Wooden beams with local wood modification

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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

According to statistics, in 80% of cases, the failure of elements of wooden structures of historical and cultural heritage monuments occurs for reasons caused by biological and structural defects of wood [1]. These include rotting of the support and contact zones of wooden structures with metal, stone and reinforced concrete structures. Formation of defects in the form of cracks and delamination of wooden elements due to variable temperature and humidity conditions of operation; influence of defects located in the most loaded areas of the structure. The task of ensuring safe operation and maintaining the health of wooden elements is urgent.

The calculation of wooden structures and elements in most cases is made under the assumption of elastic work of the material. Therefore, there are certain limitations when calculating beyond the elasticity limits. Upon loading with an external load, there are three stages of operation of wooden beam structures: conditionally elastic, elastic-plastic, and the stage of destruction. In the transition from conventionally elastic stage of the work wood to the elastic-plastic stage and the stage of destruction in a very tense compressed area beam construction formed of plastic deformation of the material (plastic hinge), while the neutral axis is shifted in a stretched area of the element. When the
tensile strength limit is reached, the element is destroyed under normal stresses. Thus, if there is no weakening in the stretched zone in the form of defects or defects, in general, the destruction of the wood bending element begins with the compressed zone, which requires strengthening [2]. There are many ways to strengthen the span zones of wooden beams. The most common method is to increase the cross-sections of elements [3-7], and the reinforcement is usually made on the side sections to avoid additional work on disassembling floor structures. In such cases, it is impossible to effectively position the reinforcement elements in extremely stressed zones, which leads to overspending of material and loss of the architectural appearance of structures. Reinforcement with steel rolled products [8-11] is limited by the temperature and humidity conditions of the premises. Increased humidity leads to corrosion of external reinforcement elements and requires additional protection. Taking into account these requirements, the most promising are composite external reinforcement systems based on carbon [12-22], glass [23-27] and aramid fibers [28], as well as aluminum-matrix materials [29-31] due to the small dimensions of the reinforcement system, low specific weight and high strength. The disadvantages of such solutions are the high cost of materials, accelerated aging in conditions of increased UV radiation, etc. The use of reinforcement elements with glued carbon lamellae, reinforcing steel and composite rods [32-36] is most relevant in new construction due to the complexity of the technological process of milling grooves and gluing reinforcing elements. These options either change the appearance of the building structure, or are not applicable in construction conditions. Since the middle of the XX century, wood modification has been used to increase the load-bearing capacity and improve the performance of wooden structures. The modification technology allows to obtain a wood composite with high physical and mechanical characteristics, low anisotropy of properties, low water absorption, biological and chemical resistance [37, 38]. The main disadvantages include the need for continuous processing of blanks with polymer compositions, which leads to increased consumption of the modifier and the need for expensive large-sized equipment. The use of local modification of wood will allow you to directly change the physical and mechanical characteristics of wood in extremely stressed zones of elements without significant consumption of modifier and the need for specialized equipment. Thus, research in this area is relevant.

The purpose of this work is studying the strength of wooden beams with local modification of wood in the compressed zone.

The subject of research is the stress-strain state of beams with wood modification.

To achieve this goal the following tasks were set:

1. To evaluate the technological parameters of polymer compositions, on the example of modification of small wood samples with compositions based on epoxy resin, urea-formaldehyde resin, dimethacrylic polyester solution.

2. To determine of mechanical characteristics of modified wood samples when crushed along the fibers.

3. To study the issue of the stress-strain state of wooden beams with local modification of wood in the compressed zone and comparison of the obtained data with reference values of similar solid-wood structures.

2. Methods
To determine the compressive strength along the fibers in accordance with Russian State Standard 16483.10–73, four series of samples were manufactured. The minimum number of samples of each series was determined on the basis of Russian State Standard 16483.0-89 and amounted to 5 pieces. The dimensions of the samples are 20x20x30 (h) mm. the Tests were carried out in the test machine REM–100–A–1. Accepted marking and composition of the modifier: 1 series – mark "D", is a control and made of pure wood; 2 series-mark "ED", 100 mass parts of ED-20, 15 mass parts of polyethylene polyamine, 15 mass parts of dibutylphthalate, 15 mass. CH. acetone; 3 series-brand "KFV", 100 mass parts of urea formaldehyde resin, 20 mass parts of 10% oxalic acid solution; 4 series-dmpe brand 100 mass parts of dimethacrylic polyester solution, 2 mass parts of 8.9% methylethylketone peroxide, 4 mass parts of 1% cobalt octoate; 0.5 mass parts of distilled water.
To determine the modulus of elasticity of modified wood when compressed along the fibers in accordance with Russian State Standard 21523.8-93, three series of samples were produced. The minimum number of samples of each series was 3 pieces. The size of the samples is 30x30x60 (h) mm. Tests were carried out using the test machine REM–100–А–1. To fix the relative deformations, a multifunctional measuring complex TDS – 530 and strain gauges with a base of 20mm were used the composition and marking of samples were taken in the same way as tests for determining the ultimate strength when crumpled along the fibers. The general view of modified wood samples is shown in figure 1.

![Figure 1. General view of samples for determining the physical and mechanical characteristics of modified wood: a) for determining the strength limit when crumpling along the fibers according to Russian State Standard 16483.10–73; b) for determining the elastic modulus according to Russian State Standard 21523.8-93.](image1)

When producing samples of modified wood, the method of thermochemical modification was chosen using the "vacuum-pressure" method in the amount of 2 cycles of 20 minutes each. All-wood beams with a cross section of 100x200 mm and a span of 4.5 m were used as billets for beam structures at the initial stage, holes were drilled according to a template for installing injectors in increments of 200 mm in length. The depth of the holes is assumed to be 95 mm. Vertical boundary between conventional and modified wood is located at a distance of 0.95 m, counting from the support. General view of the tested beam structure is shown in figure 2.

![Figure 2. General view of the structure under study.](image2)

The injectors were installed using an elastic sealing material at the interface between the wood and the metal connector. A general view of the local modification process is shown in figure 3. After forming the vacuum bag, the structure was vacuumed and 20 minutes later, a low-viscosity modifier based on dimethacryl polyester was fed for 30 minutes under a cyclically varying excess pressure of 0.2 – 0.4 MPa.
The study of beam structures was carried out in two stages. At the first stage, the integral modulus of elasticity of a wooden beam was determined. At the second stage, the stress-strain state was studied, and the nature of the failure was determined depending on the design parameters. Vertical movements and angles of rotation were measured by deflection meters, the draft of supports by hour-type indicators with a division price of 0.01 mm.

Loading was performed according to an eight-point scheme on a lever test bench (figure 4), which allows simulating a uniformly distributed load along the span with sufficient accuracy. The load conversion factor is $n=8.5$. The loading stage is assigned equal to 1/10 of the destructive load. The loading time at each stage is assumed to be 3 minutes, and the duration of each step is 15 minutes. As part of experimental studies of the strength and deformability of wood-composite beams, 2 series of three beams were tested in each. The first series (DB mark) is a control one made of solid wood, the second series of beams (DMB mark) is made with a local modification of the compressed zone.

Figure 3. Technological process of manufacturing beams with local modification of wood.

Figure 4. Design of the test installation for testing beams with a span of 4.5 m:
1 – wood composite beam; 2 – resisting beam I No. 45 + No. 30B1; 3 – connecting coil shaft; 4 – steel wires Ø6mm; 5 – baskets with loading; 6 - indicating gauges, 7 – PAO-6 lever arm deflection indicators for measuring the support sections angular rotations, 8 – PAO-6 lever arm deflection indicators for determining beam deflections.
3. Results and discussion
The results of testing samples of modified wood are presented in table 1. The test results for determining the elastic modulus are shown in table 2. The results of testing of beam structures are shown in table 3.

Table 1. Initial data and test results of samples for compression along the fibers in accordance with Russian State Standard 16483.10-73.

| Series and No. | Size bxh,mm | P, kN | R, MPa | Statistic parameters |
|---------------|-------------|-------|--------|----------------------|
|               |             |       |        | X̅ | S | S̅ | v, % | ∆X | P̅ | p, % |
| D-1           | 18x19.1     | 16.90 | 49.15  |     |   |  |  |     |    |    |
| D-2           | 19.4x19.5   | 16.90 | 44.67  |     |   |  |  |     |    |    |
| D-3           | 19.1x18.8   | 15.50 | 43.17  |     |   |  |  |     |    |    |
| D-4           | 19.1x20.8   | 17.87 | 44.99  |     |   |  |  |     |    |    |
| D-5           | 18.5x19.4   | 17.21 | 47.94  |     |   |  |  |     |    |    |
| ED-1          | 19.1x19.1   | 19.61 | 53.76  |     |   |  |  |     |    |    |
| ED-2          | 19.4x19.5   | 20.10 | 53.13  |     |   |  |  |     |    |    |
| ED-3          | 19.1x18.8   | 20.27 | 56.46  |     |   |  |  |     |    |    |
| ED-4          | 19.2x20.8   | 20.16 | 50.48  |     |   |  |  |     |    |    |
| ED-5          | 18.5x19.4   | 21.91 | 61.03  |     |   |  |  |     |    |    |
| KFV-1         | 18.6x19.1   | 19.61 | 55.20  |     |   |  |  |     |    |    |
| KFV-2         | 19.8x19.5   | 23.91 | 61.92  |     |   |  |  |     |    |    |
| KFV-3         | 19.1x20.8   | 23.22 | 64.65  |     |   |  |  |     |    |    |
| KFV-4         | 19.1x20.8   | 22.29 | 56.11  |     |   |  |  |     |    |    |
| KFV-5         | 18.5x19.4   | 21.95 | 61.16  |     |   |  |  |     |    |    |
| DMPE-1        | 21.1x19.56  | 34.00 | 82.54  |     |   |  |  |     |    |    |
| DMPE-2        | 20.4x20.0   | 33.43 | 81.69  |     |   |  |  |     |    |    |
| DMPE-3        | 19.3x20.0   | 35.10 | 90.80  |     |   |  |  |     |    |    |
| DMPE-4        | 19.6x21.0   | 34.01 | 82.27  |     |   |  |  |     |    |    |
| DMPE-5        | 20.0x19.4   | 33.95 | 87.51  |     |   |  |  |     |    |    |

Table 2. Initial data and test results for determining the modulus of elasticity of modified wood samples according to Russian State Standard 21523.8-93.

| Series and No. | Size bxh,mm | Elastic modulus E, GPa | Statistic parameters |
|---------------|-------------|------------------------|----------------------|
|               |             |                        | X̅ | S | S̅ | v, % | ∆X | P̅ | p, % |
| ED-1          | 29.8x30.5   | 18.60                  |     |   |  |  |     |    |    |
| ED-2          | 28.7x29.5   | 18.21                  | 18.64 | 0.45 | 0.26 | 2.39 | 0.99 | 5.14 |
| ED-3          | 30.1x30.0   | 19.10                  |     |   |  |  |     |    |    |
| KFV-1         | 29.7x30.1   | 19.21                  | 19.31 | 0.40 | 0.23 | 2.07 | 1.11 | 5.95 |
The nature of destruction of polymer composite samples is shown in figure 3. The general view of modified wood samples when determining physical and mechanical characteristics is shown in figure 5. The nature of destruction of polymer composite samples is shown in figure 3. The general view of modified wood samples when determining physical and mechanical characteristics is shown in figure 5. The diagram "Stress-relative deformations" and the graph of increasing the modulus of elasticity of modified wood samples in comparison with conventional wood are shown in figure 6.

![Figure 5. General view of samples in the determination of physical-mechanical characteristics of modified wood: a) nature of fracture of samples of the "ED" series; b) series "KFV"; c) a series of "DMPE"; d) general view of test to determine the modulus of elasticity of impregnated wood.](image)

According to the results of experimental studies, the increase in the strength of modified samples during compression along the fibers in comparison with solid wood for the "ED" series was 16%, the "KFV" series – 23%, and the "DMPE" series – 46%. The destruction is plastic in nature with the formation of a characteristic "fold". The smallest increase in strength for samples of the "ED" series is due to an increase in the viscosity of the modifier BASED on the ED-20 resin, associated with active evaporation of acetone during the degassing of the composition in a vacuum chamber. Therefore, the use of vaporized diluents to reduce the viscosity of the modifier in technological processes involving vacuum is ineffective. An increase in the modulus of elasticity of modified wood compared to the usual for samples of the "ED" series - 40.9%; "KFV" – 48.2%; "DMPE" - 53.6%. The general view of a beam with local modification of wood and the nature of its destruction is shown in figure 7.
The destruction of the DMB series beams occurred at an average linear load on the beam of 11.97 kN/m, which exceeds the calculated load by 1.93 times, and had a plastic character. The destruction beams of DMB-2 was started in the compressed zone with the formation of plastic folds, then there was a break of the stretched fibres of wood or had a destruction by weakening in the form of a bitch in the stretched area, beams DMB-1, DMB-3 in the stretched zone of the impairments in the form of knots without the formation of plastic hinge in the compressed area. The "load-strain" diagram of the tested beam structures is shown in figure 8.
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%.

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.

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.

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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