THREE-DIMENSIONALLY REINFORCED WOVEN MATERIALS.

2. EXPERIMENTAL STUDY

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The article presents experimental data on the deformation and strength characteristics of a number of materials reinforced with three-dimensionally woven multilayer glass fabric, which are compared with the corresponding data for traditional glass-reinforced plastics. The accuracy of the formulas proposed [1] is evaluated. The effect of prestressing the warp and weft fibers on the mechanical properties of the material was investigated. The effectiveness of simultaneous prestressing of the warp and weft was evaluated; the magnitude of the optimal force was established.

Technology of Manufacture and Technique of Testing Specimens. The investigated materials differed in degree of curvature of the warp fibers and reinforcement coefficient. They are arbitrarily denoted by the letter P and numerals, of which the first two denote the average angle of inclination of the warp fibers \( \theta \) [1] expressed in degrees and the last denote the volume content of reinforcement \( \chi \) in percent. The volume content of the binder is denoted by \( \chi_0 \), the warp fibers by \( \chi_1 \), the weft fibers by \( \chi_2 \), and consequently \( \chi = 1 - \chi_0, \chi_1 + \chi_2 = \chi \).

The average angle of inclination of the warp fibers is determined by a microscope according to the method described in [2]. The percentage content of resin was determined by combustion. The ratio of the number of fibers of the warp and weft was equal to \( \chi_1 / \chi_2 = 1.71 \).

The characteristics of the composite material with straight fibers needed for calculating the characteristics of the material with curved fibers (by the formulas of [1]) were calculated on the basis of the simplest Voight and Reiss models (see, for example, [3]):

\[
\begin{align*}
E_1 &= \frac{\chi_0 E + (1 - \chi_0) E''}{\chi_0}, & E_2 &= \frac{\chi_0 E + (1 - \chi_0) E''}{\chi_0}, \\
E_i &= \frac{E''}{\chi_0}, & G_{13} &= G_{23} = \frac{G''}{\chi_0}, & \nu_{13} &= \nu_{23} = \chi' + \chi_0'.
\end{align*}
\]

(1)

The elastic characteristics of the reinforcement of aluminum-borosilicate glass (denoted by one prime) and binder (two primes) are equal to

\[
\begin{align*}
E' &= 7360 \text{ kgf/mm}^2; & G' &= 3050 \text{ kgf/mm}^2; & \nu' &= 0.2; \\
E'' &= 290 \text{ kgf/mm}^2; & G'' &= 107 \text{ kgf/mm}^2; & \nu'' &= 0.35.
\end{align*}
\]

(2)

The specimens on which the deformation and strength characteristics were determined, were cut from plates. The thickness of the plates was determined (i.e., was equal to or a multiple of it) by the thickness of the multilayer fabric with consideration of the change of its size during molding.
TABLE 1

<table>
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The plates, measuring $350 \times 300 \text{ mm}^2$ in plan, were manufactured in a press mold equipped with a device which permitted prestressing of the warp and weft fibers and also simultaneous prestressing in both directions before molding [4]. After manufacture the plates were held at room temperature for 90 days before testing to eliminate the effect of relaxation processes.

All tests were carried out with short-term loading, the elastic constants were determined at the stresses for which (at a given loading rate) the stress–strain diagram could be considered linear. The specimens were tested in tension, compression, bending, torsion, and shear. The characteristics obtained were marked by superscripts +, −, b, t, and s, respectively.

The specimens were tested for tension and compression by the method presented in [5]. Deformations were measured by resistance strain gauges with a base of 20 mm glued in longitudinal and transverse directions on both sides in the middle of the specimen, or by calibers, described in [6]. The readings of the gauges were recorded simultaneously with the applied force via an amplifier on the oscillograph tape. The characteristic diagrams obtained on loading at a rate of 6 mm/min are shown in Fig. 1.

In the case of bending of freely supported beams loaded by a force in the middle of the span [7] we determined the shear moduli $G_{xz}$ and $G_{yz}$ (the $x$ axis is directed along the warp and the $y$ axis along the weft). The shear modulus in the plane of the reinforcement $G_{yx}$ was determined from torsion tests of square plates [8, 9].

Elastic Constants in the Principal Orthotropic Directions of the Material. The complete set of characteristics determined for all investigated materials is given in Table 1 (the values of the moduli and strengths are given everywhere in kgf/mm²). The data for traditional glass-reinforced plastics are given there for comparison. Each characteristic was determined from tests of at least six specimens, the coefficient of variation nowhere exceeded 10%.

TABLE 2

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<th>Characteristics</th>
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