DYNAMIC STRENGTH IN EXPLOSIVE LOADING FOR SHELLS MADE OF ORIENTED FIBROUS COMPOSITES (REVIEW)

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Composites are often needed for economic reasons and sometimes to provide qualitatively new or unique properties. Structures in which there are tight specifications for the material of the load-bearing body include vessels (chambers) or protective structures for withstanding disruptive gas-dynamic loads as well as ecologically hazardous products from accidental explosions such as explosives or the cores in nuclear reactors.

The main results from recent experiments on oriented composites in this area are briefly surveyed. In the survey [1], which desalt with the dynamics of shells, those aspects are dealt with only partially. In [2], the conclusions from [3, 4] are used in stating that fibrous composites are promising in explosion-loaded structures. In [5], a survey was presented of the experimental data up to 1986 on dynamic failure in shells and vessels made from glass-fiber materials and traditional steel, which confirmed the major advantages of the first for shells subject to extreme pulse loads.

We therefore consider the main features in the behavior of a shell made of a composite on internal pulsed (explosive) loading and the substantial advantages of such materials over traditional ones.

In [3, 4], studies were made on the response and failure in glass-epoxide circular cylindrical shells made by wet winding of glass cloth on a former, with the cloth impregnated with a setting epoxide agent; R = 100, 150, 440 mm, relative thicknesses $\bar{\delta} = \delta/(R + \delta) = 3.7 \cdot 10^{-2}$, $9.1 \cdot 10^{-2}$, $16.7 \cdot 10^{-2}$ and $21.3 \cdot 10^{-2}$, and length $L = 4(R + \delta)$, with explosive loading at the center of the cavity by a spherical charge initiated from the center. The cavity was filled in one case with water [3] and in the other with air [4] at normal atmospheric pressure. Similar situations were used in the experiments in the other papers considered here.

The main results from [3, 4] are as follows.

1. Virtually elastic behavior (with constant Young's modulus) up to failure with circumferential strains in the first phase of expansion about 4%, no matter what the relative thickness, the dimensions of the geometrically similar shells, and the initial strain rate in the range $0.21 \cdot 10^3$-$1.2 \cdot 10^3$ $1 \cdot sec^{-1}$ [3].

There is no effect on the strength and deformability from scale changes by factors of 1.5 and 4.4 because of the retention of the same diameter for the main force-bearing element (the glass fiber), so there are no conditions for there to be a marked scale effect of energy origin [2, 3, 5].

2. The limiting relative mass of explosive $\hat{\xi}$ is about 0.4% ($\xi = m_{ex}/M$, with m_{ex} the mass of the explosive and M the mass of the shell with length 4R) when the shell is filled with water, and the shell failed in the first phase of expansion with circumferential strains of about 4% [3]. On filling with air, the limiting strain for a singly loaded shell was [4] in the range 2.1-2.5%, and $1.15\% < \hat{\xi} < 1.42\%$. There is an increase in $\hat{\xi}$ between the low-compressibility medium (water) and air because of a reduction in the energy transfer coefficient, i.e., the part of the energy consumed in deforming the shell. However, in the present case, failure with strains $\geq 2.5\%$ occurred not in the first expansion phase but after one or more radial oscillation periods. As the load increased up to what was known to be the failure load, the failure occurred as with water in the first phase of expansion with about 4% strain, i.e., in the present case the deformability and strength margins were not fully utilized.

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Fig. 1

3. The strength of a glass-epoxide shell is dependent on the number of explosive loadings in air [4]. If the shell can withstand strain up to 4% on single explosive loading, then with 2% strain, it can withstand three such loadings, and with 1% strain, up to 23. However, a shell in which through cracks are formed in the first loading does not lose its general structural integrity on subsequent loading by the same charge, so the material is not very sensitive to that type of macrodefect.

4. A glass fiber-epoxide shell has various advantages over a steel one [4] on account of the differences in level and type in the energy absorption during deformation and failure. For example, if the charge produces an elastic strain in the glass-fiber material ≥ 2.5%, a steel shell (steel with σ_s = 250 MPa) with the same ξ shows plastic circumferential strains ≥ 15%. In a large structure, a steel shell may have internal or external defects, which may reduce the plasticity, and here a marked scale effect of energy origin [6] can result in catastrophic brittle or quasibrittle failure. Section 1 shows that a fibrous glass-plastic material may have a substantial advantage over steel as regards $\hat{\xi}$ [4]. The type of failure in a glass-epoxide shell is also more favorable. At the lower strength threshold, i.e., when through cracks are formed, there are no dangerous fragments, and the shell does not split into parts and the cracks have restricted length about equal to R (Fig. 1).

That type of failure is governed by features of the loading and dynamic response in a cylindrical shell: when the shock wave and the flow of explosion products are reflected from the wall, the radial pulse is distributed along the generator in proportion to the projection of the gas-dynamic explosion pulse on the normal to the inner surface [7]. Axisymmetric modes of oscillation are excited in the first phase of expansion with maximal circumferential strains in a zone of width about R, which remain maximal throughout the response time if the stability of the axisymmetric forms is maintained. The meridional bending and stretching strains were half the maximal circumferential ones.

Subsequent studies confirmed that there are no marked scale effects in glass-epoxide cylindrical shells with geometrically similar changes in size by factors of 9.3 (R = 75 and 700 mm, δ/R = 4.6%, L/R = 4) on explosive loading in air [8]. The dynamic response [7, 8] shows that the main reason for the reduction in the initial circumferential strain at which the shell may fail after one or more tension—compression phases lies in the parametric instability in the axisymmetric oscillation modes, which go over to bending ones. This produces local rises in stress and the formation of meridional cracks, which have a periodicity along the circumference related to the relative thickness in the central most heavily loaded zone of width ≈ R.

That failure mechanism is due to the oscillations being only lightly damped in air (in contrast to the reaction in water), together with initial defects in shape and properties in the material, and also nonideal symmetry in the loading. The limiting strain in the first radial expansion is sensitive to the relative thickness [7], which can be confirmed in [9] (δ/R varied from 2.3 to 20%). A major factor is also the elastic modulus of the glass-fiber material in the circumferential direction, since in [9], tests were performed on cylindrical shells having R = 100 mm and L/R = 2 in which the circumferential elastic modulus was elevated (instead of the $E_y = 2.4\cdot10^4$–$3.3\cdot10^4$ MPa for earlier specimens

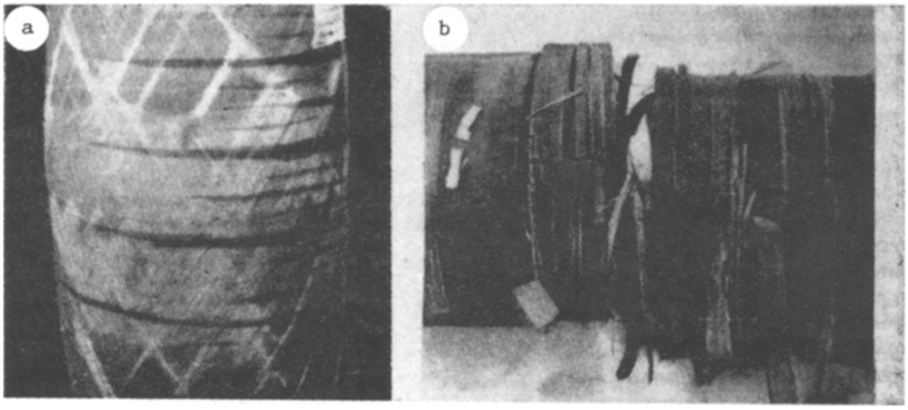

Fig. 2

[3, 4, 7, 8], the material was used with $E_y = 3.85\cdot10^4-4.8\cdot10^4$ MPa), and a reduction in the limiting strain from 2.1-2.5% to 1.5-1.7% was obtained for shells having $\delta/R \approx 15\%$. The failure explosive load there increased from 1.15-1.45% to 1.4-1.6%. Clearly, there are various types of fiber and various possible structures for the layered reinforcement, so it is complicated to make an optimum choice in order to provide the maximum specific strength in explosive loading.

It is possible to raise ξ considerably by reinforcing the glass-fiber layer with a layer of steel [10]. The plastically deformable steel, if thick enough ($\geq$ 1/8 of the thickness of the glass-fiber material used in [3, 4]), damps the radial oscillations well, which prevents those oscillations from losing stability and raises the limiting strain to about 4%. The dynamic features of a two-layer shell are only slightly altered (the slope of $\varepsilon(\xi)$ is increased by not more than 20-30%), so there is an improvement in the specific carrying capacity relative to a pure glass-fiber shell (ξ increased from 1.15-1.4 to 1.7-1.9% for $\delta/R = 16\%$, and from 0.47-0.77 to over 1.88% for $\delta/R = 5\%$).

An interesting result was obtained [11] in research on the reaction and strength in internal explosion in cylindrical shells formed by dry winding on a former of glass cloth (type I) and carbon cloth (type II). The dynamic strength of a type I shell was almost twice that of type II (on $\hat{\xi}$) with deformabilities up to about 5 and 4% correspondingly. It was concluded that the fiber basis is the decisive element for the strength of a composite under pulsed loading.

The roles of the fiber type and binder elasticity have been examined [12] in tests with shells having R = 150 mm, $\delta/R = 8.5-11.9\%$, which had the same mode of reinforcement with wet-wound strip, with glass-fiber filaments (type VM-1), and SVM organic fiber, with alternating spiral layers ($\phi_1 = \pm45-60°$) and annular ones ($\phi_2 = 90°$) and a 1:1 thickness ratio for them. Raising the elasticity of the fiber had little effect on the dynamic behavior and strength, and the criterion for choosing an elastic fiber for a pulse-loaded shell can be taken as the product of the speed of sound c and the limiting strain $\hat{\varepsilon}$ under dynamic stretching conditions (it is numerically equal to the initial limiting velocity of expansion in a ring element not leading to failure). That criterion explains the [11] results (comparison of glass and carbon fibers) and the [12] ones (the SVM fiber, which had much higher specific static strength than the glass fiber, or similar to the latter in dynamic strength, and also in $c\hat{\varepsilon}$, which were 348 and 321 m/sec correspondingly, although it is true they were estimated from the static parameters).

This criterion is also confirmed by a study [13] on shells with an analogous reinforcement scheme and analogous dimensions but with a combination of glass, organic, and carbon fibers, including from one to three types of fiber in a single packet, i.e., hybrid composites. It was found [13] that adding the high-modulus carbon fiber (with lower limiting deformation and lower $c\hat{\varepsilon}$) to the layers formed by winding glass on organic fibers did not raise the specific carrying capacity by comparison with pure glass or organic shells with epoxide binder.

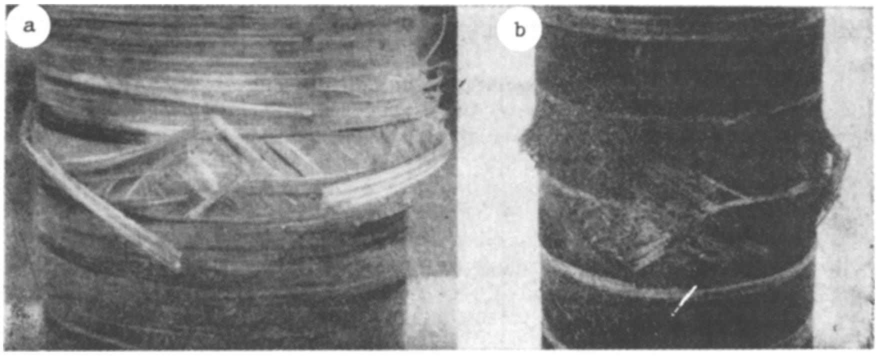

Fig. 3

Glass fiber is thus the best material for pulse-loaded composite shells on the basis of the physical criterion and cost.

A fiberglass material based on glass cloth has the fibers bent on account of the weaving, so there are preliminary stresses in the unloaded state (in addition to the stresses from the tension during winding and the shrinkage stresses on binder solidification). This reduces the carrying capacity. Also, when cloth is used, it is difficult to form a shell with double curvature, e.g., to form smooth transitions to the ends in winding spherical or ellipsoidal shells.

There is considerable freedom of choice in the reinforcement when one winds shells of cocoon type with filaments or fairly narrow strips formed from filaments or bundles, as full use is made of the strength because the fibers are straight and the damage is reduced because of the reduced number of operations in manufacture.

In [14], the first steps were taken in optimizing the reinforcement of fiberglass shells formed by winding with filaments or strips of filaments. The studies mainly concerned shells having R = 1.50 mm, δ/R = 9.3-10.9% and of length 4R reinforced with spiral and ring winding and alternating layers with thickness ratios of 1:1 and 1:2.5. The specimens with spiral winding had $\phi = \pm 30°$, while the spiral-ring ones had $\phi_1 = \pm 60°$ and $\phi_2 = 90°$ with a 1:1 layer thickness ratio. This gave $\hat{\xi} \approx 2.3 \cdot 10^{-2}$ in air with maximm circumferential strain $\hat{\varepsilon} \approx 3\%$. The structure affected the reaction and mode of failure considerably. Pure spiral winding with $\phi = \pm 30°$ gave scope for residual strain by mutual displacement of the strips and bulging as the binder failed (Fig. 2a). Pure ring winding results in mainly ring cracks because of the low strength of the bonding agent (Fig. 2b). The strongest type of reinforcement fails in the same way as shells based on glass cloth, but with meridional cracks less prominent, and instead there were periodic bulges of deconsolidated material (Fig. 3a and b), with failure setting in not in the first phase of expansion but during the vibrations. These conclusions were confirmed in [15], where a wider range of reinforcement structures was considered. Homogeneous reinforcement schemes (only spiral layers or only ring ones) have dynamic carrying capacity reduced by a factor 1.5-2 by comparison with the best combined structure, which has alternating ring and spiral layers having identical calculated static strengths in the circumferential direction.

In [16] it was found that one can provide failure in the first phase of radial expansion* if the limiting strain is constant at ≈ 4.8-5.0%, which corresponds to the limiting strain in static tension for magnesium—aluminum silicate glass fiber with high elastic modulus used. Tests were done on similar shells with combined spiral-ring reinforcement but with varying angle of the spiral winding, $\phi_1 = \pm 35\text{-}65°$. It was shown that the limiting strain in dynamic failure of the most highly stressed ring layers is insensitive to the reinforcement angle for the adjacent spiral ones.

Some early experiments have been done with spherical metal-composite shells reinforced by spiral winding with layer alternation with reinforcement angles in the range $\phi = \pm 15\text{-}75°$

*By raising the explosive loading (air filling) and by filling the cavity with water or by reinforcement with a layer of steel.

Fig. 4

(Fig. 4), where there was a difference from a cylindrical shell, in which the tension is close to uniaxial, in that isotropic fiber stretching in all the layers did not alter the limiting failure strain (failure did not occur for strain $\leq$ 4.6%, whereas it did occur for $\varepsilon \leq$ 5.2%). This enables one to use the limiting fiber strain as a universal criterion for the dynamic strength in an oriented composite. An explosion chamber was developed having a cylindrical steel-fiberglass shell, which could withstand a single explosion of a chemical explosive whose mass constituted up to about 1% of the chamber mass. In spherical geometry, the weight factor for such a chamber shows improvement by not less than a factor three, which was confirmed in experiments on a chamber model 500 mm in diameter.

In [17], the coefficient of variation was derived for the dynamic strength and deformability in wound glass-fiber tubes subject to internal explosive loading, which constituted $\approx$ 11-13% and which is close to data for traditional constructional materials and enables one to provide the required reliability in a composite explosion chamber.

The following conclusions are drawn.

1. A composite shell based on oriented fibers is not subject to marked scale effects on the strength if there is geometrically similar increase in the dimensions while the diameter of the fiber is maintained.

2. The highest specific carrying capacity on centrally symmetric internal explosive loading occurs in a cylindrical composite shell based on glass fiber with alternatig spiral layers with reinforcement angles $\phi = \pm 30\text{-}65°$ and ring layers of equal thickness.

3. There are additional improvements in specific carrying capacity and limiting strain from the use of a damping supporting layer of steel with thickness $\geq$ 1/8 of the fiberglass thickness, which prevents parametric stability loss and failure of the elastic composite shell at a lower load.

4. The limiting strain in the ring layers $\hat{\varepsilon} \approx$ 4.8-5.0% is insensitive to reinforcement angle variation for the adjacent spiral layers on explosive loading, and also is insensitive to the degree of loading. The coefficient of variation has been determined for the dynamic strength and deformability in a cylindrical fiberglass shell.

It is possible to design an explosion chamber consisting of a metal-composite cylindrical shell with a ratio of the limiting explosive charge that can be contained to the mass of about 0.01 or 0.03 (on transfer to spherical geometry). These developments are promising for safety in emergency explosive energy release in chemical and nuclear reactors, and also during the transportation of explosive substances or oil and gas in major pipelines and so on.

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SPALLING FAILURE IN A POLYMER CYLINDER ON UNSYMMETRICAL PULSE LOADING

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Polymer materials are widely used. Components formed from highly filled rubber-type materials work under a great variety of conditions involving wide ranges in strain rate, including the rate range characteristic of shock-wave loading.

A description has been given [1] of how the strain rate affects the strength of a polymer consisting in the main of cellulose. In [2], there is a discussion of the behavior of filled elastomers (rubber) on strong pulsed loading. In [3], conditions for spalling failure in a fuel mixture based on polyurethane rubber were examined. In [2, 3], the studies concerned spalling due to reflection of stress waves from planar boundaries, with the main emphasis on failure associated with tensile stresses arising either from the reflection of a single front or from the interaction of two or more reflected fronts. There has been virtually no study on failure in elastomers due to interference between stress waves arising from reflection from curved surfaces. Interest attaches to how the properties of a highly filled elastomer and the geometry affect the spalling failure on strong pulsed loading.

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