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Laminar polymer composites for wooden structures

Слоистые полимерные композиты для деревянных конструкций

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Ключевые слова: слоистые полимерные композиты; стеклоткань; стеклопластик; отверждающая матрица; клеевая композиция; деревянные конструкции; сжато-изгибаемые элементы; контактное формование; вакуумная инфузия

Abstract. The lack of a clear regulatory framework governing the use of polymer composites to strengthen wooden structures, stimulates the conduct of numerous studies in this area. An important task is to obtain reinforcing materials with the best physico-mechanical and operational parameters. The choice of the type of curing adhesive has a great influence to characteristics of polymer composites such as viscoelastic parameters of the material, adhesion properties on the contact surfaces, the presence of internal defects, etc. The paper describes a method for determining the physicomechanical characteristics of a composite material based on experimental studies. The stand, test samples and the pattern array of tensometric sensors for testing according to Russian State Standard GOST R 56800-2015 "Polymer composites. Determination of tensile properties of unreinforced and reinforced materials have been presented. Dependences of stress-strain, modulus of elasticity, Poisson's ratio, tensile strength for laminate polymer composite have been obtained. Comparative analysis of the obtained results for various adhesive compositions has been performed. According to the results of experimental studies, it was found that the physicomechanical characteristics of polymer composites based on epoxy matrix are higher than those of polyurethane matrix composites due to uniform filling of the filler volume, as well as better wettability of the reinforcing fibers. In conclusion, the article draws conclusions about the effect of the adhesive composition on the mechanical characteristics of the obtained composites have been made, relevance and applied significance of the investigation for strengthening the compressed-flexural elements of wooden structures has been justified.

Аннотация. Отсутствие четкой нормативно-правовой базы, регулирующей возможность применения полимерных композитов для усиления деревянных конструкций, стимулирует проведение многочисленных исследований в данной области. Важной задачей является получение армирующих материалов с наилучшими физико-механическими и эксплуатационными параметрами. Большое влияние на характеристики полимерных композитов оказывает выбор типа отверждающей клеевой матрицы, от которого зависят вязкоупругие параметры материала, адгезионные свойства по контактным поверхностям, наличие внутренних дефектов. В работе описана методика определения физико-механических характеристик композитного материала на основе экспериментальных исследований. Представлен стенд, испытательные образцы и схема расстановки тензометрических датчиков для проведения испытаний по ГОСТ Р 56800-2015. Получены зависимости «напряжения – деформации», значения модуля упругости, коэффициента Пуассона, прочности при растяжении для слоистых полимерных композитов. Выполнен сравнительный анализ полученных результатов для различных клеевых композиций. По результатам экспериментальных исследований установлено, что физико-механические характеристики полимерных композитов на основе эпоксидной матрицы выше, чем у композитов на основе полиуретановой за счет равномерного заполнения объема наполнителя, а также лучшей смачиваемости армирующих волокон. В заключении сделаны выводы о влиянии клеевой композиции на механические характеристики полученных композитов, обоснована актуальность и прикладное значение исследований для усиления сжато-изгибаемых элементов деревянных конструкций.

1. Introduction

Development of the building science at present and in the foreseeable future is inseparably linked with the trends towards the efficient use of resources, the reduction of the material consumption of structures, elements and units, increasing their operational reliability while reducing labor costs for production and installation. Dynamic development of non-traditional structural materials based on glass, carbon and aramid fabrics, improvement and cheapening of technology for their production opens up a wide range of applications of strengthening for wooden elements of building structures. Combination of high mechanical and performance characteristics, low weight of composite materials in comparison with traditional ones, such as steel and concrete, simplicity of erecting in the construction conditions, mainstreams the use of composites in large reinforcement volumes for different purposes [1–5]. At the micro level, composite polymeric materials consist of two or more components. A continuous component is called a matrix, and the reinforcing is called a filler. The mechanical characteristics of the composite are largely determined by the reinforcing material, and the role of the matrix is reduced to a uniform transfer of forces between the filler fibers, so it must have some specific characteristics: to have low viscosity and high wettability of the filler surface, to create strong adhesion bonds with the reinforcing material at the interface, provide a continuous environment without pores, shells, voids, acting as stress concentrators.

A large amount of research is devoted to the strengthening of wood bent elements with canvases, fabrics, lamellae and laminates [6–21]. The use of reinforcing material in the stretched zone of elements allows reducing the effect of wood flaws, making full use of its strength characteristics. Carbon fiber-based fillers have the best physicomechanical characteristics, but the widespread use of this material is constrained by its high cost. The cheapest replacement of the latter is fiberglass. Composite material based on it (GFRP) has a tensile strength comparable to the tensile strength of pure wood, which will maximize the use of its physico-mechanical characteristics when reinforcing wooden bending elements in the stretched zone. The following reinforcement schemes for wooden elements are possible depending on the type of the material used:

1. The use of laminate composites obtained by impregnating glass, carbon or aramid fabrics under construction site conditions (GFRP, CFRP, AFRP).

2. The use of laminate material – half-finished composite materials presenting a fabric or tape made of fibrous material, pre-impregnated and cured by polymer compositions at the factory.

The advantage of the first scheme is the reinforcement cost reduction due to a more flexible approach in the selection of reinforcing material and polymer compounds for solving specific engineering problems. Materials obtained at the factory have higher performance due to the advanced production technology.

The technological process of impregnation and gluing the laminate polymer composites to the surface of reinforced elements has a significant effect on the mechanical characteristics of the resulting composite materials. The simplest method of preparation is contact molding. The method consists in lamination of the curative composition and reinforcing fibrous material with further impregnation to achieve the required reinforcement coefficient of the structure. In this case, each layer is compacted, leveled, the air bubbles are removed, the non-glued areas are eliminated. The disadvantage of the technology lies in the uncontrolled increase in the volumetric weight of the curative polymer in the composite that significantly degrades its mechanical and performance characteristics.

The resin content of this technology can significantly exceed the reinforcing material volume content that has adverse effects on the actual work of the reinforcement elements and leads to a significant overconsumption of materials.

The second method of producing laminated polymeric composites is the method of vacuum infusion (vacuum bag). The technology is based on the creation of a leak-proof working space with reinforced material embedded in it internally, by which a polymer curing compound is injected by means of preliminary atmospheric desaturation. Mechanization of the working process is provided, the negative influence of the human factor is reduced, the labor intensity and the duration of work are reduced significantly, and the release of harmful substances into the environment is reduced in comparison with the contact method. In turn, the content of the curative glue mould is minimal (it is up to 40 % of the volume of the reinforcing material in industrial methods), which allows to achieve high physical-mechanical and operational properties of the laminate polymer composite.

The question of determining the mechanical characteristics of polymer composites and the effect of the curing matrix has been taken up since the beginning of their mass introduction, occurring in the second half of the 40s of the 20th century. The main field of application of structural composite materials for a long time remained the space and aviation industries, and the molding of composites was carried out in the factory with the proven technology of obtaining them. Since the 80s, thanks to the accumulated experience in design, calculation, and a large volume of experimental studies, a wide application of polymer composites in the construction industry has begun. An important advantage along with high specific modulus of elasticity and specific strength of composite materials is the possibility of their application "locally", directly on the construction site, which reduces the laboriousness of the work, reduces the weight of the reinforcement elements.

Evaluation of the strength of polymer composites is a multifaceted task L.J. Broutman, C.C. Chamis, A. Kelly, J.O. Outwater, P.I. Zubov, S.L. Shreiner, L.I. Lepilkina, studied the effect of adhesion properties on the matrix-filler interface etc. The works devoted to the theory of viscoelastic operation of polymer composite materials were published by B.W. Rosen, G.K. Shmitz, K.H. Boller, A.Ya. Malkin, G.M. Bartenev, A.V. Zakharenko etc. At present, a large volume of research of composite materials is devoted to viscoelastic operation of multilayer plates based on matrix equations using the theory of hereditary damage accumulation [22–29]. Matrix and filler are paid special attention to joint work of the matrix and filler, and the use of new materials leads to the need for updating and refining existing knowledge on the example of specific engineering problems.

The lack of normative documentation in the field of using composite materials to strengthen wooden structures, in contrast to reinforced concrete, where a large number of inter-industry standards and the main document in the person of JV 164.1325800.2014 "Strengthening of reinforced concrete structures with composite materials", actualizes further studies and generalization of existing experience in this issue. In addition, the joint work of composite materials and wood is a difficult task both because of the anisotropy of the wood and due to the presence of pronounced rheological properties of the materials.

The study of the stress-strain state of compressed-bent elements reinforced with composite materials is a complex task, the solution of which must be done step-by-step. The aim of the presented study is to determine the physical and mechanical properties of glass-fiber laminate composites, as well as to study the degree of influence on the temporary strength and modulus of elasticity of the curing matrix of widely used polyurethane and epoxy adhesives in contact molding of the composite. To achieve this purpose, it is necessary to solve a number of tasks:

1. Perform short-term tests of samples according to Russian State Standard GOST 56800-2015 "Polymer composites. Determination of tensile properties of unreinforced and reinforced materials" on the basis of glass fiber cloth T-13, matrix of epoxy glue "ED-20" and polyurethane adhesive "Laprol PP-3152"

2. Carry out the processing of the results and plot the stress-strain curves for the samples obtained.

2. Methods

To simulate the real behavior of wooden structures reinforced with composite materials, it is necessary to carry out a complex of numerical and laboratory investigations. The actual values of the mechanical characteristics of the laminated polymer composites are obtained after tensile tests of the check samples in accordance with GOST 56800-2015 "Polymer composites. Determination of tensile properties of unreinforced and reinforced materials" or GOST 25.601-80 "Design calculation and strength testings. Methods of Mechanical testing of Polymeric Composite Materials Test for Tensile Properties on Plane Specimens at Normal, Elevated and Low Temperatures". Elastic modulus, Poisson's ratio, ultimate tensile strength are determined, stress-strain diagrams are constructed.

The article is devoted to the influence of curative glue mould type and the molding method on the mechanical characteristics of the laminate polymer composite. The structural fiberglass T-13 in the amount of 15 layers has been used as a reinforcing material and a two-component epoxy ED-20 resin with polyethylene polyamine hardener and a one-component polyurethane adhesive Laprol PP-3152 as a glue mould. Samples are carried out by the contact molding according to GOST 56800-2015. The mould type based on the epoxy resin ED-20 meets the manufacturability requirements, preparation simplicity and cheapness. In turn, performance factors can be increased by adding dibutyl phathalate plasticizing agent or slate modifier slamor to the composition. The second is a surperficially active substance that increases the wetting properties of epoxy compositions, reduces the cost of the hardener by 15–20 %, significantly reduces the initial viscosity thus improving the composition penetrating properties, herewith being more affordable and cheaper than its counterpart. One-component polyurethane adhesive Laprol PP-3152 does not require preparatory work, the introduction of additional plasticizers and additives. The composition is cured by moisture from air and wood. However, when forming the prepregs on this glue basis, the mould curing occurs unevenly, an airtight layer of the cured resin and glass fabric is formed in the edge zones making further polymerization of the sample difficult. Among other things, the volume of the adhesive composition increases significantly due to "swelling" during curing, microbubbles of air appear in the adhesive seam disrupting the prepreg homogeneous structure, thereby reducing its strength and deformation characteristics. Two series of 5 samples in the form of rectangular cross section blades in each have been mold as part of the investigation. The blades dimensions are shown in Figure 1. Holes in which steel short shoots have been installed during the tests have been made at the end sections of the sample-blades, preventing reduction in the cross section during compression of the locking grips and further destruction of the sample. Resistive strain sensors have been installed in two mutually perpendicular directions to determine the relative deformations in the middle part of the sample (Figure 2). Strain sensors with a base of 20 mm, transverse sensors with a base of 5 mm have been used to measure the relative longitudinal strain. Before beginning the test, the samples are labeled, the thickness and width of the sample working part are measured at three points: at the edges and in the middle to an approximation of 0.025 mm, then the average value of each parameter is calculated and used in the calculations.

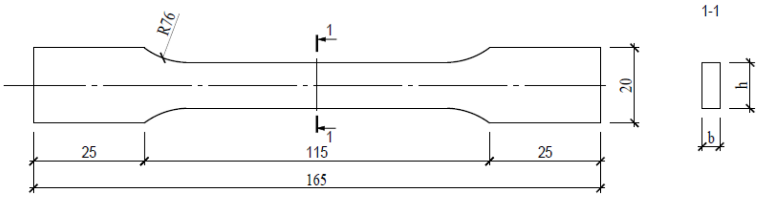


Figure 1. Flat sample for tensile tests in accordance with GOST 56800-2015

As a bench testing the REM-100 tensile machine has been used. Loading speed has been 5 ± 25 % mm/min. The following mechanical characteristics of the laminate polymeric composites have been determined during the tests: elasticity modulus, tensile strength, strain yield or conditional strain yield, breaking extension, yield point elongation, Poisson's ratio.

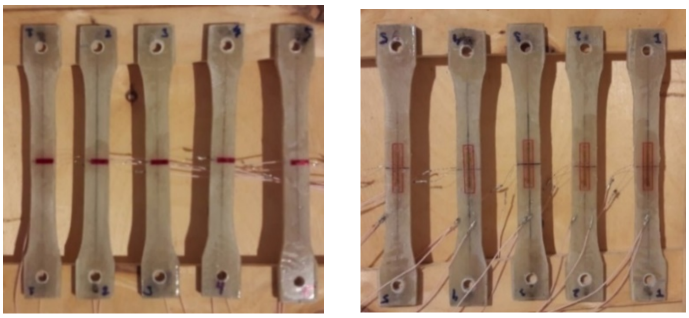


Figure 2. General view of the blades samples for tensile tests with installed strain sensors

The Poisson's ratio ν has been determined by the formula:

$$\nu = \frac{\Delta\varepsilon_{II}}{\Delta\varepsilon_{II}}, \quad (1)$$

where $\Delta\varepsilon_{II}$ is the change of the relative transverse strain of the sample when the voltage is changed by $\Delta\sigma$, $\Delta\ \varepsilon_I$ is the change in the relative longitudinal strain of the sample when the voltage is changed by $\Delta\sigma$. The values, in turn, have been determined by the strain sensors indications [30].

3. Results and Discussion

The initial data and test results of two series of samples on the laminate curative mould from epoxy resin ED-20 and polyurethane adhesive Laprol PP-3152 have been presented respectively in Tables 1 and 2.

Table 1. The initial data and test results of series of samples on the laminate curative mould from epoxy resin ED-20

Woven fiberglass T13 – 15 layers, mould – two-component epoxy resin ED-20							
Sample number	Section width b, mm	Cross-sectional hight h, mm	Working zone cross sectional area, mm^2	Tensile strength yield $\sigma_в$, MPa	Conditional strain yield ε_p,%	Elasticity modulus E, GPa	Poisson's ratio ν
I	13.4	5.7	76.38	225.86	16.45	15.30	0.1
II	13.1	6.1	79.91	216.94	16.15	15.86	0.1
III	13.5	5.7	76.95	227.91	16.41	14.11	0.1
IV	13.3	5.9	78.47	203.99	16.42	13.49	0.1
V	13.1	5.8	75.98	215.63	16.90	12.91	0.1

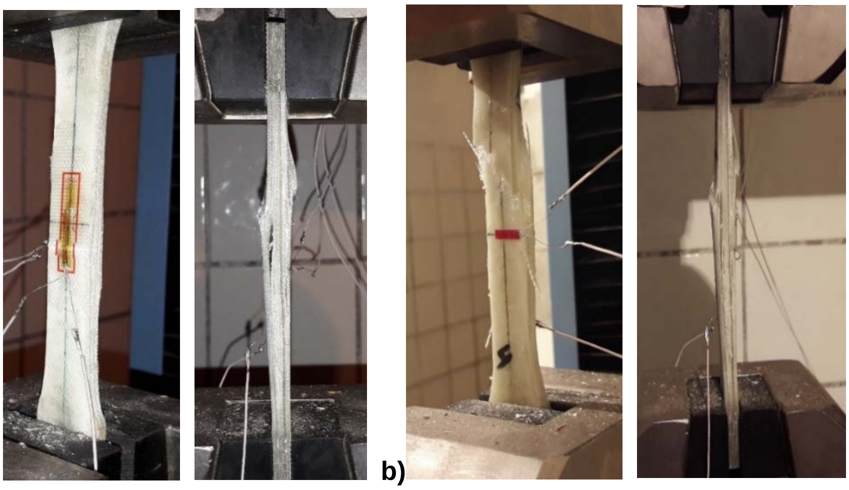
Table 2. The initial data and test results of series of samples on the laminate curative mould from polyurethane adhesive Laprol PP-3152

Woven fiberglass T13 – 15 layers, polyurethane adhesive Laprol PP-3152							
Sample number	Section width b, mm	Cross-sectional hight h, mm	Working zone cross sectional area, mm^2	Tensile strength yield $\sigma_в$, MPa	Conditional strain yield ε_p,%	Elasticity modulus E, GPa	Poisson's ratio ν
I	13.3	6.3	83.79	125.75	19.80	8.11	0.2
II	13.3	6.8	90.44	125.94	23.26	6.13	0.2
III	13.3	6.7	89.11	1143.0	17.62	8.41	0.2
IV	13.2	7.3	95.92	86.26	14.71	5.72	0.2
V	12.9	7.1	91.59	114.64	21.68	5.99	0.2

The destruction of the samples was brittle and occurred in the calculation zone. The integrity of the prepregs in the grips was ensured until the destruction.

The fragile nature of fracture with matrix shift, according to the studies of F.M. Ernsberger, points at weak adhesion of the matrix of polyurethane glue "Laprol PP-3152" and filler made of glass fabric T-13 and destruction along the interface, which significantly reduces the strength of the composite as a whole. In turn, the samples of the first series collapsed brittle with pulling out of the fibers, which is preferable from the point of view of the working conditions of the composite material.

The nature of the destruction of the samples is shown in Figure 3.



a) **b)**

Figure 3. Brittle fracture patterns: a – the first series with pulling out the fibers, b – the second series with shear failure of the matrix

Diagram of the stress-strain relationship for two series of blade patterns is shown in Figure 4. To achieve the correct values of mechanical characteristics, the section must be corrected to obtain a zero point, with allowance for the strain axis or the elongation axis. The point of intersection N is a point of zero strains with a fulfilled correction, from which all elongations or strains, including plastic yield of NQ_1, NQ_2, are to be calculated. The longitudinal elastic modulus can be calculated by dividing the stress at any point on the straight line Q_1D_1, Q_2Q_2 by the strain at the same point (measured from point N) [30]. According to the test results, it has been found that the elasticity modulus and the tensile strength of a series of samples on the epoxy resin ED-20 curative mould is twice as high as that of samples on a polyurethane adhesive Laprol PP-3152. Point D2 characterizes the onset of shear deformation in the matrix for the second series of samples. The relative conditional strain yield of the samples before destruction is 16–20 %. On-line tests of samples by standards allow to obtain the true values of the composite materials mechanical characteristics, however from the point of view of trial design they are quite laborious, long and, in the case of expensive materials, economically impractical. In this case, the following formulas have been used for the preliminarily evaluation of the materials elasticity modulus:

$$E = E_f V_f \cdot E_m V_m$$
$$V_f + V_m = 1, \quad (2)$$

Where E_f, V_f are the modulus of elasticity respectively, the tensile strength yield, and the volume ratio in the reinforcing fiber composite, E_m, V_m is the same for the curative polymer.

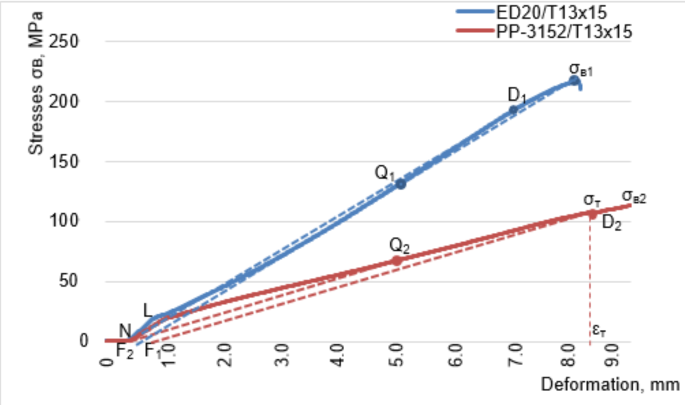


Figure 4. Diagram of the stress-strain relationship for two series of blade patterns

To evaluate the obtained results and to confirm the analytical system formulas (2), mathematical calculations of mechanical characteristics have been carried out. Recognized – Russian State Standard, technical conditions, material certificates allow to mark out all the initial data for calculation sufficiently. Glass fibre of E glass type with elasticity modulus of 76–78 GPa, intertwined with each other in larger fibres (rovings) have been used in the structural glass fabric T-13 for warp threads. Fiberglass has a linen weaving with 16 pieces of warp threads per 1 cm. The number of warp threads per sample width of 13.9 mm is:

$$(16/10) \cdot 13.9 = 22 \text{ pcs.}$$

15 layers of the sample fiber glass contain:

$$22 \cdot 15 = 330 \text{ warps.}$$

The trade mark of the warp yarn is EC7 54x2, where 54 denotes the linear density of the yarn in tex. Tex is a non-system unit of linear density, used in the textile industry because of the difficulty in determining the rovings diameter, denotes the weight of 1 g of warp 1 km in length. Sections of the operating area 50 mm long have been cut out and weighed after testing the samples. The average mass of the operating area has been 5.95 g for the first batch of samples and 6.3 g for the second. The weight of all warps has been determined within the operating area of 50 mm in length:

$$0.000054 \text{ g / mm} \cdot 50 \text{ mm} \cdot 330 \text{ pts} = 0.891 \text{ g.}$$

At the final stage, we have determined the volume content of the reinforcing material and mould in the prepreg:

$$V_f = 0.891/5.95 = 0.149,$$

for the curative mould respectively

$$V_m = 1 - 0.149 = 0.850.$$

The elastic modulus of the epoxy resin ED-20 has been obtained by the compressive test of the samples adhesive composition and is 2.54 GPa. Then the modulus of elasticity of the laminate polymer composite is

$$\mathrm{E} = 78 \cdot 0.149 + 2.54 \cdot 0.850 = 14.23\ \mathrm{GPa}.$$

The discrepancy between the results and in-place tests is:

$$(14.33 - 14.23) \cdot 100\% / 14.33 = 0.69\%.$$

The high convergence of the theoretical data with the experimental results shows the adequacy of the model of viscoelastic deformation of glass-fiber composites proposed by Rosen. The results obtained may indicate a significant effect of the type and amount of the adhesive curing matrix in the layered polymer composite on its mechanical characteristics. In turn, the method of forming prepregs is often not taken into account when simulating the actual operation of reinforced wooden structures. The value of the modulus of elasticity of a layered polymer composite in numerical studies is taken without taking into account the effect of the type and amount of the curing matrix, which leads to a discrepancy between the calculation results and experimental studies. Further research should be aimed at improving the technology of producing layered polymer composites in structural conditions. The production of composites with high physical and mechanical characteristics opens the possibility of significantly reducing the material consumption of building structures with a low weight of the reinforcement elements. In turn, the workability of the work actualizes the use of composite materials at large volumes of reconstruction of buildings.

4. Conclusions

Based on the tests results the following conclusions and recommendations can be made:

1. The laminate polymer composites on the base of woven fibre glass obtained by the contact molding method have insufficient mechanical characteristics for use as wooden structures reinforcement with considerable reinforcement ratio. The prepregs elasticity modulus in tension (14.33 GPa) is commensurate with the analoguos value for the 2nd grade of wood (10 GPa) that is not enough to achieve high rigidity indicators in the work of wooden structures flexural and compressed-flexural elements. In turn, the low value of the laminated polymeric composites elasticity modulus is conditioned by the uncontrolled increase in the bulk density of the polymer curative composition. This disadvantage is leveled out by the transition to a more advanced production technology to the method of vacuum infusion.

2. Low values of mechanical characteristics for the second series of samples on the base of the polyurethane adhesive Laprol PP-3152 curative mould are associated with the irragulation of the molding technology, problems with the adhesive polymerization and its increase in volume as a result of "bloating" during curing. It is necessary to carry out molding by the narrow width 200 mm tape tools because of the negative influence of the above mentioned factors, therewith it is necessary to load the samples upper plane by pressure similar to the analogous glued wooden structures technologies (0.3-0.5 MPa). In this case, the excess of the adhesive composition as a result of the volume increase during the polymerization process does not lead to a significant increase in the bulk density of the curative mould.

3. The samples destruction is of a fragile nature without a significant strain increase in (relative elongation 16.47–19.41 %), the composite material strain character is elastic, the plastic deformation zone is either absent (1 series) or slightly expressed (2 series).

4. The analytical method for determining the elasticity modulus is sufficiently precise for the materials preliminary analysis for the production of the laminate polymer composites.

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