Experimental investigations of composite wooden beams with local wood modification

A S Gribanov¹, V I Rimshin², S I Roshchina³

¹Department of building structures of VlSU, Vladimir State University named after Alexander Grigorievich and Nikolai Grigorievich Stoletovs, 87, Gorky Street, Vladimir 600000, Russia
²Housing and Utility Complex Department of NRU MGSU, Moscow State University of civil engineering (national research university), 26, Yaroslavskoe highway, Moscow 129337, Russia
³Head of the Department of building structures of VlSU, Vladimir State University named after Alexander Grigorievich and Nikolai Grigorievich Stoletovs, 87, Gorky Street, Vladimir 600000, Russia

E-mail: agri91@inbox.ru

Abstract. The dynamic development of wooden structures is inherently connected with emergence of the new structural elements having high operating parameters, increased strength and rigidity. Composite wooden structures based on wood and reinforcing material made from glass, aramid or carbon fiber on a polymer matrix fully comply with the requirements. The complex stress-strain state that occurs in the reinforced wooden elements necessitates a plainly required experimental confirmation of the assumptions and suppositions taken as theoretical. Comparative analysis of the theoretical and experimental investigation of wooden beams reinforced with carbon fiber polymer composite and modification of the wood compressed zone has been performed as a part of the research. Test installation for testing beam structures is presented, “load-strain relation” and relative deformation diagrams in the cross section of wood-composite beams are constructed. The stress-strain state of the structures at various stages of loading is analyzed. Sufficient convergence of the results of the experimental and theoretical investigations is established. The discrepancy in the first group of limit states does not exceed 3.5%, in the second group does not exceed - 9%.

1. Introduction

At the present time wide distribution and demand for wood as a structural material in our country and abroad is due to its high physical and mechanical, operational parameters, low specific weight, simplicity and low energy-output ratio in the production of the building construction elements in comparison with metal and reinforced concrete. Our country has the largest wood material base which includes more than fourth of the world timber reserves that gives additional competitive advantages and stimulates further development of investigations in the field of wooden structures.

One of the priority areas is the creation of lightweight composite bending structures based on wood. They include reinforced [1], glued-plywood [2], wood concrete [3] truss and other beam structures. Reinforcement is the most effective way to ensure high bearing capacity of elements at low material consumption and operational reliability. Along with the traditional reinforcing materials from
steel [4] and composite reinforcement [5-7], shaped [8] and sheet rolled stock, materials based on glass [9-11], carbon [12-15], aramid fiber [16] and polymer matrix have gained traction. Such operational parameters as low hygroscopicity, resistance to the ultraviolet radiation and corrosive effects of the reactive environments, in conjunction with high strength and low deformability of carbon-based polymer composites, allow the latter to find wide application in the systems of the exterior reinforcement of the wooden structures. Use of the reinforcement can significantly reduce the effect of various defects, both mechanical and natural, that expands the scope of application of the composite beam structures not only in the framework of the new construction but also during the reconstruction or major repairs of existing buildings and structures [17-21]. Wood modification is another promising direction which makes it possible to increase the strength of wood during crumpling significantly, shearing parallel and perpendicular to grain, reducing the effect of anisotropy of properties and allows to put deconstructive sections of wooden beam structures into operation [22,23]. Co-use of carbon fiber reinforcing composite material in the stretched and local modification of wood in the compressed areas will allow to improve the efficiency of the reinforcement significantly by reducing the effect of defects caused by the anatomical structure of wood and maximizing the use of the physical and mechanical properties of the materials used.

In local reference documentation, engineering and design of composite beam structures is made on the assumption of the elastic work of the materials using the reduction coefficient of the wooden beams cross sections geometrical characteristics. This design approach is applied and uses a number of assumptions which in turn allow us to obtain compact mathematical expressions for finding the required parameters.

For structural calculations at the elastic-plastic and plastic stages of the stress-strain state as well as for visualizing the transient physical processes in the structural elements at various stages of loading, the finite-element method has been used. Reliable results of the calculations have been obtained using a physically non-linear model with the application of the actual deformation diagrams of the materials used and taking into account the duration of the applied loads [24,25].

Tests of beam structures are the integral part of the investigation and are intended to confirm the accepted assumptions and suppositions when describing the physical and mathematical models of the materials and structures as a whole, to elicit the transient response at various stages of the stress-strain state, to determine the nature of the destruction and the convergence of theoretical and experimental investigations.

The purpose of the work is the experimental analysis of the stress-strain state of wooden beams reinforced with a unidirectional carbon fiber tape over the part of the span in the stretched area and local modification of wood in the compressed area and their comparison with the results of the theoretical investigations.

2. Methodology

Design of composite beam structures by the reduced geometrical characteristics has been adopted as an applied method for theoretical investigations. Evaluation of the stress-strain state of the beam structures in the elastic-plastic stage has been carried out by the finite-element method in the software package of the PC "Lira 10.6" in a physically non-linear setting of the engineering problem using the actual deformation diagrams of the materials used. The materials physicomechanical characteristics have been obtained on the basis of the tests of the polymer composite from the unidirectional carbon tape according to GOST 11262-2017 and the samples of modified wood according to GOST 21523.8-93, GOST 16483.10-73.

The method of tensometry with the use of the multichannel measuring complex TDS-530 and strain gauges with a base of 20 mm has been adopted as a technique for the experimental investigations. Investigation of the composite beam structures has been carried out in two stages. At the first stage the integral modulus of the wooden beam elasticity, that takes heterogeneity of wood, flaws, etc, into account unlike the calculated one, has been determined . At the second stage the stress-strain state of the composite beams has been investigated, the fracture pattern depending on the design parameters
has been determined. Vertical displacements and angular rotations have been measured with PAO-6 leverarm deflection indicator, the settling of supports has been measured by the indicating gage with a balance of 0.01 mm readability. Natural solid wood beams with 100x200 (h) mm cross section, with a span of 4.5 m have been used as blanks for the tests which made it possible to obtain experimental data characterizing the strength and rigidity of the existent composite structures with regard to the effect of the defects in timber. Design of the beam construction with the arrangement of strain gauges is shown in Figure 1. The polymer composite has been made on the basis of a FibArm tape 430/150 unidirectional carbon tape and ED-20 epoxy-Diane resin. Wood is modified by impregnating the polymer composition on the base of dimethacrylic polyester into the boundary compression zone of the beam cross section.

![Figure 1. General view of the investigated structure.](image)

The loading has been carried out according to the eight-point scheme on the lever testing bed (Figure 2), that allows to simulate the uniformly spread load over part of the span adequately. The direct application of loading to the structure has been carried out by means of a traction system and flexible suspensions connected through a catshaft with a basket loaded up with loading (Figure 3).

![Figure 2. 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 leverarm deflection indicators for measuring the support sections angular rotations, 8 – PAO-6 leverarm deflection indicators for determining beam deflections.](image)

![Figure 3. The coil shaft design for transferring loadings to the composite beam with a conversion factor n = 8.5: 1 – the wood composite beam; 2 – the resistance coil Ø340mm; 3 – the connected shaft Ø40mm; 4 – the single unit for the cable Ø50mm; 5 – thrust made from the rolling plate δ = 5mm; 6 – steel cables Ø6mm; 7 – distributing plate δ = 16mm; 8 – resisting beam I No. 45 + No. 30B1.](image)
The load conversion factor is $n = 8.5$. The block step is defined being $1/10$ of the rupture load. The loading time at each step is defined being 3 minutes, and the endurance time at each step being 15 minutes.

Within the framework of the investigation of the wood-composite beams strength and deformability, 2 series with three beams in each have been tested. The first series is standard and is made of solid wood (brand DB). The second series is made according to the design solutions presented in Figure 1 (mark DKMB).

3. Results and discussion

Results of the experimental investigations are presented in table 1.

| Series and brand | Design load, $P_d$ (kN/m) | Deflection (mm) | Breaking load, $P_b$ (kN/m) |
|------------------|---------------------------|----------------|--------------------------|
| DB-1             | 5.13                      | 64.21          | 8.15                     |
| DB-2             | 5.13                      | 63.19          | 7.76                     |
| DB-3             | 5.13                      | 67.2           | 8.63                     |
| DKMB-1           | 7.37                      | 79.38          | 32.25                    |
| DKMB-2           | 7.37                      | 83.73          | 34.44                    |
| DKMB-3           | 7.37                      | 76.42          | 31.24                    |

Destruction of the beams DKMB series occurred at an average linear load of 32.44 kN / m upon per beam, which is 4.4 times higher than the calculated one. It started in the compressed zone with the loss of stability of the modified wood compressed grains and the formation of the plastic “shift”. The matrix and polymer composite integrity is ensured until the limiting state coming-in; the delamination of the reinforcing material from the wood surface hasn’t been recorded. The general view of the beam DKMB series during the tests and the nature of the destruction are presented respectively in Figure 4.

![Figure 4](image-url)

**Figure 4.** Wood composite beam with the wood modification: a) general view during testing; b) nature of the destruction with the formation of plastic "shift".

"Load-strain" graphs and diagrams of relative deformations are presented respectively in Figures 5,6 according to the results of the experimental investigations.

For beams with combined type of reinforcement (DKMB series), the stress level of the modified wood at the time of the limit state coming-in has been 87-93% of the temporal compressive strength along the grain, in the composite material it has been 3-5% of the tensile strength. In the compressed zone, a plastic centroid has been formed in the form of the losing stability grain and a significant
redistribution of stresses between the wood and the polymer composite has been observed. The latter has behaved elastically up to the destruction, hindering a significant development of the deflections of the beam structure. This aspect hasn’t been fully taken into account by numerical calculations, therefore the discrepancy between the results in the plastic stage of the stress-strain state has been significant.

Figure 5. “Load-vertical displacement” relation according to the results of the experimental investigations of wood composite beams.

Figure 6. “Load-vertical displacement” relation according to the results of the experimental investigations of wood composite beams: Pd – design load, Pb – Breaking load.
4. The following conclusions based on the results of the investigations can be made

1. Destruction of the beam structures is plastic in nature and occurs across the standard cross-section in the middle of the span. Increase of the DCMB series wood composite beams load-bearing capacity in comparison with the all-wood DB series within the design loads has been 34%. Deformability reduction it has been 23%.

2. Discrepancy between the results of the theoretical investigations and experimental data on the first group of the limit states within the design loads (in the elastic stage of the beam structural behaviour) has been 3.5%.

3. In the second group of the limiting states within the maximum allowable deflection, the divergence of results has been 9%.

4. Composite reinforcing material based on the unidirectional carbon tape at the stage of the beam structures destruction has been loaded at 5-8% of the ultimate breaking load under tension. Further increase in the reinforcement ratio will not lead to the significant increase in the load-bearing capacity. Destruction of the beam structures reinforced with composite material has been determined by the strength of the wood compressed zone.

5. For beams with the combined type of reinforcement, increase in strength and decrease in the structures deformability has occurred in proportion to the modification coefficient. The volume level in the modified wood at the time of the limit state coming-in has been 87-93% of the temporary compressive strength along the grains, in the composite material it has been 3-5% of the tensile strength.

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