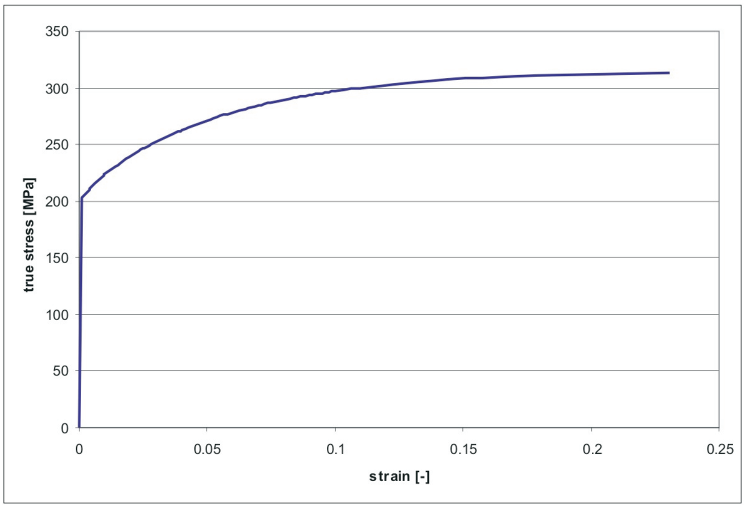

Figure 4 Material stress–strain relation obtained in laboratory for steel in tensile test

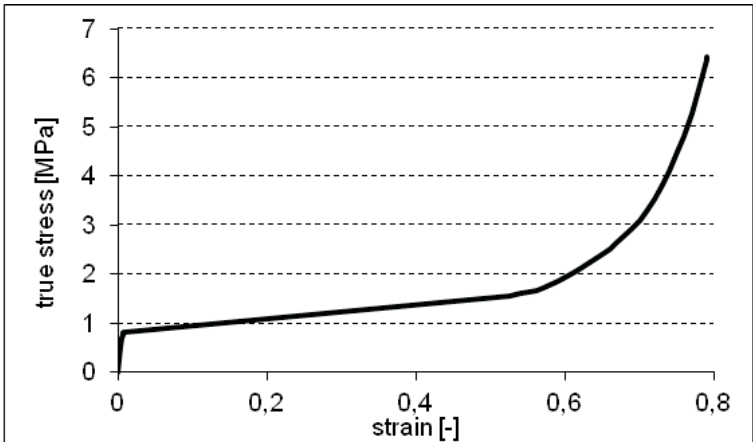

Figure 5 Material stress–strain relation obtained in laboratory for aluminum foam in compression test

For both the materials the multi–linear characteristics have been assumed approximating as close as possible the true strain–stress relations obtained in the laboratory tests.

For the assumed pressure distribution the load was applied uniformly to all elements with the same value in a given time step.

In the numerical analysis the dynamic responses of considered structures loaded by pulse pressure have been searched for.

In the dynamic analysis the equilibrium equation has the following form:

$$\{P\} = [M] \cdot \{\ddot{u}\} + [C] \cdot \{\dot{u}\} + [K] \cdot \{u\} \tag{1}$$

where [M] is a structural mass matrix, [C] is a structural damping matrix and [K] is a stiffness matrix.

In the analysed cases the damping can be neglected and then equation (1) can be written as follows:

$$\{P\} = [M] \cdot \{\ddot{u}\} + [K] \cdot \{u\} \tag{2}$$

Substituting time derivative of displacement {ü} by increment of displacement {u} in consecutive discrete instant of time *t* the new equilibrium equations included inertia forces are obtained in each time step. For the equation obtained the solution algorithms used in static analysis can be employed. In ANSYS software the Newmark method is used to perform the integration over time and for equations solution in a consecutive time step the Newton–Raphson algorithm is applied.

5. Results of calculations

The results of numerical calculations are presented in Figs 6–11 showing the time dependent plots of strain energy (Figs 6, 8, 10) and effective stresses (Figs 7, 9, 11) for a steel shell (”empty shell”) and a structure consisting of a steel hemisphere filled with aluminum foam, loaded by three assumed distributions of blast pressure (see section 2). The pressure maximal value p_0 equals 5.0 MPa and 5.5 MPa, respectively.

It is found that in case of pulse ”I” (Fig. 6), when $p_0$increases from 5 MPa to 5.5 MPa, the shell without filling (”empty” shell) is destroyed being fully plastic (the effective stresses reach the ultimate strength – compare material stress–strain curve in Fig. 4 with effective stress plots shown in Fig.6b). For pressure distributions denoted as ”pulse II” (Figs 8, 9) and ”III” (Figs 10, 11) for p_0 changing from 5 MPa to 5.5 MPa the maximal value of strain energy increases several times and large regions become plastic. For the third type of blast pressure distribution the plastic deformations appear in the second stage of pulse duration (when $p_0 = 5.5$ MPa).

Structures consisting of a hemispherical steel shell and foam filling behave quite differently – for each type of blast pressure distribution the strain energy values vary not very significantly and the effective stresses values stay in the elastic range.

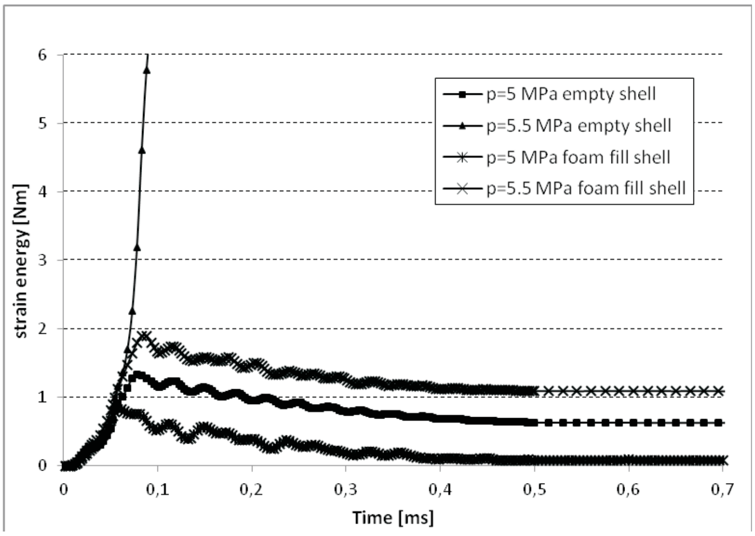

Figure 6 Strain energy versus time relations for steel shell and for foam filled shell subjected to pulse I (see Fig. 2)

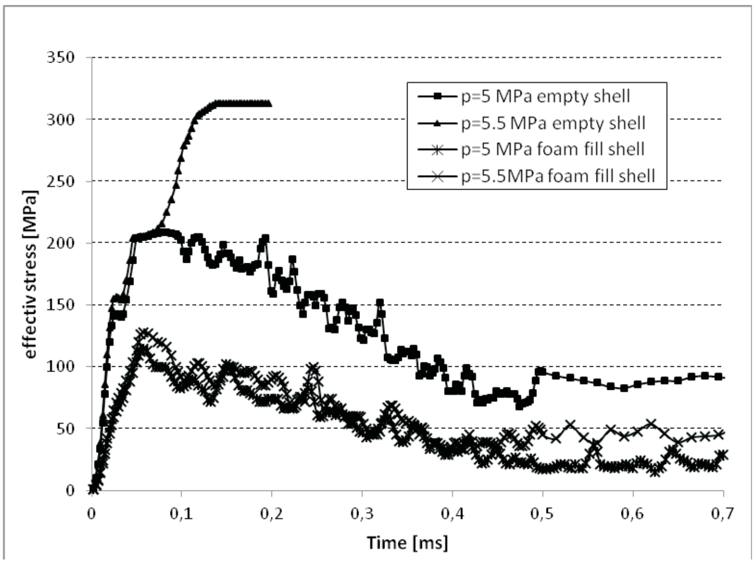

Figure 7 Effective stress versus time relations for steel shell and for foam filled shell subjected to pulse I (see Fig. 2)

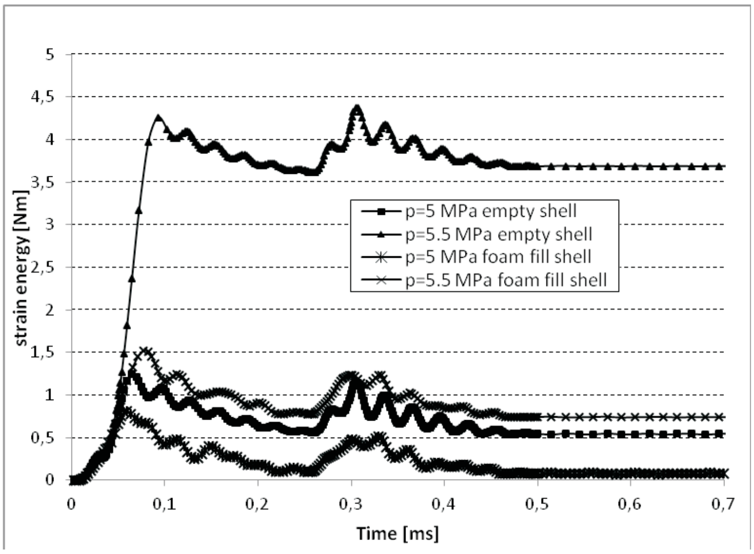

Figure 8 Strain energy time relations for steel shell and for foam filled shell subjected to pulse II (see Fig. 2)

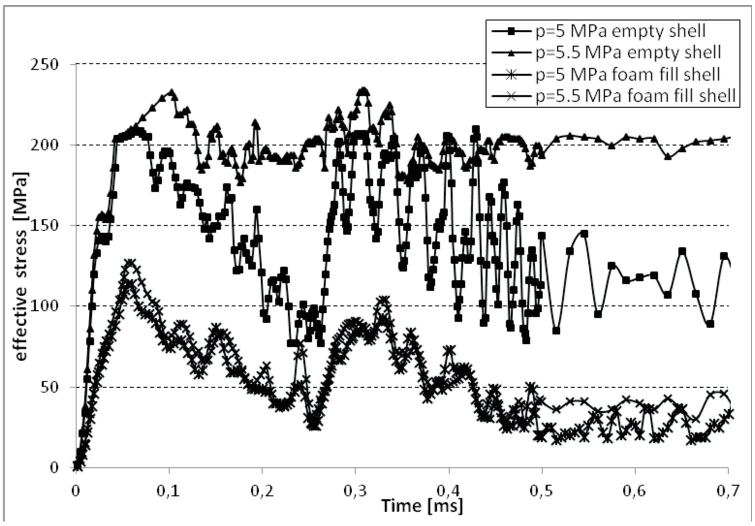

Figure 9 b) Effective stress time relations for steel shell and for foam filled shell subjected to pulse II (see Fig. 2)

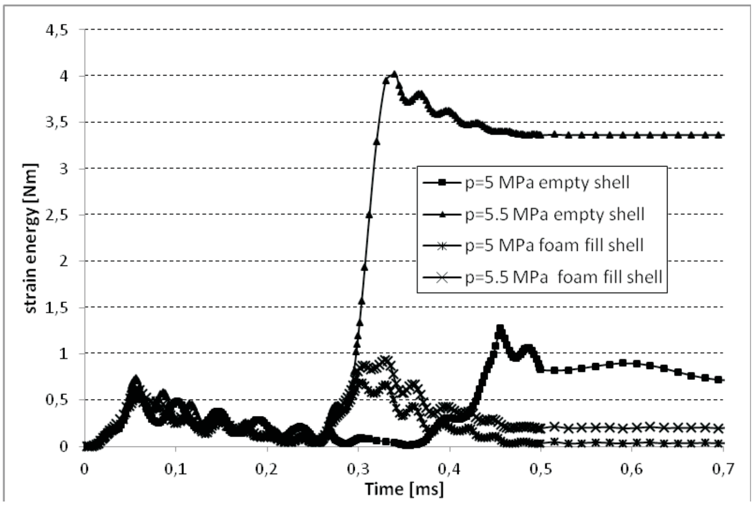

Figure 10 Strain energy and effective stress time relations for steel shell and for foam filled shell subjected to pulse III (see Fig. 2)

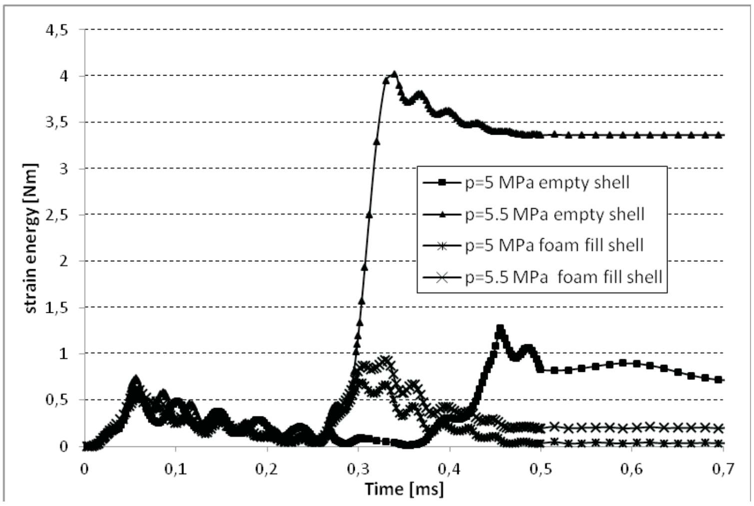

Figure 11 Strain energy and effective stress time relations for steel shell and for foam filled shell subjected to pulse III (see Fig. 2)

6. Conclusions

It should be underlined that the assumed maximal values of pressure are in range of a half of real peak value of blast pressure [1, 2]. At the values considered in the presented investigations shells without filling were destroyed while the aluminium foam filling of low strength properties have resulted in substantial decrease of effective stresses. It is worth to mention that the foam density is small (in comparison with steel) so it does not increase the mass of a structure in a significant way.

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