CFRP composites for strengthening wooden structures

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Abstract. The purpose of this work is to study the strength of wooden beam structures with local modification of wood in the compressed zone. To achieve this goal, the physical and mechanical characteristics of modified wood were determined using modifiers based on ed-20 epoxy-diane resin, urea-formaldehyde resin, and dimethacrylic polyester. The best physical and mechanical characteristics were obtained for samples using dimethacrylic polyester: the ultimate strength was 84 MPa, the elastic modulus was 21 GPa. The increase in strength compared to solid wood was 46%, and the increase in the modulus of elasticity was 54%. Tests of beam structures with a span of 4.5 m and a cross section of 100x200 mm with local modification of wood in the compressed zone with a polymer composition based on dimethacrylic polyester were carried out. The increase in the strength of beams with local modification in the compressed zone compared to solid wood was 11% within the design loads, and the increase in stiffness by 18%. The "load-strain" relationships are constructed based on the test results. It is established that the greatest effect can be achieved when using external reinforcement systems together in a stretched zone by reducing the influence of defects and defects in beam structures and local modification of the extremely stressed compressed zone.

1. Introduction

One of the important tasks in addition to the development of new wooden structures is to ensure the failure-free operation of existing elements. Structures with defects that reduce their load bearing capacity require reinforcement. The traditional methods of reinforcing wooden structures include methods of increasing cross-sections in extremely stressed zones [1-6]. In cases where the dimensions of the cross-sections of elements and the construction height of structures are limited, the strengthening of elements is performed by external reinforcement systems. The most common reinforcement systems are based on sheet or shaped rolled products [7-10]. The disadvantages of the method include low corrosion resistance of reinforcement elements and the need for additional measures to prevent the corrosion process. The use of steel or composite reinforcement in wooden elements in construction conditions is difficult due to the complexity of the technological process of selecting longitudinal grooves for gluing rods [11-19]. The most technological ways to strengthen wooden structures is the use of composite external reinforcement systems. The advantages of the method include ultra-small dimensions of reinforcement systems with their high strength and rigidity, high resistance to aggressive media. Currently, research is actively developing aimed at finding new compositions of composite materials for structural purposes and developing technologies for their production [20-22]. Polymer composites based on glass [23-27], aramid [28] and carbon fibers [25-37] are promising as a reinforcing material for strengthening wooden
The main disadvantages of glass and aramid fibers include creep, hygroscopicity, low resistance to ultraviolet light, and lower physical and mechanical characteristics compared to carbon fibers.

An important task for the correct design of composite external reinforcement systems is to determine the actual physical and mechanical characteristics of the polymer composite, depending on the reinforcing materials used and the polymer matrix. Thus, manufacturers usually normalize physical and mechanical characteristics for elementary fibers (filaments). However, using a polymer matrix, the physical and mechanical characteristics of a polymer composite can vary significantly and require clarification in each case. In the process of loading with a unidirectional reinforcing material (filler), the acting forces are perceived, the role of the matrix is to redistribute the stresses between individual fibers. When the matrix of unidirectional composite systems is destroyed, the latter is completely excluded from operation. The use of bi-directional carbon belts prevents the destruction of the polymer composite matrix, but reduces the modulus of elasticity and physical and mechanical characteristics of the polymer composite as a whole by using fewer reinforcing fibers along the acting force [38]. Along with the reinforcing material, the choice of polymer matrix plays an important role. It should evenly wet individual fibers, have a continuous structure that excludes pores, cavities and other defects. To reduce the viscosity and improve wettability, various diluents are introduced into the polymer compositions. Depending on the amount of diluent used, the microstructure of the polymer composite matrix can change significantly. Summarizing the above, the task of studying the microstructure of polymer composites and obtaining their actual physical and mechanical characteristics is an urgent task.

The purpose of this work is to determine the physical and mechanical characteristics and the nature of destruction of polymer composites based on carbon fiber, depending on the type of filler and polymer matrix.

The object of research is polymer composites based on unidirectional carbon tape, bidirectional carbon fabric and polymer matrix based on ed-20 epoxy-Diane resin.

The subject of research is the stress-strain state of polymer composites with a filler of unidirectional carbon tape and bidirectional carbon fabric on a polymer matrix.

To achieve this goal it is necessary to solve a number of tasks:
1. To investigate the structure of polymer composites based on carbon fiber depending on the amount of diluent used for the polymer matrix.
2. To determine the physical and mechanical characteristics and the nature of destruction of polymer composites under study, depending on the type and amount of reinforcing material.

2. Methods
To determine the physical and mechanical characteristics of polymer composites by vacuum infusion, 6 series of 5 samples were formed in each. Each series differs in the type and number of layers of filler. The matrix used a composition based on ed-20 epoxy resin of the following composition: 100 mass parts of epoxy-Diane ED-20, 15 mass parts of the hardener polyethylene-polyamine, 15 mass parts of the plasticizer dibutyl phthalate, 5 mass parts of acetone.

The process of forming polymer composites by vacuum infusion can be divided into several stages: the preparatory stage, the polymerization stage, and the mechanical processing stage. In the preparatory stage, the base is processed with a separation compound. A layer of sacrificial fabric is laid out for partial selection of the polymer matrix from the lower face of the reinforcing material. A filler with the required number of layers of unidirectional carbon tape or bidirectional carbon fiber is laid and a uniform application of a polymer matrix based on ed-20 epoxy resin is performed over the entire surface. A layer of sacrificial fabric is laid out for the subsequent separation of the composite from other consumables. A drainage polyester material is laid to remove the excess matrix from the composite, the vacuum line is equipped and the contour is sealed using a high-temperature sealing harness and a vacuum film. At the second stage, air is pumped out of the vacuum bag and the matrix is polymerized in a cold way. To speed up the process and to obtain higher physical and mechanical characteristics of the matrix, it is recommended to use additional heating of the workpieces at a temperature of 70°C for
2-2. 5 hours. At the final stage, the resulting composite plate is mechanically cut into separate samples for testing. The general view of the obtained samples is shown in figure 1.

![Figure 1. General view of samples of polymer composites: a) from a bidirectional carbon fabric; b) from a unidirectional carbon tape.](image)

At the stage of development of technological modes for forming polymer composites and obtaining optimal polymer matrix compositions, a batch of polymer composites made of bidirectional carbon fabric was subjected to non-destructive testing based on x-ray computed tomography methods using the Phoenix x-ray (General Electric) tomography systems and software packages datosx, VGStudioMax and myVGL. Visualization of the composite based on the results of the study is shown in figure 2. According to the results of research, the porosity of samples with an increased content of acetone for parts was 15%, with the content for 5 mass parts, respectively, 3%. The heterogeneity of the matrix leads to the appearance of internal stress concentrators, reducing the strength of the polymer composite as a whole.

Determination of physical and mechanical characteristics of polymer composites for tensile strength was performed according to the normative documentation. The REM–100–A–1 breaking machine was used as a testing machine. The speed of movement of the grippers was set in the range of 5-20 m/min. to determine the modulus of elasticity, the sample was cyclically loaded within the elastic zone of the material, and the change in longitudinal deformation was measured. To determine the strength limit, the samples were uniformly loaded at a given speed up to destruction.

![Figure 2. a) General view of the microstructure of the surface and cross-section of a polymer composite based on bidirectional carbon fabric and polymer matrix based on ED-20; b) Sample of a polymer composite made of bidirectional carbon fabric and polymer matrix ED-20 with a diluent in the amount of 15 mass parts; c) the same, with a diluent in the amount of 3 mass parts.](image)
3. Results and discussion
The test results of samples made of bidirectional carbon fabric and unidirectional carbon tape on a polymer matrix made of ED-20 are presented in tables 1 and 2, respectively.

Table 1. Initial data and test results of polymer composites based on bidirectional carbon fabric.

| Series and № | The type of filler, the number of layers | Section bxt, mm | P, kN | Rσ, MPa | E, GPa | μ |
|--------------|----------------------------------------|-----------------|-------|---------|--------|---|
| UT-1-1       | Carbon fabric 0°/90°;3К, one layer      | 23.8x 0.51      | 3.6   | 302.1   |        |   |
| UT-1-2       | Carbon fabric 0°/90°;3К, one layer      | 24.1x0.53       | 4.0   | 315.9   | 10.22  | 0.2|
| UT-1-3       | Carbon fabric 0°/90°;3К, one layer      | 24.3x0.52       | 3.9   | 314.4   |        |   |
| UT-1-4       | Carbon fabric 0°/90°;3К, one layer      | 23.6x0.51       | 3.6   | 299.1   |        |   |
| UT-1-5       | Carbon fabric 0°/90°;3К, one layer      | 23.9x0.53       | 3.7   | 295.0   |        |   |
| UT-2-1       | Carbon fabric 0°/90°;3К, two layers     | 23.8x0.81       | 5.8   | 301.9   |        |   |
| UT-2-2       | Carbon fabric 0°/90°;3К, two layers     | 23.9x0.82       | 6.1   | 315.4   |        |   |
| UT-2-3       | Carbon fabric 0°/90°;3К, two layers     | 23.9x0.81       | 5.6   | 293.0   |        |   |
| UT-2-4       | Carbon fabric 0°/90°;3К, two layers     | 24.0x0.83       | 5.9   | 297.7   |        |   |
| UT-2-5       | Carbon fabric 0°/90°;3К, two layers     | 23.3x0.84       | 6.1   | 313.0   |        |   |
| UT-3-1       | Carbon fabric 0°/90°;3К, three layers   | 24.1x1.18       | 8.3   | 294.5   |        |   |
| UT-3-2       | Carbon fabric 0°/90°;3К, three layers   | 23.9x1.15       | 8.4   | 307.4   |        |   |
| UT-3-3       | Carbon fabric 0°/90°;3К, three layers   | 23.8x1.16       | 8.7   | 315.4   | 10.21  | 0.2|
| UT-3-4       | Carbon fabric 0°/90°;3К, three layers   | 24.0x1.14       | 8.6   | 317.6   |        |   |
| UT-3-5       | Carbon fabric 0°/90°;3К, three layers   | 23.3x1.17       | 8.6   | 316.5   |        |   |

Table 2. Initial data and test results of polymer composites based on unidirectional carbon tape.

| Series and № | The type of filler, the number of layers | Section bxt, mm | P, kN | Rσ, MPa | E, GPa | μ |
|--------------|----------------------------------------|-----------------|-------|---------|--------|---|
| OL-1-1       | Unidirectional feed 0°; 12К, one layer  | 24.8x0.81       | 18.5  | 920.0   |        |   |
| OL-1-2       | Unidirectional feed 0°; 12К, one layer  | 25.0x0.82       | 18.7  | 910.9   | 51.23  | 0.3|
| OL-1-3       | Unidirectional feed 0°; 12К, one layer  | 25.1x0.80       | 16.9  | 838.9   |        |   |
| OL-1-4       | Unidirectional feed 0°; 12К, one layer  | 25.1x0.81       | 18.4  | 903.6   |        |   |
| OL-1-5       | Unidirectional feed 0°; 12К, one layer  | 24.9x0.81       | 17.9  | 886.8   |        |   |
| OL-2-1       | Unidirectional feed 0°; 12К, two layers | 24.1x1.5        | 32.8  | 900.6   | 51.23  | 0.3|
| OL-2-2       | Unidirectional feed 0°; 12К, two layers | 24.2x1.52       | 33.9  | 924.2   |        |   |
| OL-2-3       | Unidirectional feed 0°; 12К, two layers | 24.3x1.51       | 32.9  | 899.0   |        |   |
The nature of destruction of polymer composite samples is shown in figure 3.

**Figure 3.** Character of destruction of polymer composite samples: a) UT series based on bidirectional carbon fabric; b) OL series based on unidirectional carbon tape.

The stress-strain diagram for the tested polymer composites is shown in figure 4.

**Figure 4.** Diagram "stress-relative deformations" based on the results of tensile tests of samples.

The destruction of ut series samples was fragile. The deformation was linear, up to the point of destruction. The relative deformation at the moment of rupture of the samples was 1.9 – 2.1%. The
destruction of samples from unidirectional carbon tape (ol series) was brittle and occurred in two stages. At the first stage, at a load of about 90% of the breaking load, the polymer matrix was destroyed and the sample was divided into separate strands. At the second stage, the entire sample was destroyed, starting with the breakage of the extreme fibers. The deformation of the samples was linear, up to the point of destruction. The relative deformation at the moment of rupture of samples of all series was 1.7 – 1.9%.

4. Conclusions
Based on the results of the research, the following conclusions can be drawn:

1. Based on tests of modified wood samples for compression along the fibers, a composition based on dimethacrylic polyester was selected as a wood modifier. The ultimate strength of such samples averaged 84 MPa, the modulus of elasticity 21 GPA, the increase in strength compared to solid wood samples was 46%, the modulus of elasticity – 54%.

2. The use of volatile diluents of polymer compositions when modifying wood using the "vacuum-pressure" method reduces the effectiveness of the method due to evaporation during the degassing process.

3. The destruction of beam structures is plastic in nature and occurs along normal sections in the middle of the span. The increase in the load-bearing capacity of wood – composite beams of the DMB series in comparison with solid wood beams of the DB series within the design loads was 11%. The decrease in deformability of 18%. A limited increase in the strength of beam structures is associated with the presence of defects in the stretched zone of the tested beam structures.

4. The greatest effect of the proposed reinforcement method can be achieved as a result of joint use of external reinforcement systems in a stretched zone by reducing the influence of defects.

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