THE BEHAVIOR OF STEEL SHELLS WHEN CHARGES OF EXPLOSIVE DETONATE INSIDE THEM

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Electrical resistance strain gauges [1, 2] and also a capacitance method [3] are used to investigate the behavior of closed steel shells under impulsive loading realized by a blast of a spherical charge of an explosive material (EM) inside them. The latter method is used in this work, since it allows a continuous record of the velocity of motion of the outer surface of the shell to be obtained with high accuracy.

1. Several forms of closed spherical and cylindrical steel shells with elliptic ends were investigated in the experiments.

The long-term strength (σ_b) and the yield point for 0.2% strain (σ_s) for the material of these shells, subjected to annealing, were determined by means of calibration test pieces and were found to be σ_b = 41 kgf/mm^2, σ = 20 kgf/mm^2 for St. 15 steel and σ_b = 55 kgf/mm^2, σ_s = 28 kgf/mm^2 for steels St. 25 and St. 35. Six spherical shells 1, ..., 6 and two cylindrical shells 7, 8 were tested. The data for them is presented below:

№	1	2	3	4	5	6	7	8
Steel	35	25	15	35	35	25	35	35
$R\approx$	166.5	166.5	166.5	161.0	96.3	150	94.5	94.5
$\delta\approx$	13.5	13.5	13.5	8.0	7.8	32	6.0	6.0
$H\approx$	—	—	—	—	—	—	75	150

Here the radius R, the length H and the wall thickness δ are given in mm.

The impulsive loading was realized by a blast of spherical charges of EM of various weight located at the center of the shells by means of a thin steel needle (Fig. 1). The construction of the entry of the needle prevented a break-out of the products of explosion. The velocity of motion of the surface of the spherical shells, dependent on time, was registered by means of two capacitance transducers [3–5]. In the tests with cylindrical shells the velocity of motion of the surface of the cylindrical part and the end was recorded. The transducers 1 and 2 were fixed independently of the shell.

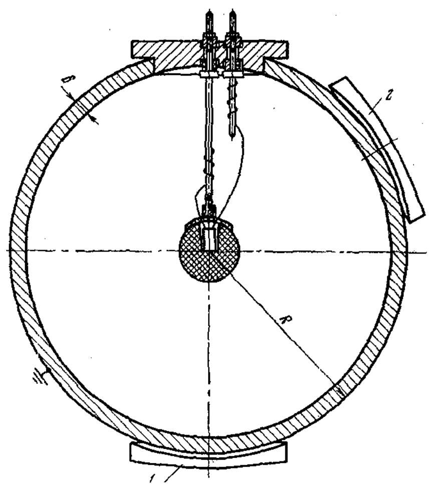

Fig. 1

An analysis of the oscillographic record gives the relation between the velocity of motion of the surface of the shell and the time, V = φ(t). In the investigation an OK-17M cathode oscillograph was used. The accuracy of measuring the velocity by the given capacitance method is 3–5%. A graphical integration of the relation V = φ(t) thus obtained gives the dependence of the displacement of the shell on the time S = f(t). The accuracy of setting up this relation, for a large number of divisions in the graphical integration, is not lower than a few percent.

2. Typical oscillograms obtained in tests with different shells are presented in Fig. 2, where the first trace corresponds to a cylindrical shell, while the second and third traces correspond to spherical shells for charges of 130 and 240 g, respectively. In Fig. 3 the relations $V = \varphi(t)$ and $S = f(t)$ are given; they have been obtained by processing the oscillograms. The frequency of elastic vibrations of the spherical shell is

$$\omega_0 = \frac{2\pi}{T_0} = \left[\frac{2E_1}{\rho(1-\mu)R^2}\right]^{1/2} \tag{2.1}$$

Here T_0 is the period of vibration, E_1 is Young's modulus, ρ is the density, μ is Poisson's ratio, and R is the radius.

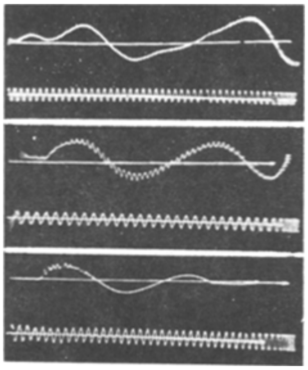

Fig. 2

If the shell in the stage of active loading passes through the yield point (dynamic), then for the description of the strain in the plastic region the frequency

$$\omega = \left[\frac{2E_2}{\rho(1-\mu)R^2}\right]^{1/2} \tag{2.2}$$

is introduced.

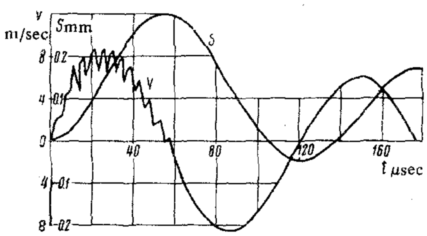

Fig. 3

Here it is assumed that the material is linearly hardening; E_2 is the modulus of hardening ($E_2 < E_1$). Unloading of the shell, after the maximum strain has been reached, takes place elastically, and is characterized by the frequency of vibration ω_0 (it is assumed that Poisson's ratio is constant in the elastic and plastic regions). Thus, the average frequency of vibration of the shell passing through the yield point must be less than the frequency of elastic vibration. The value of the kinetic energy of the shell when it moves toward the center can be sufficiently large for the material to be transformed again (during compression) into a plastic state. The secondary and even multiple transitions of the material into a plastic state in the same experiment can also take place as a result of the Bauschinger effect.

We present certain values of the first period T_1 (μsec) of vibration of the shell 1 dependent on the weight Q (g) of the EM exploding inside it.

$Q =$	135	161	192	198	242	292	292
$T_1 =$	115	130	149	150	168	176	180

The maximum charge for whose blast the shell did not pass the yield point was 130 g. The first period of vibration of the shells appreciably increases as the charge increases. The period of vibration of the shells in the elastic region agrees well with the value calculated according to formula (2.1). The limiting elastic strain of all shells tested amounts to 0.11–0.12%.

From the oscillograms obtained we see that fairly large secondary velocity pulsations exist.

The period τ of these pulsations is equated to the time of circulation of the elastic wave across the thickness of the shell, $\tau = 2\delta/C$, where C is the elastic velocity of sound in an infinite medium; for steel C = 5950 m/sec. The results of the tests point to the dependence of the amplitude of secondary pulsations and the rate of their damping on the following two factors: on the value of strain of the shell in the given experiment, and on the degree of strain preceding the given experiment. Most clearly this dependence manifests itself for shells with a small relative thickness.

Thus, if the strain of the shell during the experiment goes beyond the boundary of the elastic zone, and if before that the shell had not been subjected to a plastic strain, then the amplitude of secondary pulsations in practice is not damped out during the first several periods. Damping takes place considerably more intensively in tests with shells which before these tests were subjected to an appreciable plastic strain, or which in the process of loading in the given tests passed the yield point [6]. These phenomena are illustrated by the second and third traces of Fig. 2.

3. The stress variation in the shell in the process of vibration is schematically represented in Fig. 4.

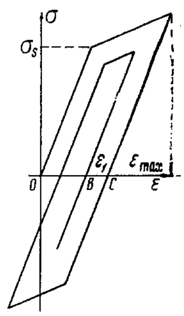

Fig. 4

The position of equilibrium, after each half-period of vibration accompanied by the transition of the material into a plastic state, is displaced by the amount of the corresponding residual strain. Point O shows the initial position of equilibrium; points C and B, respectively, show the subsequent positions of equilibrium. Point B determines the total residual strain of the shell after the test.

Thus, if the shell at least twice passes into a plastic state, then the total residual strain of the shell must differ from the value of the residual strain in the first half-period. The experimental relations $V = \varphi(t)$, $S = f(t)$ obtained in the experiment allow us to estimate the value of the stresses in the shell even in the case in which the shell undergoes considerable plastic strain.

Here it is assumed that the stress σ is constant across the thickness of the shell. The effect of the radial component of the stress, in view of its smallness in comparison with the tangential component, can be neglected. It is obvious that this assumption is close to reality only for relatively thin shells. The maximum stress in the shell is realized in the first period of vibration. As follows from the scheme of Fig. 4, this stress can be calculated from the formula

$$\sigma = \frac{\varepsilon_{max} - \varepsilon_1}{1 - \mu} E_1 . \tag{3.1}$$

Here ε_{max} is the maximum strain, ε_1 is the residual strain in the first period.

As mentioned above, ε_1 in the first period can appreciably exceed the total residual strain. Therefore, for the determination of the maximum stress in the first period we must find the corresponding value of the residual strain (ε_{max} is determined from the experimental relation $S = f(t)$).

Since the maximum velocity of the shell in the motion toward the center is reached when the stored-up elastic energy is transformed into the kinetic energy, this corresponds to its passing through the new position of equilibrium. This allows us to determine the residual strain of the shell in the first period of vibration, corresponding to this new position of equilibrium. The value of the stress* can be determined from (3.1).

From a comparison of the results of identical tests carried out on the same shell after a short time interval (0.5–1.0 hr), it follows that during deformation of the shell, noticeable hardening takes place. This is work-hardening which reduces the strain in the subsequent test. This was particularly noticeable in tests on relatively thick shells. The results of the tests carried out after a considerable time (from one to several days) show that during this time the properties of the material of the shell are practically completely restored. The results of such tests with identical charges agree well.** Making use of this we can set up the $\sigma-\varepsilon$ relation for the shells tested on the basis of tests performed after a large time interval (Fig. 5). Here σ and ε^+ are the maximum stresses and strains of shells 1 and 2 in the first half-period for each test.

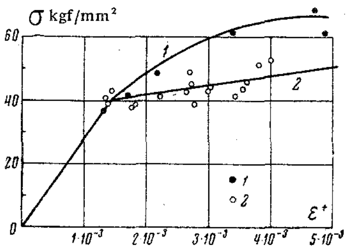

Fig. 5

For more thick-walled shells we must take into account the considerable stress gradient across the thickness of the shell.

The $\sigma-\varepsilon^+$ relations represented in Fig. 5 for shells 1 and 2 allow us easily to estimate the value of the dynamic yield point of the material of the shells; it was equal to 40 kgf/mm^2 for shells 1 and 2 (steels St. 25 and St. 35). It thus increased by approximately 40% in comparison with the static value.

4. From the values determining the behavior of spherical shells made of the same material, for a blast of charges of EM of the same composition and density, we can set up the single dimensionless parameter (the effect of the strain rate is not taken into account)

$$Q^* = Q / \delta R \rho \tag{4.1}$$

The possibility of modeling according to this parameter was experimentally investigated in tests on spherical shells 1, 4, and 5.

All dimensions of shell 5 were 1.73 times less than the dimensions of shell 1. Shell 4 had the same internal radius as shell 1, while the thickness was 1.7 times less. The results of the experiments are represented in Fig. 6 (the numbers of the shells are shown on the curves). It follows from these results that the values of the maximum strains for shells 1 and 5 are accurately given by the general relation only in the region of elastic strains ($\varepsilon^+ \leq 0.12\%$). In the region of plastic strains the experimental data differs considerably: ε^+ is notably less for the smaller shell. This difference can logically be connected with the strain rate $d\varepsilon/dt$; this is inversely proportional to the period of vibration of the shell, i.e., its radius. As the strain rate increases, the $\sigma-\varepsilon$ relation notably changes. The smaller shell will show a greater resistance to strain; this leads to smaller values of ε^+ in the test. For shells 1 and 4, having the same radii, the strain rates coincide. Therefore modeling according to the parameter Q* is valid in the entire range of strains investigated (Fig. 6).

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*Such an estimate of the stress is somewhat understated, since it does not take into account the effect of the pressure of the heated products of explosion inside the shell. An estimate of the value of this pressure shows that the error is about 10–15%.

**The restoration of the properties of steel is promoted by the appreciable heating of the shell during the experiment. According to [7], heating of steel test pieces, after their dynamic loading, up to a temperature of 93° C leads to a complete restoration of the properties of the material within 12 min, while heating up to 60° C leads to this within 100 min.

5. The static mechanical characteristics of the materials of the shells thus investigated only slightly differ. But under the conditions of blast loading the effect of the material appreciably affects the behavior of the geometrically identical shells 1, 2, 3.

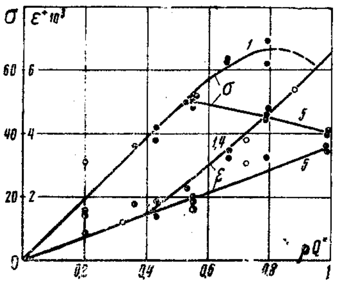

Fig. 6

The maximum positive velocites V^+ (directed from the center of the shell) for the detonation of identical charges in the shell of St. 35 steel is notably higher than in the shells of steels St. 15 and St. 25 (see table). A considerable difference exists between the values of σ_{max} and ε_{max}, as well as between the total residual strains of the shells before failure (ε_2). The asterisk in the table indicates tests in which failure of the shell occurred.

Table 1

Material	Q (г)	V^+ m/sec	$\varepsilon_{max} \times 10^3$	σ_{max} kgf/mm²	$\varepsilon_2 \times 10^2$
	135	6.5	1.72	41.0	
	167	9.0	2.19	49.0	
Cr. 3'	207	14.5	3.17	62.5	
	207	15.0	3.38	61.5	1.0
	250 *	20.0	4.5	67.5	
	140	6.5	1.38	38.5	
	172	8.5	1.81	39.0	
St. 25	207	9.5	2.66	41.5	
	254	14.5	3.00	42.5	
	302	16.0	3.56	43.5	2.5
	335 *	18.0	3.80	51.5	
	130	7.5	1.41	37.0	
	165	9.0	2.04	37.5	
	201	9.0	2.20	16.8	
St. 15	240	12.0	4.08	16.8	
	290	14.5	4.56	31.0	1.3
	400 *	16.0	4.9	28.0	

6. Under a static loading, by the same internal pressure, of the cylindrical and spherical shells of the same radius and thickness, the stresses in the wall of the cylinder are approximately twice the stresses in the wall of the sphere [8].

The real pattern of loading of closed cylindrical shells for a blast of spherical charges of EM are very much more complicated. First, the shell undergoes an axial strain; second, since the impulse taken up by a unit area of the surface varies along the length of the cylindrical shell (it is maximum in the middle section), considerable bending forces arise in the shell.

In its character the oscillographic record of motion of the cylindrical shell, obtained by means of the capacitance transducer (Fig. 2), does not differ from the oscillograms obtained in tests on spherical shells. On the oscillograms obtained by the transducers registering the motion of the end, a negative velocity (directed into the shell) is noted at first. This negative displacement is caused by the stress wave propagating along the shell, from its cylindrical part lying nearest to the charge toward its end, with the velocity of transverse waves in steel, and reaching the end earlier than shock wave of air from the charge. The tangential stresses in the cylindrical shell can be determined from the expression

$$\sigma = (\varepsilon_{max} - \varepsilon_1)E_1/(1 - 0.5\mu) \tag{6.1}$$

This estimate does not take into account the effect of the end on the stress state at the middle of the cylindrical part of the shell. In a shell with a long cylindrical part (H = 2R) the end effect does not manifest itself at the instant of maximum of expansion of the cylindrical part, since the end perturbations cannot reach it in time. In the calculation of the stresses in the cylindrical part of short shells (H = R) the effect of the end was not taken into account.

In Fig. 7 we have represented the dependence of the stress σ, kg/mm^2, in a cylindrical shell on the parameter $Q^*\rho$, $g \cdot cm^{-3}$, obtained in the experiments, for two shells constituting a combination of a cylinder and two elliptic ends. For comparison purposes we have also represented this relation for a spherical shell of the same radius (the numbers of the shells are indicated on the curves).

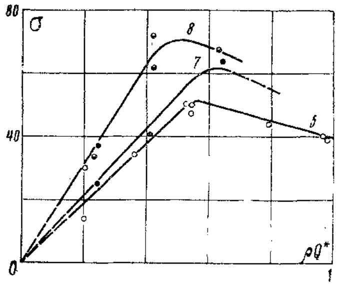

Fig. 7

From the graph thus represented it follows that the stress in the cylindrical shell with H = 2R is noticeably higher than in the cylindrical shell with H = R and in the spherical shell, for the same modeling parameter Q*.

The results obtained in the experiments on the short cylindrical shell differ only slightly from the analogous results for a spherical shell. This is explained by the small difference in their shape.

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