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Influence of wave effect on fiber stress limit under tensile tests of composite material*

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Влияние волнового эффекта на предел прочности волокна при испытаниях композитного материала на растяжение***

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Introduction. The response of composite materials to the impact of a certain kind of load is difficult to predict, therefore, research in this area has often been neglected. The work objective was to study the influence of the wave effect on the tensile strength of polymer composites of a fibrous structure.

Materials and Methods. In the tests, samples of multilayer materials of various thicknesses with continuous, long and short fibers that form a fabric, as well as a layered structure, were used. The number of layers corresponds to the resistance to the applied loads. Fibers of glass, carbon, kevlar, or their combinations were used. Isotropic materials – epoxide, polyester and vinyl ether – were used as binders.

Research Results. The tensile test results of homogeneous samples and samples of fibrous structure are obtained. In this case, the values of fiber angle varied. The stability of their intercomparison test results is established. The dependence of the maximum tensile stresses σ_{max}, MPa, (on the vertical axis) on the fiber angle θ_{max} is obtained. These stresses for a fibreless material amounted to 250 MPa. Normal and tangential stresses acting perpendicular to the fibers, as well as shear stresses of the layered material, are calculated. As follows from the analysis of the dependences for the significant tensile stresses and from the study on refraction in the section of the sample damage, it was established that the shear stress τ_{xy} was the cause of the fracture. Using an equation providing the compensation for the angle of inclination $\theta = 45$, it was determined that the shear stress of the polyester is $\tau_{xy} = 35$ MPa. This was the stress that caused subsequently the destruction of the samples.

Введение. Реакция композиционных материалов на воздействие определённого рода нагрузок трудно прогнозируема, поэтому исследованиям в этой области не уделялось должного внимания. Целью настоящей работы было изучение влияния волнового эффекта на предел прочности при растяжении полимерных композитов волокнистой структуры.

Материалы и методы. В испытаниях использовались образцы многослойных материалов различной толщины с непрерывными, длинными и короткими волокнами, образующими ткань, а также слоистую структуру. Число слоев соответствует сопротивляемости приложенным нагрузкам. Применялись волокна стекла, углерода, кевлара или их комбинации. В качестве связующих использовали изотропные материалы: эпоксид, полиэфир и виниловый эфир.

Результаты исследования: Получены результаты испытания на растяжение гомогенных образцов и образцов волокнистой структуры. При этом варьировались значения угла наклона волокон. Установлена стабильность результатов испытания путем их взаимного сравнения. Получена зависимость максимальных напряжений при растяжении σ_{max}, МПа, (на вертикальной оси) от угла наклона волокна θ_{max}. Эти напряжения для материала с безволновыми волокнами составили 250 МПа. Рассчитаны нормальные и касательные напряжения, действующие перпендикулярно волокнам, а также напряжения слоистого материала при сдвиге. В результате анализа зависимостей для характерных напряжений при растяжении и исследования рефракции в сечении разрушения образцов установлено, что причиной разрушения является напряжение сдвига τ_{xy}. С помощью уравнения, которое позволяет компенсировать угол наклона $\theta = 45°$, было определено, что значение напряжения сдвига полиэстера $\tau_{xy} = 35$ МПа. Это и есть напряжение, которое впоследствии явилось причиной разрушения образцов.

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* The research is done within the frame of the independent R&D.
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Discussion and Conclusions. The tensile stresses of the composite material decrease with increasing the fiber angle in certain areas. The destruction of all fiber samples occurred when the shear stress reached a value approximately equal to the shear stress at which the destruction of samples made only from a binder material happened. When the specimen broke, the fracture mode had the form similar to the shear failure; besides, at the moment of fracture, the object having a rectangular shape, being deformed at an angle, took the form of a parallelogram.

Обсуждение и заключения: Напряжения при растяжении композитного материала уменьшаются с увеличением угла наклона волокон в определенных зонах. Разрушение всех образцов волокна наступало тогда, когда величина напряжения сдвига достигала значения, примерно равного величине напряжения сдвига, при котором происходило разрушение образцов, изготовленных только из связующего материала. При разрыве образца форма разрушения имела вид, аналогичный разрушению при сдвиге, причём в момент разрушения объект, имеющий прямоугольную форму, деформируясь под углом, принимал форму параллелограмма.

Keywords: composite material, binding material, fibrous material, filler, structure defect.

Ключевые слова: композитный материал, связующий материал, волокнистый материал, наполнитель, дефект структуры.

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Introduction. The studies employed composite materials widely used in construction. Samples of various thicknesses from multilayer materials containing continuous, long, short fibers and fibers forming the fabric were used. The number of filler layers corresponded to the resistance to the loads applied. Fibers of glass, carbon, kevlar, or their combinations with binders were used. Binding materials are designed to develop adhesion bonds between fibers, to protect them from the environment and load distribution., Isotropic materials such as epoxide, polyester and vinyl ether were used as binders [1].

The cost of products from polymer composites depends mainly on the cost of the ingredients and the number of production stages. Violations of technological regulations causes deviations from the required structure of the material, the formation of various kinds of defects. At that, a wavy shape of the fibers is implemented (Fig. 1), the uniformity of the heterogeneous structure is violated. All this causes deterioration in the complex of mechanical-and-physical properties of the composite [2].

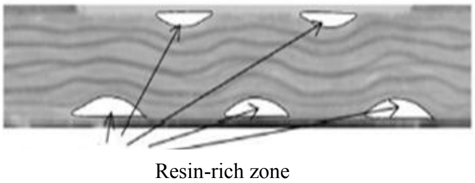


Fig. 1. Formation of waves in the fibers caused by the lack of structure of composite materials

A number of disadvantages of the reinforced composites are largely associated with impurities and flaws in the product. Flaws are formed in the process of curing the binder, which, initially being in a state of viscous flow, translated gas inclusions in the form of bubbles into the volume of the composite under the gravity die casting. Heterogeneity of the concentration of fibers and the binder in the bulk of the material occurs due to the presence of functional additives or additional filler, for example, sand (Fig. 2).

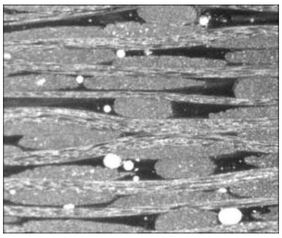
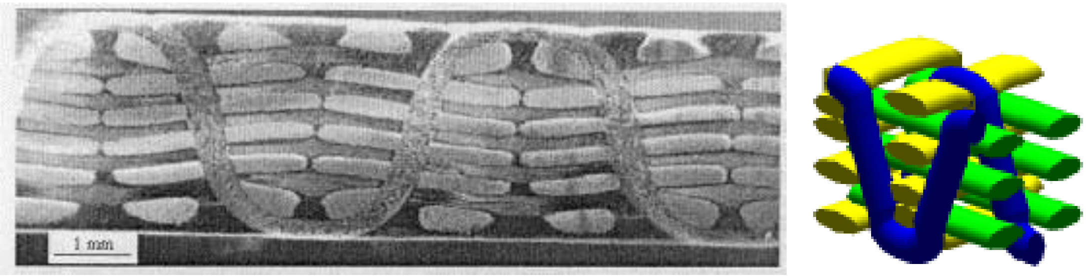


Fig. 2. Cross section of composite material containing a number of bubbles

На рис. 3 показано, что волновая ориентация волокон может располагаться в плоскости ткани, по структуре аналогичной фиброзной, а также в плоскости сплетенных волокон. Эти волокна обеспечивают стабильность структуры при транспортировке, обработке, а также облегчают технологическую проницаемость слоёв композитных материалов. Это позволяет соединять волокна в группы продольно или перпендикулярно друг к другу [3], что не препятствует образованию небольших волн в ткани.



a) *b*)

Fig. 3. Waves located in the layer plane:
a) section of the composite; *b)* spatial structure

Spatial wave structures (Fig. 4) are implemented using textile equipment. These structures are able to take the final shape of a product made from a composite material. Then, such a structure is impregnated with a binder, and the product is mold using one of the known methods.

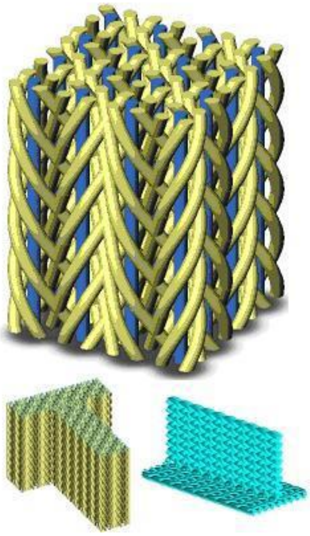
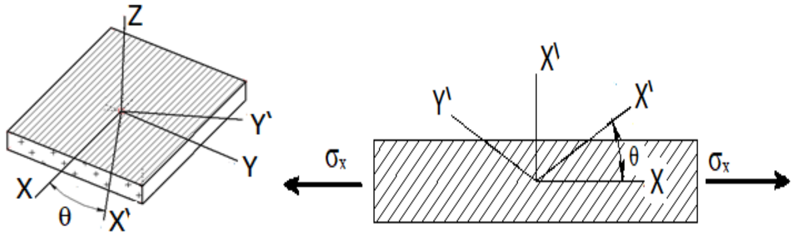


Fig .4. The location of waves in spatial fibers

In [4, 5], a method for testing spatial fiber structures with various components and in the presence of defects is described. The formation of the wave configuration of fibers in such materials can have both negative and positive effects on the properties of composite materials. In [6], a theoretical and practical search is conducted. It considers the nonlinear behaviour of composite materials reinforced with unidirectional fibers, in which waves are observed that arise under the action of tensile loads and pressure.

The work objective is to study the effect of waves on the tensile strength of a composite material consisting of polyester and fiberglass, to analyse the arising stresses, and to study the destruction of the sample due to various factors.

Analytical research. A composite material with a long-fibered filler can resist heavy load acting along the fibers, which follows from Fig. 5, *a*. However, a load that does not correspond to the direction of the fibers is distributed between them and the binder. This load depends on the angle between the direction of its action and the direction of the fiber orientation. To determine the stresses acting perpendicular to the fiber and along it, the authors used the coordinates obtained by rotating the x-y-z general coordinates by an angle θ about the z axis [7] (Fig. 5, *b*).



a)   *b*

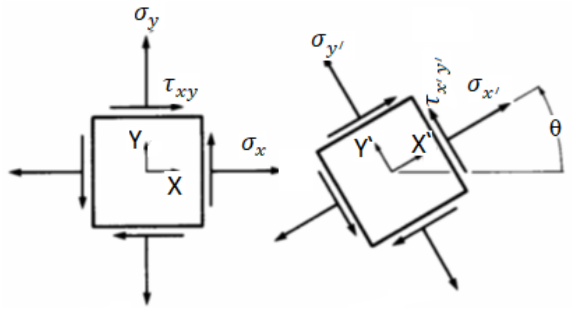
Fig .5. Interlocal coordinates of material plates: *a*) with straight fibers, *b*) with fibers at an angle.

If an infinitesimal volume element (Fig. 6, *a*) is removed from the general coordinates and rotated through an angle θ, then, using equations (1), (2) and (3), we can determine the normal and tangential stresses developed in the new position (Fig. 6, *b*) [8].

$$\sigma_{x'} = \frac{\sigma_x+\sigma_y}{2} + \frac{\sigma_x-\sigma_y}{2}\cos 2\theta + \tau_{xy}\sin 2\theta, \tag{1}$$

$$\tau_{x'y'} = -\frac{\sigma_x-\sigma_y}{2}\sin 2\theta + \tau_{xy}\cos 2\theta, \tag{2}$$

$$\sigma_{y'} = \frac{\sigma_x+\sigma_y}{2} + \frac{\sigma_x-\sigma_y}{2}\cos 2\theta - \tau_{xy}\sin 2\theta. \tag{3}$$



a)   *b*)

Fig. 6. Stresses of an infinitely small volume element:

a — in the general coordinate system, *b*) in the coordinate system at an angle

In the case of the wave configuration of the fibers, the stress state of the material is most dangerous at the maximum value of the angle (θ_{max}) since normal stresses are oriented perpendicular to the layer of the reinforcing filler. If we consider an infinitesimal element in this state (Fig. 7), then after calculating the stress values from equations (1), (2), (3) and comparing their values, we can establish causes of the sample failure.

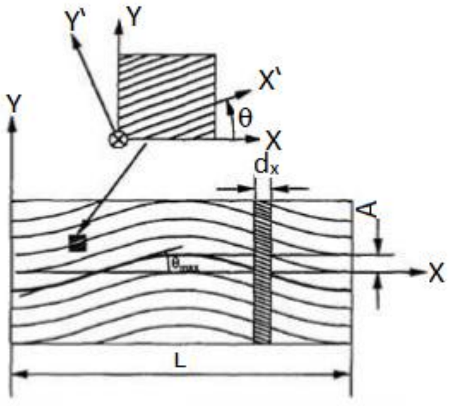


Fig.7. Infinitely small volume element at the point of maximum fiber inclination angle (θ_{max})

Materials and Methods. The influence of the wave impact on the tensile strength was studied according to *ASTM D* 638-90 [9]. Samples of sheet form made of polymer composites containing a reinforcing filler (fiberglass) and a binder (polyester) were tested; the hardener content was 2% of the total volume. Samples were prepared through the gravity die casting [10]. At that, a template consisting of glass plates with dimensions 38 × 25 × 6 mm, which contained 10 layers of fiberglass was employed; and cellophane layers were used as a buffer to prevent adhesion.

During the molding process, a small vibration was used for five minutes. Exposure for curing in the form was for 24 hours. Exposure to stabilize the structure and properties of the samples in a free state before testing was 25 days. Using special boards, samples were made without waviness and with the wave orientation of the filler. Moreover, the latter differed from each other in wave amplitude. Fig. 8 shows the formation of waves in a single board.

Fig. 8. Single Board Wave Formation

Results and Discussion. Tensile tests were carried out for samples with fibers without waviness and with fibers having a sinusoidal half-wave shape at angles of inclination: θ_{max} = 10°, 18°, 22°, 28° and 38°. The stability of the test results was established through their mutual comparison for samples without filler waviness made on five different boards. Fig. 9 shows a curve of the tensile stress variation with a change in the angle of inclination of the fiber. In this case, the tensile stress σ_{max} for a material with waveless fibers was 250 MPa.

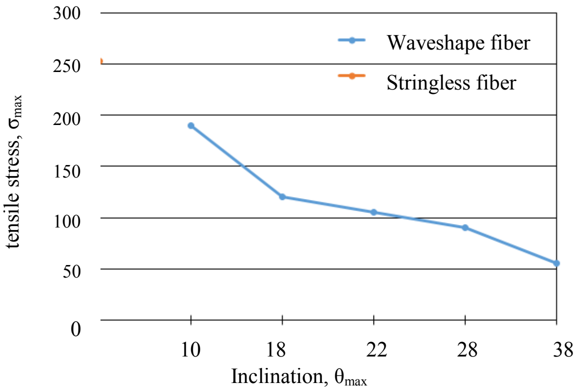


Fig. 9. Curve of variation of maximum tensile stresses σ_{max} with increasing fiber angle θ_{max}

Using the equations (1) and (3), the normal and tangential stresses acting perpendicular to the fibers, as well as the stresses of the layered material under shear, were calculated according to the equation (2).

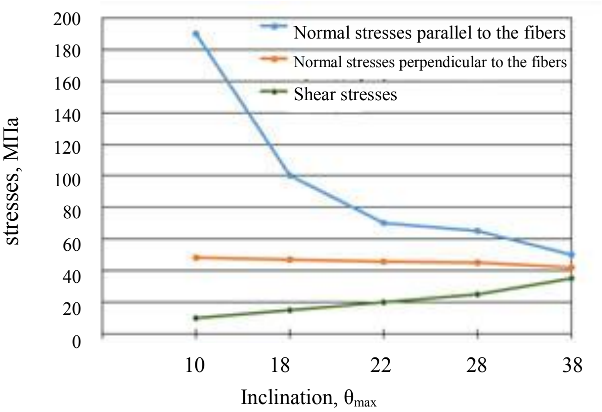


Fig. 10. Curves of changes in the angles of inclination of the wave θ_{max} with normal stresses parallel to the fibers σ_x and normal stresses perpendicular to the fibers σ_y, as well as shear stresses at shear τ_{xy}.

As a result of the analysis of dependences for the characteristic tensile stresses in the point position with the inclination of fibers θ_{max} and the study on the area of fracture of the samples (Fig. 11), it was established that the shear stress τ_{xy} is the cause of the fracture. Comparison of this stress with the maximum shear stress of the sample of polyester without fibers is given in [10]. The yield strength (σ_t) was taken equal to 70 MPa. Using the equation (2), which provides compensation for the angle of inclination θ = 45°, it was found that the shear stress of the polyester is $\tau_{hu} = 35$ MPa. This is the stress that subsequently caused the destruction of all samples. The equation (2) enables to determine the deformation of the samples at the breaking point, and also displays deformations and angular displacements proving that the destruction of the layered material is a consequence of shear stresses.

Fig.11. Refraction in the fracture section

Conclusion. Based on the research results, the following conclusions can be drawn:

1. The tensile stresses of the composite material decrease with increasing the angle of inclination of the fibers in certain areas. The result showed a coincidence with the earlier studies [11, 12].

2. It was established that the destruction of all fibrous samples occurred upon reaching a shear stress approximately equal to the shear stress at which the samples made only from a binder were destroyed. This is in agreement with [13, 14], the data differed only in respect of the stresses developing in the bonding material.

3. When the sample ruptures, the fracture form is similar to shear fracture, and at the moment of fracture, the rectangular object, being deformed at an angle, took the form of a parallelogram.

4. It is recommended to continue research in this area, the key objectives of which should include studying the effect of smaller fiber pulsation angles on the tensile strength of a composite material, as well as investigating the influence of the wave effect on the flexibility coefficient.

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