EXPERIMENTAL EVALUATION OF THE EFFECT OF PRESTRESSING THE FIBERS IN TWO DIRECTIONS ON CERTAIN ELASTIC CHARACTERISTIC OF WOVEN-GLASS REINFORCED PLASTICS

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The effect of prestressing the reinforcing fibers in either of two mutually perpendicular directions on the elastic characteristics of woven-glass reinforced plastics has been experimentally investigated. It is shown that an increase in the elastic characteristics in the prestress direction is accompanied by a decrease in the direction at right angles. Applying the same prestress in both directions considerably improves the moduli of elasticity (E_x, E_y). The possibility of using Bolotin's theory [1] and the relations proposed in [4, 6] to estimate the effect of regular distortions of the fibers on the elastic moduli of woven-glass reinforced materials is examined.

1. In studying oriented glass-reinforced plastics (GRP) it is usual to resort to an idealized model consisting of straight, strictly parallel reinforcing elements regularly arranged in a compliant polymer matrix. In reality, the macrostructure is quite different. Distortions of the fibers — both systematic and random — are an inevitable consequence of existing technology. This leads to a significant deterioration of the elastic and mechanical characteristics of the material [1-5].

One method of eliminating or at least reducing the risk of distortion of the reinforcing fibers is to prestress them during the molding process. Existing methods of making prestressed fiberglass elements (cylindrical shells, pipes) are generally based on pretensioning in one of the directions of reinforcement (warp or fill). However, as will be shown below, this is accompanied by a significant deterioration of the elastic characteristics in the direction at right angles to the prestress.

From this there follows the practical importance of an investigation of the effect of prestressing in the warp direction on the elastic characteristics of the fill and the possibility of applying a prestress in two mutually perpendicular directions. It is also desirable to study the possibility of using the simple formulas obtained in [1, 4, 6] for estimating the effect of regular distortions created by the manner of weaving the fabric on the moduli of elasticity (E_x, E_y) of a glass laminate.

2. These questions were investigated experimentally using flat specimens cut from sheets. The sheets were obtained from SKT-11 (800 mm wide) plain-weave glass cloth with the same fiber density in the warp and fill directions impregnated with phenol-formaldehyde resin. The sheets were made in the mold shown in Fig. 1a; the unstressed sheets were molded in accordance with the usual technology. To obtain prestressed sheets it was necessary to develop a special technology and equipment (Fig. 1b) capable of producing sheets of two types: with simultaneous stressing of the warp and fill reinforcement and with stressing in one of these directions. In order to prepare sheets with a given prestress we assembled a stack of pieces of cloth (350×300) and covered the top and bottom of the stack with metal plates (300×350), which were lightly compressed with clamps. The sides of the stack subjected to prestressing were molded at the polymerization temperature on a width of 20-25 mm for 20 min. This made it possible to create a relatively uniform tension in each layer and avoid "pressure transfer" from the upper layers of cloth at

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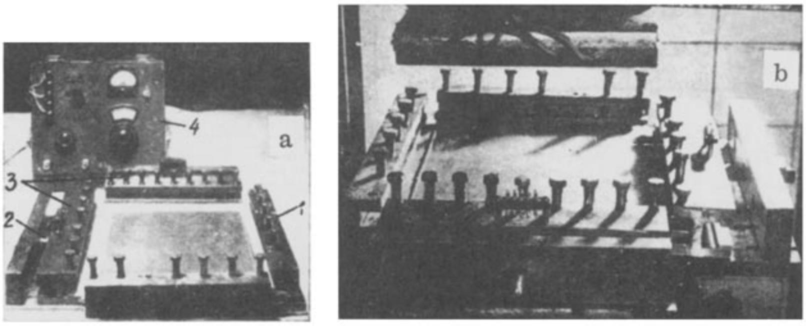

Fig. 1. Apparatus for preparing the sheets: a) stressing equipment (1 – frame, 2 – dynamometer elements, 3 – tensioning device, 4 – ISD-2 static-strain meter); b) mold and stressing equipment.

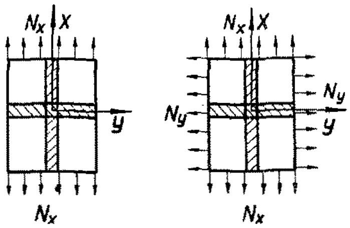

Fig. 2. Diagram illustrating the manner of cutting the specimens from the prestressed sheets.

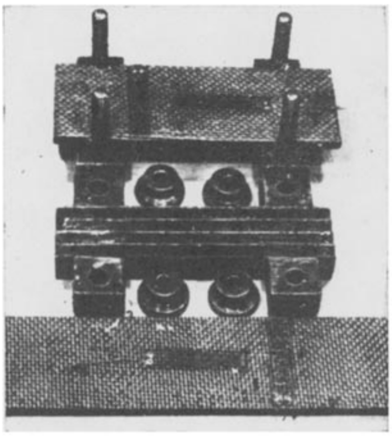

Fig. 3. Shape of tensile and compressive test pieces and device used in compression tests.

the clamping points. After the sides had been molded, the metal plates were removed and the stack placed in the stressing device (see Fig 1b). Stressing was achieved by tightening nuts on the ends of the tensioning rods. The prestress was measured with dynamometer elements and an ISD-2 static-strain meter. The dynamometer elements were the above-mentioned rods, to which strain gauges were bonded. After the reinforcement had been prestressed, the stack and the stressing device were placed in a mold (see Fig. 1b).

In preparing the unstressed and prestressed sheets the molding temperature, time and pressure and the resin content were strictly controlled. All the sheets were obtained from the same batch of glass cloth.

In order to eliminate the effect of relaxation processes the sheets were kept at room temperature for three months, after which specimens (strips measuring 250×30×3 mm) were cut and the longitudinal and transverse tensile-compressive strains were measured with strain gauges on a 20-mm base. The manner of cutting the specimens and the directions in which the testing was carried out are shown in Fig. 2. In order to estimate the difference in strength, longitudinal and transverse tensile-compressive strains were measured on the same specimens. The specimens were first tested in tension at a load not exceeding 0.5 P_b. Then from these specimens we cut strips (including the transducers), which were tested in compression in a device that prevented buckling. The shape of the tensile and compressive specimens and the device for preventing buckling in compression are shown in Fig. 3.

3. The results of the tests and the data of a statistical analysis are presented in Table 1, photographs of typical macrosections in Figs. 4 and 5. In Table 1 we have introduced the following notation: $E_{x(x,0)}^{+}$, $E_{x(x,y)}^{+}$, $E_{y(x,0)}^{+}$, $v_{x(x,0)}^{+}$, etc. The superscript denotes tension (+) or compression (–). The subscript denotes the direction of testing (coinciding with the direction in which the specimen was cut). The subscripts in parentheses characterize the presence or absence of a prestress direction. The first subscript in parentheses represents prestress along the warp, the second prestress along the fill.

It is clear from Table 1 that as the warp prestress increases there is a substantial increase in the values of $E_{x(x,0)}^{+}$, $v_{x(x,0)}^{+}$. Thus, for example, at a prestress $N_x = 0.5\,R_M$*/$E_{x(x,0)}^{+}$increased by 36% and $v_{x(x,0)}$ by 17%, the greatest relative increase in these characteristics taking place with increase in the prestress to 0.25 R_M (see Table 1). As may be seen from Figs. 4 and 5, the increase in $E_{x(x,0)}^{+}$; $v_{x(x,0)}^{+}$ with increase in prestress occurs as a result of straightening of the warp fibers. Almost complete straightening of the warp fibers takes place at $N_x = 0.5\ R_M$ (see Fig. 4).

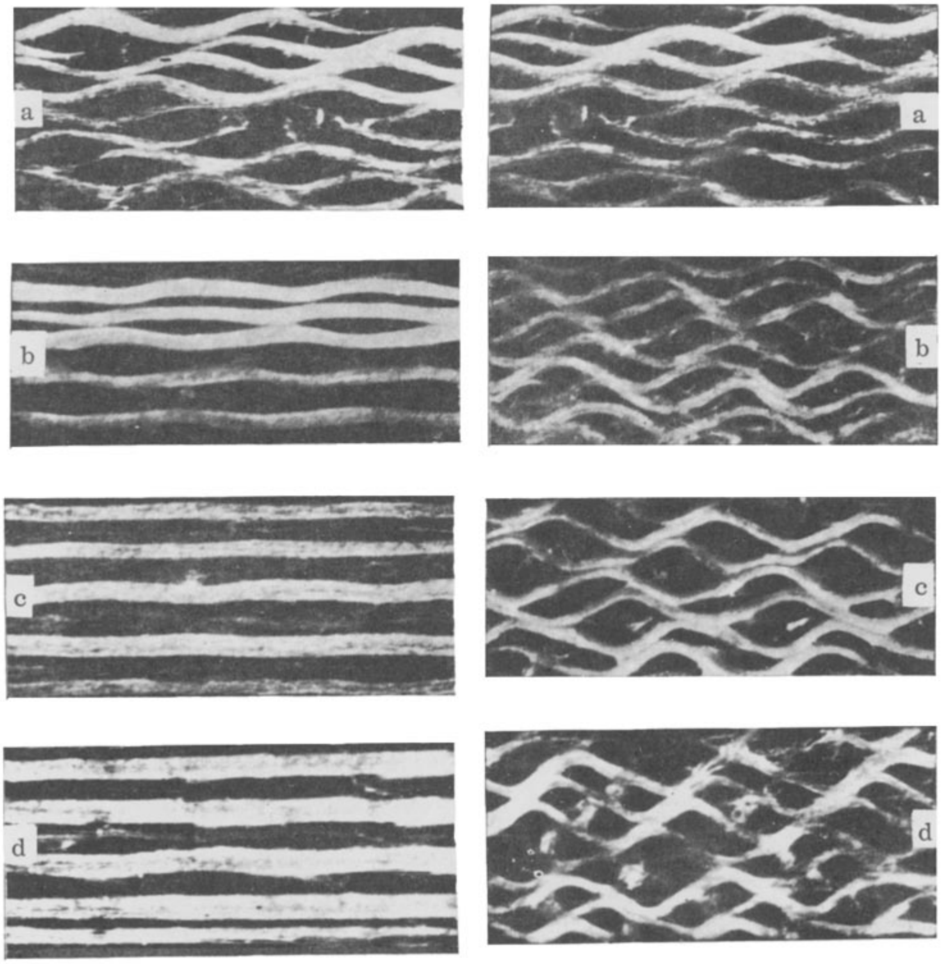

Fig. 4. Change in the distortion of the warp (left) and fill (right) fibers with increase in the prestress on the warp fibers: a) $N_x = 0$; b) 0.1 R_M; c) 0.25 R_M; d) 0.5 R_M. Magnification 10 ×.

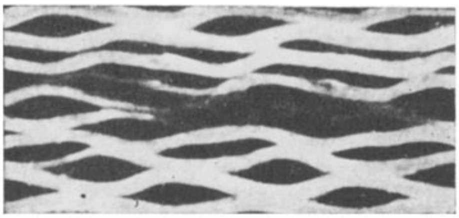

Fig. 5. Change in the distortion of the warp fibers when both warp and fill fibers are prestressed. Magnification 10 ×. $N_x = 0.1\ R_M$; $N_y = 0.1\ R_M$.

On comparing the values of $E_{y(0,0)}^+$, $\nu_{y(0,0)}^+$ determined for specimens with unstressed reinforcement and the corresponding values $E_{y(x,0)}^+$, $\nu_{y(x,0)}^+$, determined for specimens with the warp reinforcement stressed, we see that an increase in warp prestress leads to a decrease in the elastic characteristics of the fill. The creation of a warp prestress $N_x = 0.5\ R_M$ reduces $E_{y(x,0)}^+$ by 26% and $y_{(x,0)}^+$ by 40% (see Table 1). As may be seen from Fig. 4, the decrease in the values of these characteristics is a consequence of the additional distortion of the fill reinforcement.

When the warp and fill are simultaneously prestressed, the values $E_{x(x,y)}^+$, $E_{y(x,y)}^+$ increase significantly with increase in prestress (see Table 1), and the amplitude of the fiber distortions is reduced. The Poisson's ratios $\nu_{x(x,y)}^+$, $\nu_{y(x,y)}^+$ remain unchanged. The data (see Table 1, ratio E_i^+/E_i^-) show that the investigated SKT-11 material has practically equal moduli in tension and compression.

4. The existing relations [1, 4] were derived in order to take into account the effect of distortion of the reinforcing fibers or layers on the modulus of elasticity of unidirectional GRP. The existence of regular distortions and their dependence on the type of weave and the diameter of the reinforcing fibers in the case of woven reinforcement require the estimation of the effect of these distortions on the modulus of elasticity.

TABLE 1. Moduli of Elasticity and Poisson's Ratio in Tension-Compression as Functions of the Reinforcement Prestress

Modulus of elasticity and Poisson's ratio $E \cdot 10^{-5}$, kgf/cm²	Prestress along warp; specimen tested along:								Prestress along warp and fill; specimen tested along warp; $E_{x(x,y)}$; $\nu_{x(x,y)}$	
	warp $E_{x(x,o)}$; $\nu_{x(x,o)}$				fill $E_{y(x,o)}$; $\nu_{y(x,o)}$					
	Reinforcement prestress									
	0	$0{,}1\,R_M$	$0{,}25\,R_M$	$0{,}5\,R_M$	0	$0{,}1\,R_M$	$0{,}25\,R_M$	$0{,}5\,R_M$	$0{,}1\,R_M$	$0{,}25\,R_M$
E^+	1,38	1,68	1,80	1,87	1,35	1,21	1,14	1,00	1,61	1,70
$\frac{E_{min}^+}{E_{max}^+}$	$\frac{1,35}{1,42}$	$\frac{1,61}{1,80}$	$\frac{1,75}{1,88}$	$\frac{1,84}{1,91}$	$\frac{1,34}{1,39}$	$\frac{1,17}{1,28}$	$\frac{1,10}{1,20}$	$\frac{0,93}{1,06}$	$\frac{1,54}{1,70}$	$\frac{1,64}{1,76}$
V, %	2,0	4,5	2,9	1,6	2,0	4,0	4,0	5,8	4,3	2,7
n	5	5	5	5	5	5	5	5	5	5
E^N/E_0	1,00	1,22	1,31	1,36	1,00	0,89	0,85	0,74	1,17	1,23
E^-	1,38	1,61	1,72	1,75	1,36			1,05	1,58	1,65
$\frac{E_{min}^-}{E_{max}^-}$	$\frac{1,35}{1,42}$	$\frac{1,59}{1,74}$	$\frac{1,67}{1,80}$	$\frac{1,71}{1,80}$	$\frac{1,33}{1,39}$			$\frac{0,97}{1,11}$	$\frac{1,50}{1,66}$	$\frac{1,60}{1,71}$
V, %	2,2	4,3	2,9	2,0	1,8			5,5	4,0	2,6
n	5	5	5	5	5			5	5	5
E^{-N}/E_0^-	1,00	1,16	1,25	1,29	1,00			0,77	1,16	1,21
E^+/E^-	1,0	1,04	1,04	1,07	0,99			0,95	1,02	1,03
ν^+	0,130	0,143	0,148	0,152	0,133	0,100	0,093	0,080	0,133	0,134
$\frac{\nu_{min}^+}{\nu_{max}^+}$	$\frac{0,126}{0,132}$	$\frac{0,132}{0,153}$	$\frac{0,142}{0,154}$	$\frac{0,146}{0,162}$	$\frac{0,129}{0,138}$	$\frac{0,100}{0,109}$	$\frac{0,088}{0,098}$	$\frac{0,075}{0,087}$	$\frac{0,0127}{0,136}$	$\frac{0,129}{0,142}$
V, %	2,1	7,6	4,6	4,2	2,8	4,1	5,3	7,3	4,8	5,6
n	5	5	5	5	5	5	5	5	5	5
ν^{+N}/ν_0^+	1,00	1,11	1,17	1,14	1,00	0,78	0,67	0,60	1,04	1,03
$\frac{E_{x(y,0)}^+ \nu_{y(x,0)}^+}{E_{y(x,0)}^+ \nu_{x(x,0)}^+}$	1,04	0,97	0,99	0,98						

<u>Remark.</u> The experimental data in this and the subsequent tables are for SKT-11 glass-reinforced plastic with the cloth heat-treated at 250°C.

TABLE 2. Change in the Curvature of the Reinforcing Fibers with Prestress

Values of c, l, mm	Prestress along the warp; specimens tested along					Prestress along warp and fill; specimens tested along warp
	warp		fill			
	Reinforcement prestress					
	0	$0{,}1\,R_M$	0	$0{,}25\,R_M$	$0{,}5\,R_M$	$0{,}1\,R_M$
c	0,135	0,055	0,135	0,190	0,200	0,11
$\frac{c_{min}}{c_{max}}$	$\frac{0,125}{0,150}$	$\frac{0,050}{0,060}$	$\frac{0,125}{0,150}$	$\frac{0,150}{0,200}$	$\frac{0,170}{0,220}$	$\frac{0,09}{0,12}$
V, %	8,5	7,0	8,5	8,9	7,5	8,5
n	8	8	8	8	8	8
l	2,5	2,55	2,50	2,43	2,40	2,52
$\frac{l_{min}}{l_{max}}$	$\frac{2,40}{2,60}$	$\frac{2,50}{2,65}$	$\frac{2,40}{2,60}$	$\frac{2,35}{2,50}$	$\frac{2,37}{2,50}$	$\frac{2,40}{2,70}$
V, %	3,4	3,0	3,4	2,7	2,5	4,8
n	8	8	8	8	8	8

We will investigate the possibility of applying the above-mentioned relations and the formulas of [6] for woven reinforcement.

It is assumed that at $N_x = 0.5\,R_M$ the reinforcing fibers are straight and parallel; in this case $E_x^+ = 1.87 \cdot 10^5$ kgf/cm²; $G_{xz} = 7.8 \cdot 10^3$ kgf/cm²; $E_z = 6.7 \cdot 10^4$ kgf/cm². The moduli of elasticity of the resin and

TABLE 3. Comparison of Moduli of Elasticity Obtained from Analytic Relations and the Experimental Data ($\cdot 10^5$ kgf/cm^2)

Theoretical relation	Prestress along warp; specimens tested along: warp		fill			Prestress along warp; specimen tested along warp
	Prestress					
	0	0,1 R_M	0	0,25 R_M	0,5 R_M	0,1 R_M
$\tilde{E}_x = \dfrac{E_x}{1+\dfrac{E_x}{G_{xz}}\varphi^2}$ Ref [1]	1,45	1,79	1,45	1,17	1,11	1,58
$\tilde{E}_x = E_m\nu_m + \tilde{E}_f\nu_f$; $\tilde{E}_f = \dfrac{E_f}{1+\dfrac{\pi^2}{2}\dfrac{c^2}{l^2}\dfrac{\nu_f}{2}\dfrac{E_f}{G_{xz}}}$ Ref [6]	1,42	1,77	1,42	1,12	1,07	1,55
$\tilde{E}_x = \dfrac{E_x}{1+\dfrac{E_x}{G_{xz}}\dfrac{f^2}{2}}$ Ref [4]	1,39	1,77	1,39	1,09	1,02	1,53
Experimental data	1,38	1,68	1,35	1,14	1,00	1,61

Remark. The other formulas [6] give large discrepancies with the experimental data.

the reinforcement are $E_m = 2.1 \cdot 10^4$ kgf/cm^2 and $E_x = 7.00 \cdot 10^5$ kgf/cm^2, respectively, the moduli of elasticity of the GRP and the reinforcement with allowance for distortion are $\tilde{E}_x$, $\tilde{E}_f$. The relative volumes of resin and reinforcement $\nu_m = 0.51$; $\nu_f = 0.49$, respectively, since SKT-11 has the same warp and fill fiber density, $\nu_{f\,warp} = \nu_{f\,fill} = \nu_f/2 = 0.245$; as shown in [4], the mean square value of the angle formed with the x axis $\varphi = \dfrac{c}{l/2}\left(f = \dfrac{c\pi}{l}\right)$, where c is the amplitude and l the chord length of the half-wave of the regular distortions. The values of c and l were measured with a UIM-21 universal microscope. The results of the measurements and a statistical analysis of the data are presented in Table 2.

Values of the moduli of elasticity calculated on the basis of the equations of [1, 4, 6] are presented in Table 3.

The good agreement between experiment and the calculated values (see Table 3) makes it possible to recommend the above-mentioned analytic relations for estimating the effect of regular distortions (determined by the manner of weaving the cloth) on the moduli of elasticity of glass laminates.

SUMMARY

The data obtained show that for woven-glass reinforced plastics simultaneously stressing the warp and fill leads to a considerable increase in the moduli E_x, E_y. If the reinforcement is prestressed in one direction, it is necessary to take into account the reduced elastic characteristics in the direction at right angles. For a GRP reinforced with plain-weave cloth equally strong in each direction the most effective value of the prestress in one direction is $N_x = 0.25\,R_M$, which gives the greatest "overall" stiffness. For the material investigated $E_{x(x,0)^+}$ increases by 31% and $\nu_{x(x,0)^+}$ by 17%; in this case the elastic characteristics $E_{y(x,0)^+}$ fall by 15 and 33%, respectively.

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