MECHANICAL BEHAVIOR OF HIGH STRENGTH UNIDIRECTIONAL COMPOSITES UNDER 3-D STATE OF STRESS

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SUMMARY: The experimental study was carried out on the dependence of strength of unidirectional fibrous composites upon superposed hydrostatic pressure up to 500 MPa. Ring samples made of carbon and glass fiber reinforced plastics were tested under longitudinal tension. The tests showed that, as pressure increased (approximately up to p = 300 MPa), the longitudinal tensile strength of both composites increased. However, on further increasing pressure (up to p = 500 MPa) the strength decreased. It was found in the tests that the failure mode of unidirectional composites depended on the magnitude of superposed hydrostatic pressure. Failure modes differed in the position of the failure zone and the propagation of longitudinal cracks within the sample. The failure zone covered practically the whole volume of the sample at atmospheric pressure. As pressure increased, the failure zone localized. At pressure p ≥300 MPa, there was a single crack transverse to the fiber direction.

KEYWORDS: carbon fiber reinforced plastic, glass fiber reinforced plastic, longitudinal tension, hydrostatic pressure, strength, modulus of elasticity, failure mode.

INTRODUCTION

The behavior of fibrous composites under the simplest uniaxial and biaxial states of stress has been much investigated. The latest achievements in the field are described, for example, in the special issue [1].

However, more detailed are the data for uni- and biaxial states of stress, more pronounced is the need in the experimental investigations under 3-D state of stress. Two main aspects can be revealed:

- further development of adequate theoretical models predicting the behavior of composites is hampered by poor amount of the information on the behavior under 3-D state of stress

- modern industry progresses towards the development of equipment operating under 3D-stresses, and the design of such constructions is impossible without sufficient information on the behavior of composite materials under 3-D state of stress.

Testing the materials under high hydrostatic pressure is a known method to study the behavior of materials under 3-D state of stress. As was shown in [2-5], the properties of unidirectional composites significantly depend on the magnitude of superposed hydrostatic pressure. Nevertheless, both the amount of information on composite properties under 3-D state of stress and understanding the reasons of observed changes are obviously poor. The present paper deals with the investigation of the behavior of two high strength unidirectional composites – epoxy carbon (CFRP) and glass fiber reinforced plastics (GFRP) under longitudinal tension with varying hydrostatic pressure from 0 to 500 MPa.

EXPERIMENTAL TECHNIQUE

NOL-rings were used to determine the properties of the materials under longitudinal tension with superposed high pressure. The rings had the following nominal dimensions: internal radius, R = 50mm, thickness, h =0.5mm, and width, b = 7mm.

The rings were made by circumferential (hoop) winding from high strength carbon and glass fibers impregnated with epoxy resin.

Fig. 1 illustrates the test set-up. Ring sample 1 on half-disks 2 is placed into high pressure chamber 3. Multiplicators 4 and 5 produce high pressure in the interior of the chamber. Axial force is transmitted to the sample from hydrocylinder 8 through thrust ball bearing 9. The magnitude of the axial force is measured with the aid of gauge 10, which is placed directly in the high pressure zone. The set-up has two points to bring out the data from the high pressure zone (11 and 12), those are to transmit the data from the force gauge and strain gauges.. Transform oil is used as a pressure liquid in the set up. Maximum external pressure produced in the chamber is 500 MPa, and maximum axial force produced by hydrocylinder 8 is 750 kN.

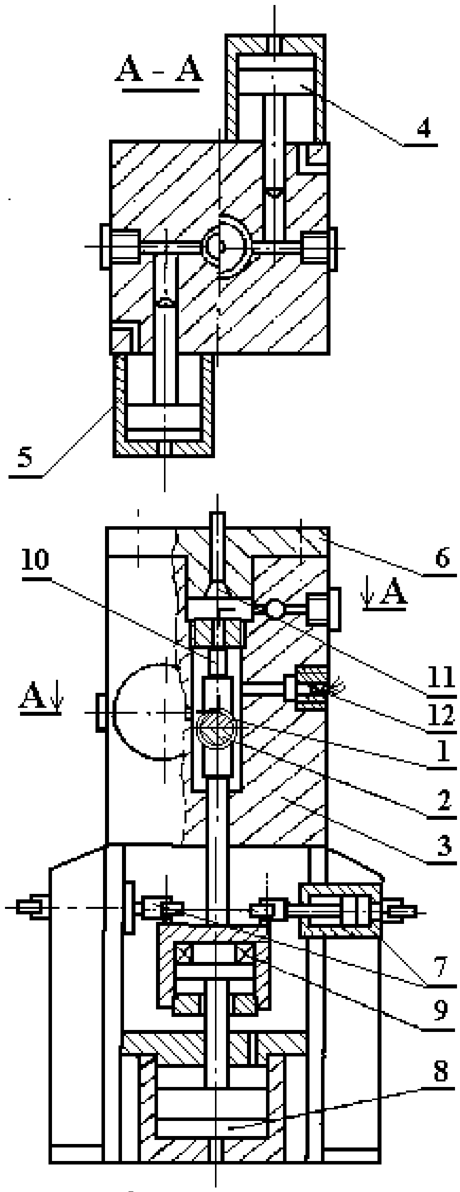


Fig. 1: High pressure test set-up

Different types of samples can be tested with the described set-up under a variety of the loads [5]. For example, tubular samples tubular samples can be loaded with internal and external pressure, axial force and torque. A pair of hydrocylinders 7 are for loading the tube sample with torsion. In the tests, internal and external pressure may be of different magnitudes. All four load factors are independent of one another. The multiplicators and hydrocylinders of the set-up are moved with a pump with pressure of 35 MPa.

The tests were carried out with the use of ring samples loaded with axial tensile force in the high pressure chamber. A half-disks device was used to apply the tensile force. Fig. 2 shows the half-disks device. The device for loading ring samples is so constructed that when rod of the axial force 3 moves up, half-disks 1 are pushed apart, and ring sample 2 is loaded with the tensile force. With the used seal scheme, a large friction force arises at moving the rod of the axial force, which is why the axial force must be registered directly in the high pressure zone. Gauge 4 for registration of the axial force is the steel cylindrical bush with strain gauges bonded on its surface.

Step-by-step (pressure + tension) loading scheme was realized. The samples were tested under tension at pressure p = 0, 150, 300 and 500 MPa. Forces and strains were recorded during the tests enabling one to study the dependence of the modulus of elasticity and strength upon hydrostatic pressure.

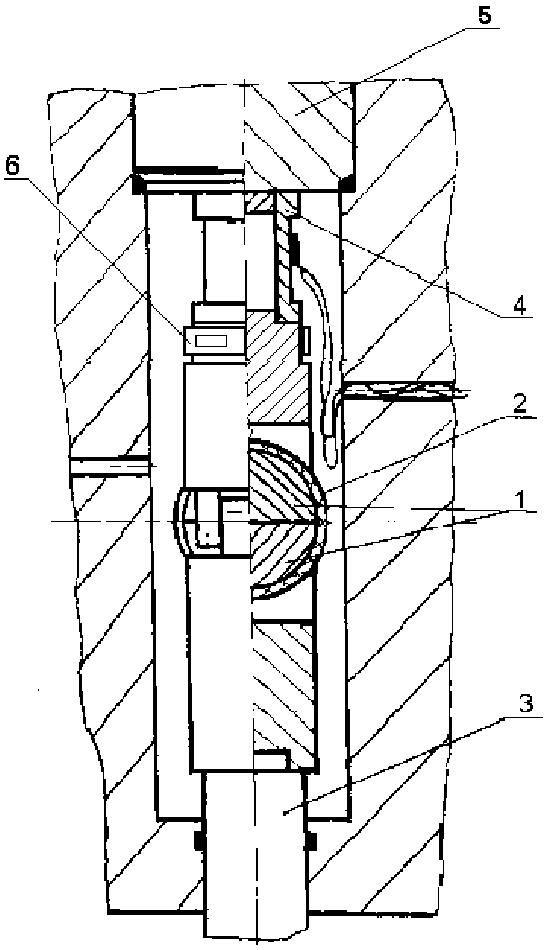


Fig. 2: Half-disks device with the gauge of the axial force

TEST RESULTS

Unidirectional Carbon Fiber Reinforced Plastic

It was found that at atmospheric pressure the longitudinal tensile strength of CFRP F^{c}_{+1} = 1710 ÌPà and longitudinal modulus of elasticity E_c= 171500 MPa (averaged magnitudes).

Figs 3 illustrates the dependence of the longitudinal tensile strength, σ_c*, of the unidirectional CFRP upon superposed hydrostatic pressure. Strength magnitudes for 24 tested samples are drawn on the plot. The dependence of the longitudinal tensile strength upon pressure for CFRP may be approximated with the square function as follows:

$$\sigma_c^* = F^{c}_{+1} + Í_0 \cdot ð + Í_1 \cdot ð^2 \qquad (1)$$

where coefficients H_0 and H_1 are found with the least square method: H_0 = 4.289 and H_1 = - 0.00756 MPa^{-1}.

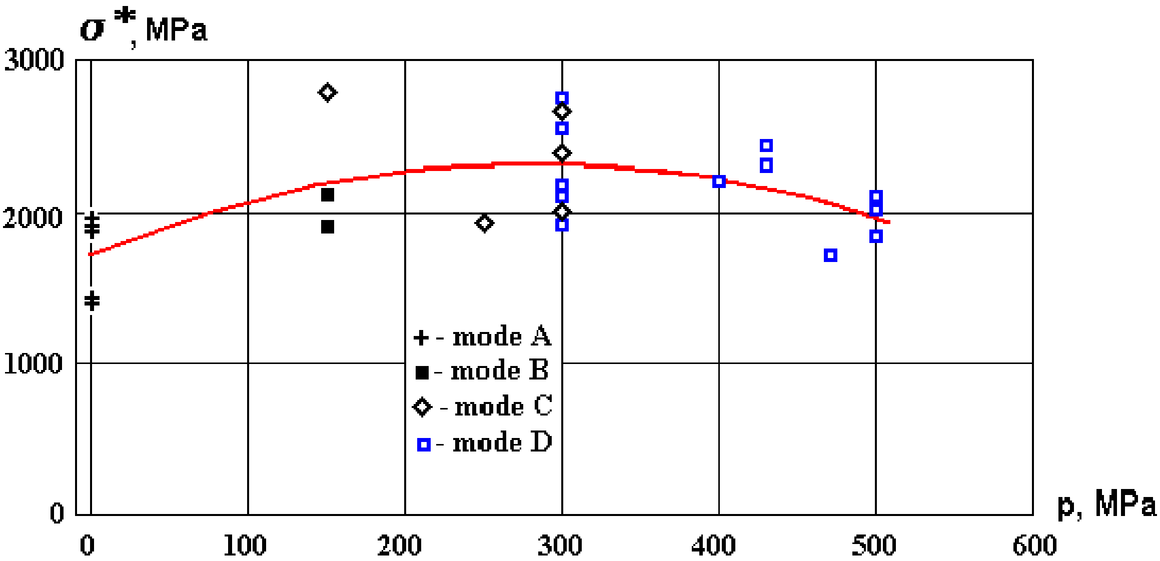
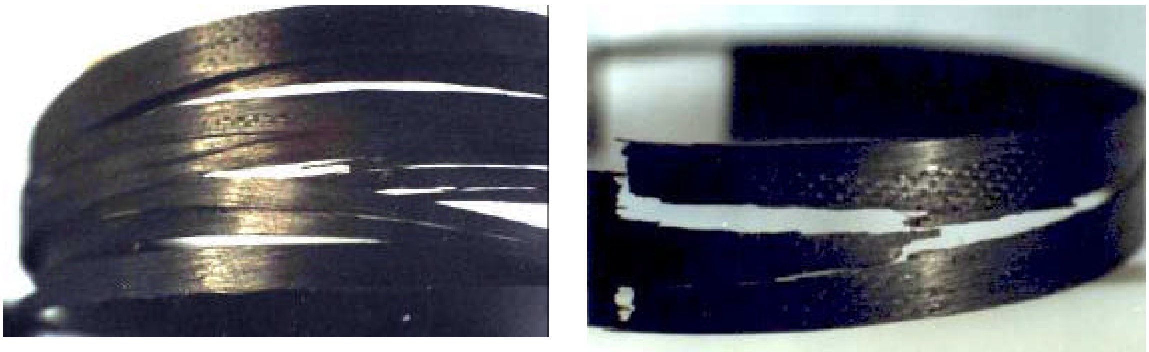


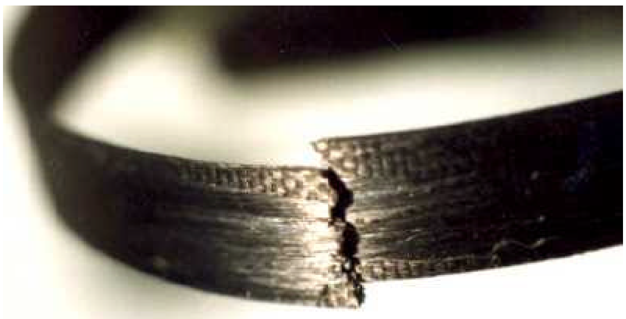
Fig. 3: Longitudinal tensile strength of unidirectional CFRP versus superposed hydrostatic pressure



a)

b)

c)



d)

Fig. 4: Failure modes for CFRP

It was found in the tests that the failure mode of unidirectional carbon fiber plastic significantly depends on the magnitude of superposed hydrostatic pressure. By convention all failure modes may be divided into four groups. Below is given a description of failure modes; the photos of broken samples are shown in Fig. 4.

Failure mode "A"

The ring specimen is divided into a multitude of free fiber bundles by the cracks parallel to the fibers. The cracks spread along the whole perimeter of the ring sample. The points of broken fibers are accidentally distributed in different points of the sample. The failure mode is typical for carbon fiber rings tested at atmosphere pressure. Fig. 4a demonstrates the described failure mode.

Failure mode "B"

Longitudinal cracks are less in number as compared to mode "A", and the cracks, as a rule, do not spread along the whole ring length. The point with broken fiber looks more local. The mode is typical for the samples tested at pressure p = 150 MPa. Failure mode "B" is shown in Fig. 4b.

Failure mode "C"

In the case we observe a local point of failed fibers and short longitudinal cracks in the material with the length of several millimeters. The place of failure is not smooth (uneven). The failure mode was observed for a single CF sample tested at p = 150 MPa and for several samples tested at pressure p = 300 MPa. Fig. 4c illustrates failure mode "C".

Failure mode "D"

In the case the failure crack goes along a single line perpendicular to the fiber direction. Longitudinal cracks are practically absent. The failure mode is typical for the most part of the samples tested under p = 300 MPa and all samples tested under p = 500 MPa. Failure mode "D" is given in Fig. 4d.

Unidirectional Glass Fiber Reinforced Plastic

At atmospheric pressure we determined the following characteristics for GFRP: the longitudinal tensile strength, F^g_{+1} = 1710 ÌPà and longitudinal modulus of elasticity E_g = 171500 MPa (averaged magnitudes).

Figs 5 illustrates the dependence of the longitudinal tensile strength, σ_g^*, of the unidirectional GFRP upon superposed hydrostatic pressure. Experimental points are drawn along with an approximating curve. The dependence of the longitudinal tensile strength upon pressure for GFRP may be approximated with the square function as follows:

$$\sigma_g^* = F^g_{+1} + G_0 \cdot ð + G_1 \cdot ð^2 \qquad (2)$$

where coefficients G_0 and G_1 are found with the least square method: G_0 = 3.995 and G_1 = - 0.00827 MPa^{-1}.

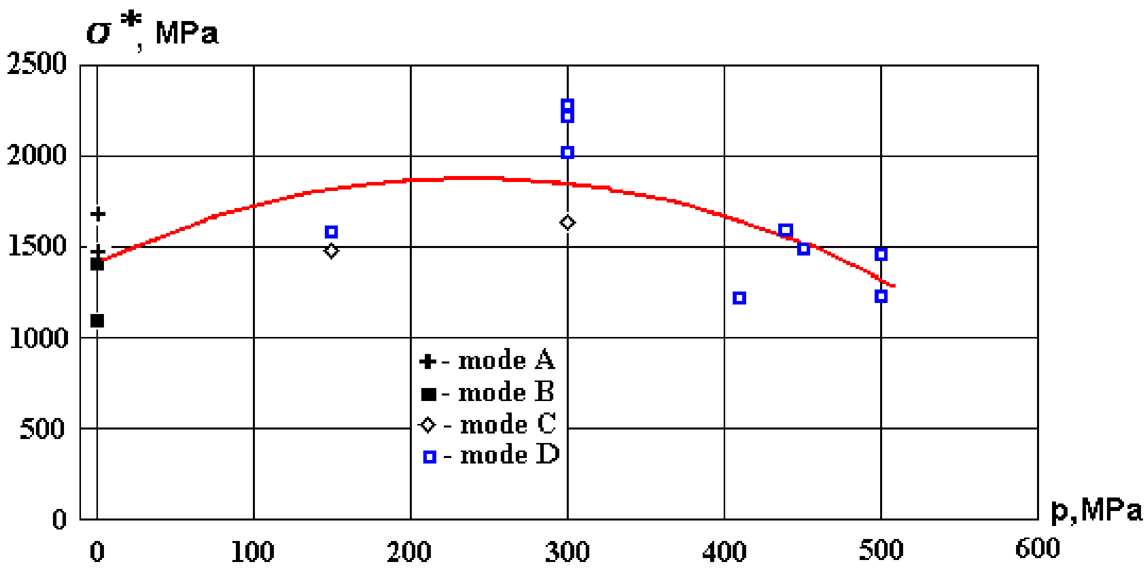
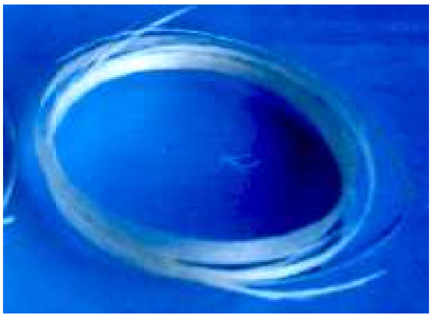


Fig. 5: Longitudinal tensile strength of unidirectional GFRP versus superposed hydrostatic pressure



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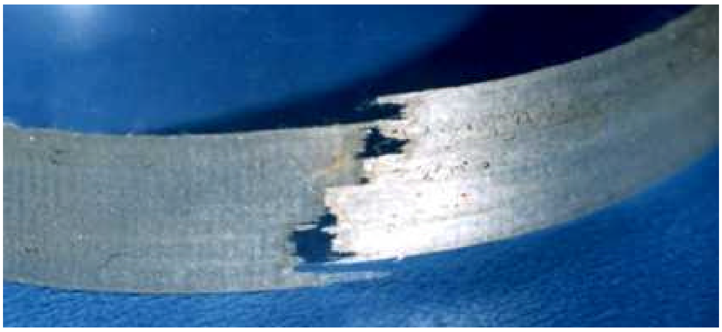

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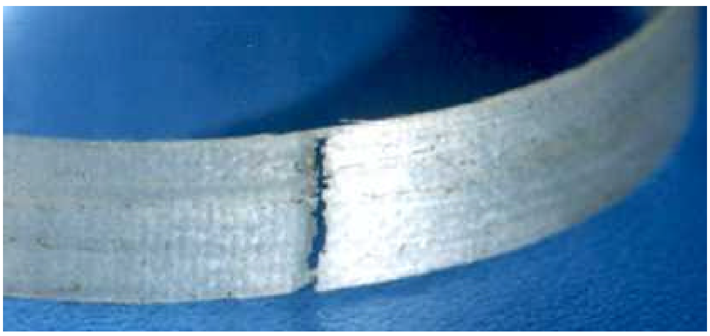

d)

Fig. 6. Failure modes for GFRP

Failure modes of GFRP rings differ somewhat from failure modes observed for CFRP rings. At atmospheric pressure, we observed both mode “A” (see Fig. 6a) and mode “B” (see Fig. 6b). Failure modes “C” (Fig. 6c) and “D” (Fig. 6d) were observed at pressure p = 150 MPa, while failure mode “B” did not take place at the pressure (compare with CFRP). Failure mode “D” was typical for pressures p = 300MPa and 500 MPa (see Fig. 6d). As a whole, the tendency toward localization of the broken zone retains for GFRP samples with increasing hydrostatic pressure.

DISCUSSION

The state of stress under consideration is the sum of two states of stress. The first state of stress is uniaxial tension along the fibers: stress σ is created by the loads from the half-disks. The second state of stress is uniform compression with hydrostatic pressure, p.

The results of the tests showed that the magnitude of superposed hydrostatic pressure (in the interval p = 0-500 MPa) significantly affected the longitudinal tensile strength of carbon and glass fiber reinforced plastics. The pressure-dependence of the longitudinal tensile strength is of non-monotonic character: as pressure increases approximately up to p = 300 MPa, the longitudinal tensile strength of both composites increases as well, but on further increasing pressure (up to p = 500 MPa) the strength decreases. By contrast, the longitudinal modulus of elasticity of investigated composites is practically pressure-independent.

In the tests we have observed principal changes in failure modes. We recognized four failure modes: A, B, C, and D differing in the position of the failure zone and the propagation of longitudinal cracks within the sample. The failure zone can cover practically the whole volume of the sample (mode “A”) and can have a form of a clear single crack transverse to the fiber direction (mode “D”). It was observed that the change in the failure mode was directly related to the level of hydrostatic pressure as each pressure level correlated with a single (or “neighboring”) failure mode. The results of the tests show that the failure mode significantly governs the magnitude of the longitudinal tensile strength of the composites.

Let us consider possible schemes of the effect of hydrostatic pressure on the formation of the cracks and failure modes of unidirectional composites under tension. The processes of crack propagation are multi-alternative processes in unidirectional composites. In particular, those depend on the ration between the stresses in several characteristic points of the crack and the strength of the fiber/matrix interface and/or on transverse tensile strength and shear strength of the fibers.

The results of the tests enable us to suggest that the two effects are present in the action of hydrostatic pressure on the longitudinal tensile strength of unidirectional composites. First of all, hydrostatic pressure prevents the development of shear cracks in the fiber/matrix interface. Shear stresses arise as the result of fracture of individual fibers and inexact coincidence of the tensile stress direction and fiber direction (the latter reason is common for ring samples, which are cut off from cylindrical wound tubes). The decrease of the length of such delaminations prevents the possibility of the selection for failure of the weakest parts of the fibers within the sample volume, i.e. prevents composite failure in the fiber bundle mode. Decreased is the potential of spreading shear cracks along the fiber length in the hoop direction, i.e. the potential for a specific failure mode, namely “unwinding” of the ring sample with a limited number of ruptured fibers. It is clear that such action of hydrostatic pressure results in increasing the average strength of unidirectional composites.

Another side of the action of hydrostatic pressure is that the pressure affects the process of propagation of transverse (in relation to the fiber direction) cracks. As is known, the fiber/matrix interface is the main barrier for the development of the transverse crack in the unidirectional composite, or, to be more exact, this is the possibility for the appearance of the delaminations in the fiber/matrix interface caused by the growing transverse crack [6]. It seems likely that high hydrostatic pressure ($p > 300$ MPa) “interlocks” the potentials for the appearance of such delaminations in front of the growing transverse crack. This results in the appearance of the single transverse crack cutting the sample and pronounced decreasing the longitudinal tensile strength. Note that in the zone of the σ - ð curve maximum, in which different failure modes are equiprobable, one can observe the largest scatter in experimental data.

CONCLUSION

The analysis of the data published in world literature and the results of the present tests enable one to conclude the following:

A. In the present work new, unknown before experimental data were obtained on the behavior of high strength unidirectional composites under longitudinal tension and hydrostatic compression. This is true for the types of investigated materials, experimental procedure and the intervals of studied load parameters.
B. For the fist time was observed and studied a broad set of different failure modes of unidirectional composites with varying the hydrostatic load component.
C. A theoretical conception is proposed, which adequately describes observed changes in the mechanisms of failure of investigated materials.

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