MODELING THE STRESS–STRAIN STATE OF A CYLINDRICAL SHELL UNDER EXPLOSIVE LOADING USING THE EXPLICIT DYNAMICS METHOD

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The study presents a numerical simulation of the stress–strain state of a thin-walled cylindrical shell subjected to internal explosive loading using the Explicit Dynamics method in ANSYS Workbench. The finite element model with an impulse pressure law was used. The results show that the maximum stresses are localised in the central zone of the shell, where plastic deformations are formed and creep is accumulated, which ultimately leads to residual strains and fragmentation.

Keywords: cylindrical shell, ANSYS Workbench, Explicit Dynamics, explosive loading, stress–strain state, equivalent stresses, plastic deformations, creep, residual strains, fragmentation

Introduction. The study of thin-walled structures strength under internal explosive loading is a relevant scientific and practical problem [1, 2]. The effectiveness of shell fragmentation is determined by the formation of fragment groups with a prescribed spectrum. However, achieving this result is complicated by contradictory requirements. On the one hand, the increase of firing range requires higher internal ballistic parameters, and, consequently, enhanced shell strength (700 MPa or higher). On the other hand, ensuring of fragmentation effect requires retaining the shell's fragmentation capability.

The shell material is subjected to intense dynamic loading, which initiates plastic deformation, creep accumulation, and subsequent fracture, resulting in fragment formation under the instantaneous pressure growth conditions. A key research task is to predict the mechanisms of these processes and to determine the quantitative and qualitative characteristics of fragmentation [1, 2], particularly the parameters of fragment groups. Such results provide a scientific basis for the rational selection of materials and structural features of cylindrical shells, considering both strength requirements and controlled fragmentation.

The explicit dynamics method implemented in the Explicit Dynamics module of the ANSYS Workbench software package is effective for reproducing these highly transient processes [3]. Unlike implicit approaches, where each time step requires solving a system of equations, the explicit scheme computes the system state directly, making it particularly suitable for simulating short-term explosive and shock phenomena.

This work aims to investigate numerically the stress–strain state of a thin-walled cylindrical shell under internal explosive loading, with emphasis on plastic deformations, creep accumulation, and fragmentation prediction.

Theoretical principles. The explicit dynamics analysis is based on the solution of the equation of motion:

$$M\ddot{u}(t)+C\dot{u}(t)+Ku(t)=F(t)\,. \tag{1}$$

where M is the mass matrix, C is the damping matrix, K is the stiffness matrix, $u(t)$ is the displacement vector, and $F(t)$ is the external forces vector.

In the explicit time integration scheme, particularly the central difference method, accelerations and velocities are determined directly from the known state at the previous time step. This provides high computational efficiency for modelling transient explosive and shock processes.

The elastic response of the material is described by Hooke's law for isotropic linear elasticity:

$$\sigma=D\cdot\varepsilon\,. \tag{2}$$

where σ is the stress vector, ε is the strain vector, and D is the matrix of elastic constants.

The stress state was assessed using the von Mises equivalent stress criterion:

$$\sigma_{eq}=\sqrt{\tfrac{1}{2}\left[(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2\right]+3\left(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2\right)}\,, \tag{3}$$

where σ_x , σ_y , and σ_z are the normal stresses along the coordinate axes, and τ_{xy} , τ_{yz} , and τ_{zx} are the shear stresses.

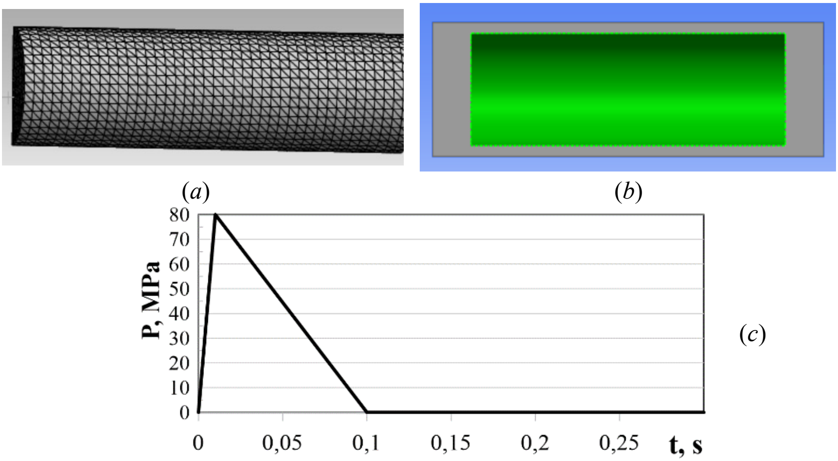
Creep effects were incorporated using the generalised Norton power law:

$$\dot{\varepsilon}_{cr}=A\sigma^n e^{-Q/(RT)}\,. \tag{4}$$

where $\dot{\varepsilon}_{cr}$ is the creep rate, A, n, Q are material constants obtained experimentally, R is the gas constant, and T is the absolute temperature.

The use of this model made it possible to take into account the accumulation of residual deformations even under short-term impulse loading, which is critical for predicting fragmentation processes.

Problem statement. The object of this study is a thin-walled cylindrical shell with an end plug (Fig. 1) [1, 2]. The geometric parameters are as follows: outer radius $R=30$ mm, wall thickness $t=5$ mm, and length $L=200$ mm. The shell material is steel with an elastic modulus $E=210$ GPa, Poisson's ratio $\nu=0.3$, and density $\rho=7850$ kg/m^3.



(*a*) (*b*) (*c*)

Fig. 1. Cylindrical shell model and loading conditions:
a) the finite element mesh; *b*) the internal pressure application area;
c) pressure–time curve.

The shell was discretised with a finite element mesh of tetrahedral elements having a typical size of approximately 3 mm (Fig. 1*a*) for numerical calculations. The resulting model contained 1285 finite elements, which ensured sufficient accuracy in capturing the local stress concentration zones.

The load was applied to the internal volume of the cylindrical shell in the form of a pressure pulse (Fig. 1*b*). The pressure increased from 0 to 80 MPa over 0.01 s and then gradually decreased to zero by 0.10 s (Fig. 1*c*). This pressure–time curve reproduces the characteristic behaviour of an explosive process in a confined volume.

Results. Distribution of von Mises equivalent stresses at the moment of peak pressure (t = 0.01 s) is presented in Fig. 2. The maximum stresses σ_{eq} are concentrated in the central region of the cylindrical shell, which corresponds to the zone of maximum action of the explosive load. The peak stress reached approximately 358 MPa, approaching the yield strength of steel and indicating the initiation of plastic deformation in this region.

Fig. 2. Equivalent stresses distribution at the peak load (t = 0.01 s)

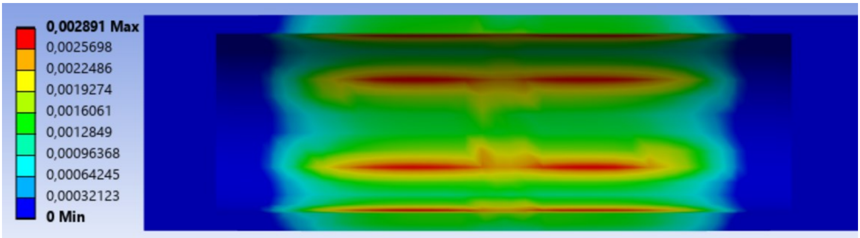


Fig. 3. Creep strain distribution after the completion of loading ($t = 0.30$ s)

The distribution of creep strains after the completion of the pressure pulse ($t = 0.30$ s) is shown in Fig. 3. The largest creep strains are also concentrated in the central region, coinciding with the location of maximum equivalent stresses. This confirms that the accumulation of residual strains is directly driven by the action of peak stresses in this zone. Constructively, the upper and lower parts of the shell, having greater structural thickness, exhibit considerably lower creep strains. Consequently, the central region of the cylindrical shell is identified as the critical zone of active fragmentation, governing its post-loading performance and initiating fragmentation under internal explosive loading.

Conclusions. The explicit dynamics method in the ANSYS Workbench environment has proven effective for the reliable reproduction of short-term processes induced by internal explosive loading in thin-walled cylindrical shells. The application of the pulse law of pressure variation enabled obtaining a detailed picture of stresses and strains distribution. It was established that the zone of maximum equivalent stresses and creep accumulation are concentrated in the central part of the shell, leading to the formation of residual deformations after the completion of the pressure pulse. The identified regularities confirm that this zone initiates of subsequent fragmentation as a final stage of the process. These findings are of decisive importance for the substantiated selection of materials and design parameters of cylindrical shells, considering both their strength and tendency to predictable fragmentation.

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