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PROTECTION OF AN EXPLOSION CHAMBER AGAINST FRACTURE BY A DETONATION WAVE

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The results of numerical simulation of the protective properties of layered and porous shields that are used to reduce peak stresses and to prevent failure of the walls of an explosion chamber under detonation loading are presented. It is shown that porous shields have stronger protective properties than layered shields of the same thickness.

Protection of the walls of cylindrical chambers completely filled with high explosive (HE) against the destructive action of detonation waves is of importance for a wide range of technical devices. The problem of retainment of the working capacity of the chamber after a finite number of loadings is of paramount importance, although it is often necessary to ensure the integrity of a structure over a limited time interval. In the first case, it is required to decrease the peak stresses in the walls to acceptable values, for example, below the yield point of the material, and, in the second case, it is necessary to decrease them to a level that makes it possible to retain the structure integrity in a given time interval.

A decrease in loads at the detonation product–metal interface results in a decrease in tensile stresses and in the degree of damage in the chamber walls [1]. A mere increase in the wall thickness is not always an optimal solution of this problem, and, therefore, a more efficient method for preserving the integrity of a structure to be tested should be found. There are two approaches to reduction of the stress acting on the inner surface of the chamber: an increase in the pressure-pulse duration in the layered shield owing to multiple reflection of waves from layers with different acoustic impedances [2] and also owing to energy dissipation of the pressure pulse under plastic deformation of high-porosity materials [3]. In the second case, the pressure decay is also due to a marked increase in the chamber volume and to a strong pressure dependence on the detonation-product density (Landau–Stanyukovich polytrope).

We consider the problem of determination of the stress-strained state and also the problem of occurrence and growth of damage in the walls of a cylindrical chamber under the action of the detonation-product pressure. Between the HE charge and the inner wall of the chamber, there were damping shields of two types: (a) alternating layers of materials of different density and (b) a metal layer of different porosity. To estimate the efficiency of the approaches that were proposed to decrease peak stresses and the degree of fracture, the results obtained were compared with data for an unshielded chamber wall. The cross section of a chamber with a damping shield is shown schematically in Fig. 1, where r_0 is the HE-charge radius and r_1 and r_2 are the inner and outer radii of the chamber, respectively.

Basic relations that describe the spatial axisymmetric motion of a porous high-strength compressed elastoplastic medium are based on the laws of conservation of mass, momentum, and energy [4, 5]. All values in the relations correspond to a porous medium, and these relations are supplemented by the kinetic equation that describes the growth and implosion of spherical pores [5, 6]. In solving the one-dimensional problem, we used the complete kinetic equation from [6]. However, as was mentioned in [5] and confirmed by numerical calculations, we can ignore the inertial term in this equation and use the reduced relation from [5].

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The pressure in a porous medium was determined from the equation of state for a solid component:

$$p = p_s(V_s, E)/\alpha.$$

We used the equation of state of the same form as in [5] for copper, as in [4] for lead and polyethylene:

$$p_s = k_1 x + k_2 x^2 + k_3 x^3 + \Gamma_0 E,$$

and as in [7] for steel:

$$p_s = a_1 y + a_2 y^2 + a_3 y^3 + (a_4 + a_5 y)E/V_s.$$

The parameter $\alpha = W/W_s$ is related to the porosity Φ by the relation $\Phi = (\alpha - 1)/\alpha$. The strength characteristics of a porous material were determined as in [5]:

$$\sigma = \sigma_s/\alpha, \qquad \mu = \mu_s(1-\Phi)\Big(1 - \frac{6K_s + 12\mu_s}{9K_s + 8\mu_s}\,\Phi\Big).$$

In the above relations, p is the pressure, W_s is the specific volume of the matrix, W is the specific volume of the porous material, E is the specific internal energy; k_1, k_2, k_3, a_1, a_2, a_3, a_4, a_5, and Γ_0 are coefficients, $x = 1 - V_s$, $y = 1/V_s - 1$, V_s is the relative volume, σ is the yield point, μ is the shear modulus, K_s is the bulk modulus, and the subscript s denotes the matrix material.

A system that describes the motion of detonation products as a nonviscous nonthermoconducting gas is obtained from the relations for an elastoplastic medium if the parameters governing the strength properties are set equal to zero.

As an equation of state of detonation products, we used the Landau–Stanyukovich polytrope [3]. In simulating the detonation of a HE charge, we used the approach reported in [8]. With the HE compressed in a computational cell to the critical density ρ_*, the equation of state that describes the behavior of HE as a solid is replaced by the equation of state of detonation products. Ignition of the main charge by a detonator is modeled by several cells with higher HE density and, hence, with elevated pressure of detonation products.

To solve the problem stated, we used the finite-difference method [4], which realizes completely the convenience of the Lagrangian approach to description of the motion of a continuous medium, i.e., this method allows one to trace shock waves (SW) and also contact and free boundaries with acceptable accuracy. To suppress nonphysical oscillations behind the SW front, a combined artificial viscosity was introduced in the numerical scheme. The tensor viscosity, which is realized in triangular cells adjacent to the calculated node of the grid, makes it possible to protect the grid against "hourglass"-type distortions.

A special calculation procedure of displacement of the contact boundaries with respect to each other is based on the no-sliding condition along the normal and on the sliding condition along the tangent to the interface. Here the main and auxiliary groups of cells adjacent to the interface from both sides are formed. The groups interchange their places either at each step or in a definite number of steps. In the no-sliding case, the procedure describes the no-slip condition automatically. The solution algorithm assumes the possibility of spalling (jumping off) the metal–metal contact surfaces if the corresponding conditions are satisfied.

As a test, we considered the problem of discontinuity decay at the detonation product–chamber wall (copper and hexogen) contact surface for the case of a sliding detonation wave (DW). From the analytical solutions of [3], we obtained the following values: pressure $p = 22.2$ GPa and velocity $u = 520$ m/sec. A numerical solution gives $p = 22.7$ GPa and $u = 523$ m/sec. Additionally, we compared the pressure dependence on the specific volume for copper of different porosity. We used the same experimental curves as in [7]. We also solved numerically one-dimensional plane problems on collision of two porous plates at different velocities. Calculation results are presented in Fig. 2. On the basis of the tests, one can draw a conclusion on the efficiency of the physical and mathematical models of the interaction of detonation products with solid and porous materials that we applied.

In the case of a sufficiently long chamber, consideration can be confined to the one-dimensional problem. The damping shield consists of a sequence of alternating lead and polyethylene layers or a porous aluminum layer. In the first case, the thickness of the lead and polyethylene layers is the same as in [2], where the process of SW cumulation in layered media was studied. In our calculation, the thickness of the layers is increased

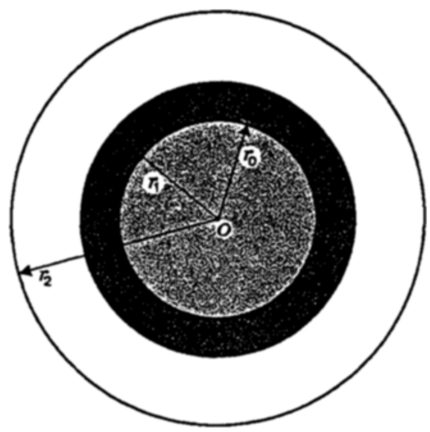

Fig. 1

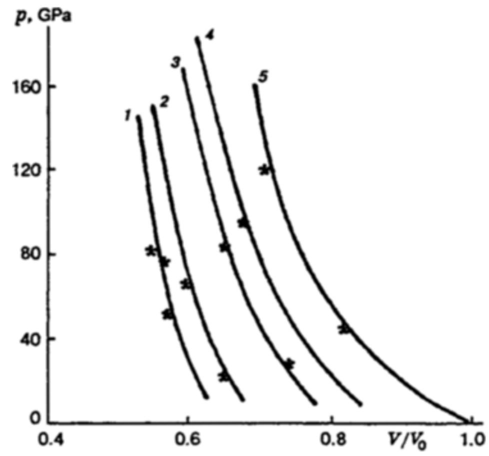

Fig. 2

Fig. 1. One-dimensional scheme of calculation.

Fig. 2. Pressure vs. specific volume for porous copper: solid curves correspond to experimental data and points refer to calculation results; $\Phi = 0.64$ (1), 0.71 (2), 0.82 (3), 0.88 (4), and 1.00 (5).

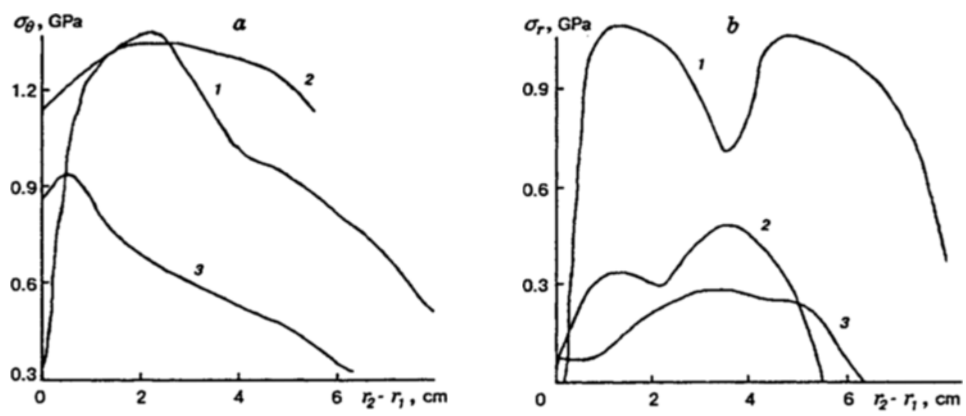

Fig. 3. Distribution of circumferential (a) and radial (b) stresses over the thickness of the chamber wall: 1) chamber without a damping shield; 2) nine-layer (polyethylene–polyethylene) damping shield; 3) porous damping shield.

in the direction of SW motion, which gives rise to an increase in the pressure-pulse duration and a decrease in the amplitude values of the tensile and compression stresses in the chamber walls. The porosities of lead and polyethylene are ignored. For the case of a normal incidence of DW on the multilayer-structure wall, we used a self-similar distribution of the parameters behind the front of a divergent cylindrical DW as an initial condition for detonation products [3]. Loading of the wall of the multilayer structure by a sliding DW is reproduced approximately in a one-dimensional calculation using the model of [9].

The problem stated was solved with the following physicomechanical characteristics of the materials:

For lead: $\rho_0 = 11.35$ g/cm^3, $\Gamma_0 = 2.77$, $k_1 = 47.74$ GPa, $k_2 = 73.29$ GPa, $k_3 = 11.22$ GPa, and $\sigma = 0$;

For polyethylene: $\rho_0 = 0.91$ g/cm^3, $\Gamma_0 = 1.64$, $k_1 = 0.7653$ GPa, $k_2 = 16.38$ GPa, $k_3 = 31.71$ GPa, $\mu = 0.9$ GPa, and $\sigma = 0.057$ GPa;

For steel: $\rho_0 = 7.86$ g/cm^3, $a_1 = 153$ GPa, $a_2 = 174$ GPa, $a_3 = 53.2$ GPa, $a_4 = 191.2$, $a_5 = -38.6$,

Fig. 4. Damage zones for solid (a) and porous (b) shields: 1) chamber; 2) shield; 3) detonation products.

$\mu = 81.4$ GPa, and $\sigma = 1$ GPa.
The initial HE density was $\rho_0 = 1.4$ g/cm^3, and the detonation velocity was $D = 0.3$ cm/μsec. As a porous shield, we used porous aluminum. The physicomechanical characteristics of the matrix material were as follows: $\rho_0 = 2.7$ g/cm^3, $\mu = 24.8$ GPa, $\sigma = 0.3$ GPa, and $\alpha = 1.8$. Dimensions r_0 and r_2 are fixed, and the thicknesses of the protecting shield and the wall can vary in different variants of calculations, while the total thickness of the chamber wall and the damping shield was constant and equal to the thickness of the unprotected chamber wall.

At the first stage, we solved the problem of sliding detonation. We considered the maximum (for the loading time) values of radial σ_r and circumferential σ_θ stresses over the thickness of the steel chamber wall protected by layered and porous shields. These stress distributions were compared with those for a steel wall without protecting shields. For ten (lead–polyethylene) layers, which begin with lead and end with polyethylene (layers as in [2]), we observed a reduction in σ_r, but the value of σ_θ was somewhat larger than that for the unprotected steel chamber wall. Therefore, we performed calculations for various combinations of materials in the initial and final layers of the protecting layered shield and for a different number of the layers themselves. The initial layer is in contact with detonation products, while the final layer is in contact with the chamber wall. The layers are alternated sequentially: lead–polyethylene, etc.

Calculations have shown that the most optimal combination consists of nine (polyethylene–polyethylene) layers and that the eight-layer structure (polyethylene–lead) is slightly less efficient. The first combination was used in subsequent calculations upon a more intense loading by a DW incident on the normal. The results obtained were compared with those for an unshielded wall and for a wall shielded by a porous shield. One can see from Fig. 3 that the most efficient protection was ensured, as in the case of sliding detonation, by a porous layer, which decreased the peak tensile stresses in the walls of the protected chambers. As was mentioned above, the total thickness of the protected chamber wall and the damping layer equals the thickness of the wall of the original unprotected chamber.

With allowance for the effect of the bottoms on deformation of the chamber walls, calculations should be carried out in a spatial axisymmetric formulation. The main results were obtained for closed thick-walled copper tubes with the following physicomechanical parameters:

Copper: $\rho_0 = 8.9$ g/cm^3, $\mu = 46$ GPa, and $\sigma = 0.255$ GPa;

Explosive (*pentholyte*): $\rho_0 = 1.65$ g/cm^3 and $D = 7655$ m/sec.

The chamber length was 8 cm, the inner radius of the chamber was 2 cm, the thickness of the left and right bottoms was 0.5 and 1 cm, respectively, and the tube outer radius was 3 cm. The thickness of the protective copper tube was 1 cm, its inner radius was 1 cm, and the porosity $\Phi = 0.5$. In this case, the bottoms were not protected by porous shields. The HE charge was covered by a porous or solid casing and was placed in the chamber. We set the ideal-slip condition between the charge casing and the chamber wall, and their jump off from each other was assumed to be possible during the force interaction.

Figure 4a shows instant configurations and the damage-growth zone for the unprotected chamber wall. The regions in which the level of damage grows are shaded. Filled cells denote the maximum value of the parameter α in the given section of the chamber wall. The peak value of α in this band reaches 1.212, and $\alpha \leqslant 1.021$ in the zone adjacent to the inner tube surface. The maximum deviation of the outer and inner

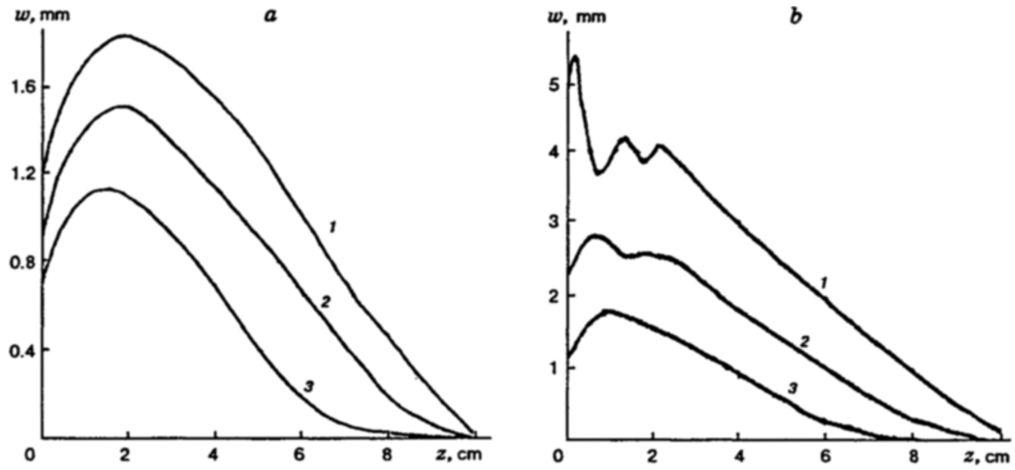

Fig. 5. Radial displacements of the outer (a) and inner (b) chamber surfaces when the thickness of the porous layer is 0.5 (2) and 1 cm (3) (curve 1 refers to the initial position of the chamber wall).

surfaces relative to the initial configuration is 0.15 and 0.21 cm, respectively. The maximum particle velocity attained at the chamber wall at the moment considered (12 μsec) was equal to 430 m/sec. Insertion of the porous shield (Fig. 4b) led to a marked increase in the inner volume of the chamber and to stronger damage in its walls compared with the case where the chamber walls are not protected by any porous shield (see Fig. 4a). With the porous shield, $\alpha \leqslant 1.004$ (initial value $\alpha = 1.0003$), which is considerably smaller than the level of damage in the unprotected chamber (see Fig. 4a). The maximum displacements of the outer and inner surfaces of the chamber wall in these calculations were 0.052 and 0.102 cm, respectively. The maximum particle velocity in the chamber wall was 263 m/sec, which is much smaller than in the case of a solid copper shield. Comparison of the two (porous and solid) structures confirms the results of the one-dimensional calculation that the first shield has the clearly expressed protective properties.

The above-considered closed thick-walled shell was loaded by a powerful HE with large values of the parameters at the DW front. The use of damping shields makes it possible to avoid spalling phenomena and to reduce the rate of expansion of the shields of the explosion chamber in the required time interval, but does not exclude subsequent shield fracture by the other mechanisms.

Figure 5 shows the results for the chamber loaded by detonation products of the phlegmatized HE ($\rho_0 = 1$ g/cm^3 and $D = 5000$ m/sec) which has smaller parameters at the Chapman–Jouguet point compared with the above HE. The tube length was 10 cm, the thickness of the bottoms was 1 cm, and the outer and inner radii were 4 and 2 cm, respectively. In this variant, the porous shield was firmly fixed to the chamber wall and was 0.5 and 1 cm thick.

An increase in the degree of damage was observed neither for the unprotected chamber wall nor for that protected by porous layers of different thickness. The damping properties of the shields were manifested in the kinematic characteristics of the interaction of the chamber with detonation products. All results in Fig. 5 correspond to the moment $t = 22$ μsec. The maximum particle velocities at the same chamber wall at this time and for the same sequence of porous layers are equal to 318, 220, and 199 m/sec, respectively. One can see a sharp decrease in these values as the shield thickness grows, which exhibits its strong protective properties.

Thus, we have shown that layered and porous shields can efficiently reduce the peak stresses in the walls of explosion chambers subjected to the action of high and phlegmatized explosives. It has been noticed that porous shields possess stronger protective properties compared with layered structures of the same thickness. The protective properties of the shields show up in weaker spalling phenomena and in smaller kinematic characteristics (velocity and displacements) of fracture of the chamber walls.

REFERENCES

1. E. F. Gryaznov, E. V. Karmanov, V. V. Selivanov, and S. V. Khakhalin, "Morphology of fracture of cylindrical shields at the wave stage," *Probl. Prochn.*, No. 8, 89–92 (1984).
2. A. S. Kozyrev, V. G. Kostyleva, and V. T. Ryazanov, "Shock-wave cumulation in layered media," *Zh. Éksp. Teor. Fiz.*, **56**, No. 2, 427–429 (1969).
3. K. P. Stanyukovich (ed.), *Physics of Explosion* [in Russian], Nauka, Moscow (1975).
4. M. L. Wilkins, "Elastoplastic flow calculation," in: *Calculation Methods in Hydrodynamics* [Russian translation], Mir, Moscow (1967).
5. J. N. Johnson, "Dynamic fracture and spallation in ductile solids," *J. Appl. Phys.*, **52**, No. 4, 2812–2825 (1981).
6. M. M. Carrol and A. C. Holt, "Static and dynamic pore-collapse relations for ductile porous materials," *J. Appl. Phys.*, **43**, No. 4, 1626–1636 (1972).
7. R. Kinslow (ed.), *High-Velocity Impact Phenomena* [Russian translation], Mir, Moscow (1973).
8. V. Ya. Gol'din, N. N. Kalitkin, Yu. L. Levitan, and B. L. Rozhdestvenskii, "Calculation of two-dimensional flows with detonation," *Zh. Vychisl. Mat. Mat. Fiz.*, **12**, No. 6, 1606–1611 (1972).
9. V. A. Odintsov and T. G. Statsenko, "Fracture of cylinders at the wave stage," *Izv. Akad. Nauk SSSR, Mekh. Tverd. Tela*, No. 2, 113–119 (1980).