INVESTIGATION OF THE MECHANICAL STRENGTH OF CYLINDRICAL APPARATUS MADE OF ORTHOTROPIC GLASS FIBER

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The internal excess pressure in cylindrical apparatus with a wall thickness-to-internal diameter ratio $\delta/D \leq 0.5$ produces a plane stress condition.

In the North Donets Branch of NIIkhimmash (Scientific-Research Institute of Chemical Engineering), in order to study the mechanical strength of shells of vessels and cylindrical apparatus made of orthotropic glass fiber, tests were carried out on tubular specimens, made of glass fiber, of which each layer was strengthened in the direction of the action of the principal stresses. As a result of the tests, the strength criterion was determined.

The specimens (Fig. 1) were made by using the method of separate transverse winding and longitudinal packing of glass fiber threads impregnated with polyester PN-1 binding agents on a rotating mandrel. The ratio of the quantity of transverse fibers to the longitudinal fibers was 2:1. After polymerization, the specimens were removed from the mandrels for the machining* of their end faces and surface for the grips, and then held at normal temperature for one month.

The equation for the criterion describing the region of equal strength for the plane stress condition has the form [1]:

* The external specimen surface formed during winding was not treated after polymerization, to prevent damage to the fiber and variation in wall thickness. Since it is not possible to measure the specimens accurately because of the large number of transverse depressions, the mean value of 80 measurements carried out in the working section was taken as the design value for the wall thickness.

TABLE 1

Internal hydrostatic pressure p, kgf/cm^2	σ_1, kgf/cm^2	σ_2, kgf/cm^2
50	1190	$\frac{8240}{-2990}$
100	2380	$\frac{7520}{-3570}$
175	4170	$\frac{7000}{-3870}$
Corresponding to the condition $\sigma_1/\sigma_2 = 1$	5340	$\frac{5280}{-}$
220	5250	$\frac{-}{-3150}$

Note: The numerator shows the values for limiting tensile stresses, and the denominator shows the values for limiting compressive stresses.

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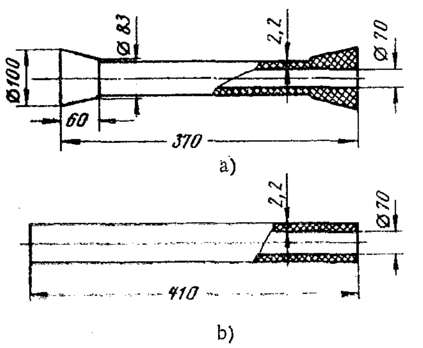

Fig. 1. General view of glass fiber specimens: a) for tests in linear and plane stress conditions; b) for the determination of the compression strength in the direction of tangential stresses.

$$\sigma_1^2 + K_1\sigma_2^2 + K_2\sigma_1\sigma_2 + K_3\sigma_1 + K_4\sigma_2 + K_5 = 0, \tag{1}$$

where σ_1 and σ_2 are stresses in the tangential and axial directions, respectively: K_1, K_2, K_3, K_4, and K_5 are coefficients calculated from experimental data.

To determine the coefficients K_1, K_2, K_3, and K_4, the specimens should be subjected to tensile tests along the axis of the action of the stress σ_1 and to tensile tests along the axis of the action of the stress σ_2, respectively; and to determine the coefficient K_5, a biaxial stress condition with equal and reversed stresses σ_1 and σ_2 should be produced in the specimens. This stress condition should be equivalent to the stress condition of pure shear along the areas which form an angle of 45° with the direction of these stresses.

By denoting the limiting values for tensile, compression, and shearing strength in the direction of the principal axis of stresses by σ_{t1}, σ_{t2}, σ_{c1}, σ_{c2}, and $\tau_{s45°}$ and by substituting these strength values into the formula (1), we shall obtain a system of five equations

$$\begin{aligned}
&\sigma_{t1}^2 + K_3\sigma_{t1} + K_5 = 0;\\
&K_1\sigma_{t2}^2 + K_4\sigma_{t2} + K_5 = 0;\\
&\sigma_{c1}^2 - K_3\sigma_{c1} + K_5 = 0;\\
&K_1\sigma_{c2}^2 - K_4\sigma_{c2} + K_5 = 0;\\
&\tau_{s45°}^2 + K_1\tau_{s45°}^2 - K_2\tau_{s45°}^2 + K_3\tau_{s45°}^2 - K_4\tau_{s45°}^2 + K_5 = 0.
\end{aligned}$$

On solving these, we shall find the unknown coefficients:

$$\begin{aligned}
&K_1 = \frac{\sigma_{t1}\sigma_{c1}}{\sigma_{t2}\sigma_{c2}}; \qquad K_3 = \sigma_{c1} - \sigma_{t1};\\
&K_2 = 1 + \frac{\sigma_{t1}\sigma_{c1}}{\sigma_{t2}\sigma_{c2}} + \frac{\sigma_{c1}-\sigma_{t1}}{\tau_{c45°}} - \frac{\sigma_{t1}\sigma_{c1}}{\sigma_{t2}\sigma_{c2}}\left(\frac{\sigma_{c2}-\sigma_{t2}}{\tau_{c45°}}\right) - \frac{\sigma_{t1}\sigma_{c1}}{\tau_{c45°}^2}; \qquad K_4 = \frac{\sigma_{t1}\sigma_{c1}}{\sigma_{t2}\sigma_{c2}}(\sigma_{c2}-\sigma_{t2});\\
&K_5 = -\sigma_{t1}\sigma_{c1}.
\end{aligned} \tag{2}$$

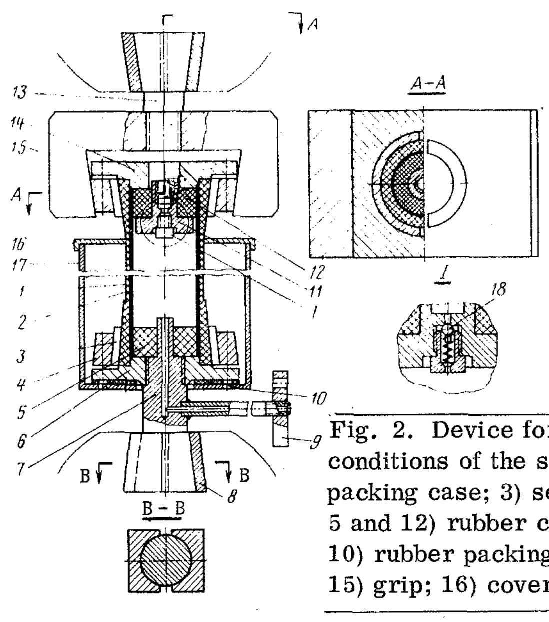

Fig. 2. Device for producing linear and plane stress conditions of the specimen: 1) specimen; 2) rubber packing case; 3) semi-race; 4, 6, 9, and 14) flanges; 5 and 12) rubber collars; 7) special angle; 8) block; 10) rubber packing; 11) shock absorbing bush; 13) bolt; 15) grip; 16) cover; 17) protective jacket; 18) ball.

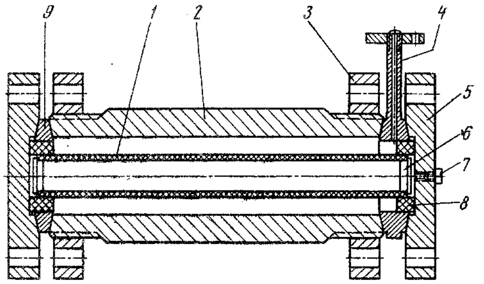

Fig. 3. High-pressure chamber for compressing tubular specimens in the σ_1 direction: 1) specimen; 2) body; 3 and 5) flanges; 4) branch; 6) insert; 7) plug; 8) rubber collar; 9) lens.

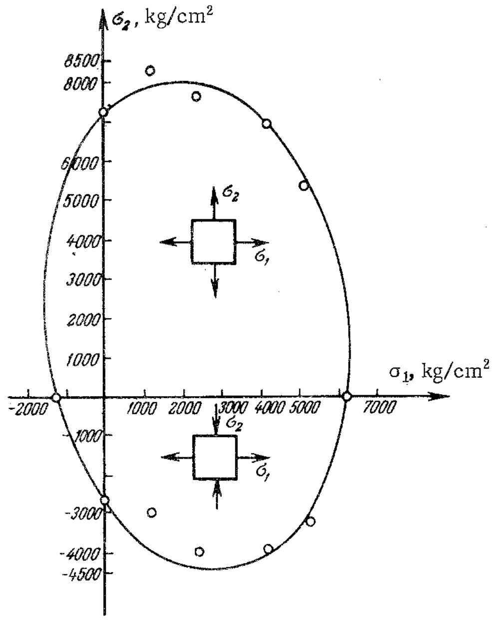

Fig. 4. Results obtained from tests on tubular specimens for short-time loads.

To carry out the listed tests, special devices (Figs. 2 and 3) were designed and constructed. The specimens were loaded by means of a universal GMS-20 testing machine and a manual hydraulic pump feeding water into the specimen or into the chamber in which the specimen is placed.

The magnitudes of the forces and pressure were recorded by means of the dynamometer of the machine and of a manometer.

On determining the tensile strength in the σ_1 direction, the specimen placed in the device, with the parts 3, 4, 5, 13, and 15 removed (Fig. 2), was mounted in the testing machine between the plate and the ball support and loaded by hydraulic pressure.

To determine the compression strength in the σ_1 direction, the specimen (see Fig. 1b) was placed in the high-pressure chamber (Fig. 3) and then loaded as in the preceding case.

The tensile and compression strength in the σ_2 direction was determined in force conditions of the testing machine. In the first case, the specimen placed in the device (Fig. 2), with the parts 2, 5, 10, 11, 12, 16, and 17 removed, was fastened in the grips of the testing machine, and in the second case, it was mounted on the ball support.

In all cases, the fracture of the specimen occurred in the working part and its nature confirmed the absence of loss in strength.

The plane stress condition of the specimens was ensured by the combined action of the GMS-20 machine and the internal hydrostatic pressure produced by the manual pump. Moreover, the specimens in two-directional tensile tests under the combined effect of the machine and the pump, were mounted in the device as shown in Fig. 2, and in tensile tests by internal pressure and compression by means of the machine, in the same way as during the determination of the tensile strength in the σ_1 direction.

The relation between the stresses σ_1 and σ_2 in the process of loading was not maintained constant, with the exception of the test when the specimen was fastened only on one side (in a similar way to the experiment at $\sigma_1/\sigma_2=2$ for isotopic or identically reinforced anisotropic materials). Thus, in the tests, conditions were created which are most frequently encountered on operating cylindrical apparatus.

At first, the specimen was loaded by a given internal pressure, and then additionally loaded by means of the testing machine right up to fracture. The liquid pressure inside the specimen was maintained constant except for the case when the specimen was fastened on one side, i.e., when the loading was carried out only by internal pressure.

The two-directional tensile tests of the specimens were carried out at hydrostatic pressures 50, 100, and 175 kgf/cm^2 and pressures corresponding to the condition $\sigma_1/\sigma_2=1$, and tensile tests in the σ_1 direction and compression tests in the σ_2 direction were carried out at hydrostatic pressures 50, 100, 175, and 220 kgf/cm^2.

In two-directional tensile tests with a stress ratio $\sigma_1/\sigma_2<1$, the specimens cracked along the cross section, and at $\sigma_1/\sigma_2=1$, only one out of five tested specimens cracked along the generatrix.

In the whole range of hydrostatic pressures and stresses produced by the testing machine, the specimens cracked along the cross section.

No stress condition which is equal to pure shear in the areas forming an angle of 45° to the directions σ_1 and σ_2 was produced. The value $\tau_{s45°}$ equal to σ_1 for the condition $\sigma_1 = |-\sigma_2|$ was determined from the curve plotted through the experimental points (Fig. 4).

The coordinates of each point were determined as the arithmetic mean from the results of tests on five specimens.

The stresses were determined from the following formulas*:

$$\sigma_1 = \frac{3pD_{int}}{4\delta};$$

$$\sigma_2 = \frac{3pD_{int}}{4\delta} \pm \frac{3T}{\pi D_{mean} \cdot \delta},$$

where p is the fluid pressure inside the specimen, in kgf/cm^2; D_{int} and D_{mean} are the internal and mean diameters of the specimen, respectively, in cm; δ is the wall thickness of the specimen, in cm; T is the stress produced by the testing machine, in kgf.

The values for the ultimate strength for the linear stress condition were as follows: $\sigma_{t1} = 6360$ kgf/cm²; $\sigma_{c1} = 1270$ kgf/cm²; $\sigma_{t2} = 7120$ kgf/cm²; $\sigma_{c2} = 2950$ kgf/cm²; $\tau_{s45°} = 3970$ kgf/cm².

The values for the ultimate strength in a plane stress condition produced by different hydrostatic pressures are given in Table 1.

After calculating the coefficients from the formulas (2) and substituting the values obtained into Eq. (1), the latter takes the form

$$\sigma_1^2 + 0.385\sigma_2^2 + 0.105\,\sigma_1\sigma_2 - 51\,\sigma_1 - 16\,\sigma_2 - 807 = 0.$$

Figure 4 shows the limiting strength curve plotted using Eq. (3). The following conclusions can be drawn from the tests.

The use of glass fiber reinforced by layers in the direction of principal stresses at a transverse /longitudinal thread ratio 2:1 in the manufacture of cylindrical apparatus operated under a vacuum is not expedient because of the low mechanical strength of the material in the article.

The functions $\sigma_2 = f(\sigma_1)$ and $\sigma_1 = f(\sigma_2)$ are two-valued in the sections $0 < \sigma_1 \leq \sigma_{1\,max}$ and $0 < \sigma_2 \leq \sigma_{2\,max}$, respectively. Moreover, the values for the limiting stresses on the areas perpendicular to the directions of σ_1 and σ_2 on the sections of the curve for $0 < \sigma_1 \leq \sigma_{1\,max}$ and $0 < \sigma_2 \leq \sigma_{2\,max}$ in the plane stress condition are higher than those for the corresponding stresses $\sigma_{1\,max}$ and $\sigma_{2\,max}$ in the linear stress condition. Thus, the results of mechanical tests on the investigated material in the linear (uniaxial) stress condition cannot be directly used for designing vessels and apparatus operated under internal excess pressures (in biaxial stress conditions).

LITERATURE CITED

1. K. V. Zakharov, Plasticheskie Massy, No. 8 (1961).

* The formulas were obtained from the condition that the breaking load is not related to the wall thickness but to the thickness of the bearing layer, i.e., to the layer reinforced in the direction corresponding to the principal stress. This approach corresponds most closely to the actual stress distribution since it is in good agreement with the results obtained from tests on unidirectional specimens.