Strength of wood reinforced with a polymer composite for crumpling across the fibers

M S Lisyatnikov¹, T O Glebova¹, S P Ageev² and A M Ivaniuk³

¹ Vladimir State University named after Alexander and Nikolay Stoletovs, Vladimir, Russian Federation
² Northern (Arctic) Federal University named after M.V. Lomonosov, Arkhangelsk, Russian Federation
³ National University of water management and nature resources used, Rivne, Ukraine

mlisyatnikov@gmail.com

Abstract. A method for strengthening beams on a support with a polymer composite based on fiberglass and an epoxy matrix with the inclusion of carbon nanotubes in its composition is proposed. To prove the effectiveness of reinforcement and determine quantitative and qualitative characteristics, experimental studies were conducted on standard wooden samples with and without reinforcement. Before conducting the experiment, it was planned in order to achieve maximum measurement accuracy with a minimum number of experiments and maintain the statistical reliability of the results. As a result of planning, a multi-factor formula was obtained for determining the strength of the sample depending on any combination of three variable factors: the reinforcement coefficient, the quantitative component of carbon nanotubes, and the curing temperature of the composite. The tests were performed under normal conditions. As a result of compression tests across the fibers of experimental samples, it was found that the strength limit of reinforced samples in comparison with wooden ones without reinforcement increases to 39 %, and the destruction is plastic.

1. Introduction

One of the types of wooden and wood-glued structures are beams [1-6]. The nature of the work of beam elements is bending. The criteria for wood performance in this case can be reduced to the theory of classical destruction [7]. Accordingly, in the vast majority of cases, the loss of load-bearing capacity or structural failure [8, 9] occurs in the middle of the span under the influence of normal stresses in the stretched and compressed zone of the beam. In this regard, the bulk of solutions for strengthening beams are aimed at reducing the influence of normal stresses in the middle of the span, and strengthening the support zone is mistakenly neglected.

Under the influence of a uniformly distributed load [10], the following stress conditions occur in the support zone of beam structures: chipping along the fibers (shear); crumpling across the fibers (surface compression from the support reaction); stretching at an angle to the fibers.

Based on this, defects and foci of the first signs of failure [11-14] often occur outside the zone of maximum stress. The nature of destruction in the form of separation on the main platforms when chipping will be characteristic of high wooden beams of overlap and coating, glued beams-inserts in
cross-beam systems. The strength of the beam [15, 16] at the supports must be evaluated as a bent anisotropic element using the criteria for the strength of wood in a complex stressed state.

It is also worth noting that the destruction of the beam structure on the support is also possible when the wood is destroyed due to unsatisfactory operating conditions.

The feasibility of evaluating glued wooden beams at an angle to the fibers also occurs in the vicinity of the application of concentrated forces, including increased support reactions, in areas of steep undercutting, especially at stretched edges, on curved sections with a bend that reduces the curvature of the element, etc.

After analyzing all of the above, we can conclude that the complex strenuous work of wood [17] due to anisotropy of the structure, as well as the need in certain cases to strengthen the support zones of beam structures.

To strengthen beam structures on supports, classical methods of reinforcement are used: restoration of the section with overlays, installation of a prosthesis, gluing steel rods, etc.

There are also methods of strengthening [18, 19] support zones of beam structures, involving the use of polymers, enclosing in the body of wood reinforcing compounds, or pasting the support zones with tapes and nets made of carbon fiber. To increase strength [20-24] reference area specifically used for crushing the installation of wooden prisms with a vertical arrangement of fibers, the diverter strips, etc. in addition, one of the perspective directions of strengthening of structures may be the use of new lightweight composite materials, metal-based [25-27].

We have developed a method of strengthening, consisting in the device of the cage on the support part of the beam, made of fiberglass impregnated with an epoxy composition (ED-20), with the addition of carbon nanotubes (CNTS). The number of clip layers varies from 1 to 5. The use of adhesive compositions [28, 29] based on fiberglass and nanotechnologies in strengthening the supporting zones of wood-glued beam structures requires special research, including experimental studies.

The object of research is wood reinforced with a polymer composite made of fiberglass, epoxy resin and carbon nanotubes.

The subject of the study is the strength of wood reinforced with a polymer composite for crumpling across the fibers.

The purpose of the study is to perform experimental studies to determine the strength of wood reinforced with a polymer composite for crumpling across the fibers.

The following tasks were set:

1. Set the maximum strength indicators and the destructive load of experimental wooden samples and samples with surface reinforcement.
2. To identify the dependence of the strength limit of experimental samples on the coefficient of reinforcement, the concentration of carbon nanotubes and the curing temperature of the composite.

Establish the nature of destruction [30-33] of the tested wooden and reinforced samples.

2. Methods

Experimental studies of the physical and mechanical characteristics of wood and reinforced samples when compressed across the fibers were carried out on the MI-50U test machine.

Before conducting an experiment, it is necessary to plan it [34]. The main goal of experiment planning is to achieve maximum measurement accuracy with a minimum number of experiments performed and maintain the statistical reliability of the results.

The methodical grid of experiments to determine the rational strengthening of the support section of a glued beam is based on a combination square developed for three primary factors of influence, each of which consists of three options. Ed-20 epoxy-Diane resin was chosen as a permanent factor. The coefficient of reinforcement, the quantitative composition of CNTS and the curing temperature of the polymer are variable factors.
To identify the influence of each of the variable factors, you need to set at least three different values or options for it. With the minimum number of experiments, the most evenly cover the entire area of the table of possible combinations of influencing factors [35, 36]. To do this, we can further develop the idea of the so-called "Latin square". It is suggested to look for the dependence of the result on three factors and plan the experiment so that there are no repeated combinations in any row or column. Figure 1 shows one of the possible plans for this combination of three factors, each of which can take three values.

![Figure 1. Scheme design of experiments for three factors](image)

This planning of the experiment allows us to narrow the number of experiments from 27 to 9 with an acceptable decrease in the accuracy of the dependencies of secondary strength and deformability factors on the primary factors: "r" (reinforcement coefficient), "c" (the quantitative component of CNT), "t" (the curing temperature of the composite).

Factor "r" - takes into account the effect of the composite clip layers on the strength of the reinforced wood-glued beam, changes 1, 3, 5 layers.

Factor "c" - takes into account the influence of the concentration of carbon nanotubes in the adhesive composition on the strength of the reinforced wood-glued beam, changes 0.1 %, 0.3 %, 0.5 %.

Factor "t" - takes into account the effect of the curing temperature of the composite on the strength of the reinforced wood-glued beam, varies 20, 40, 60 °C.

It is necessary to find empirical formulas that would cover the influence of these factors. The study of the strength properties of experimental models was carried out on samples with surface reinforcement. In the course of research, the values of deformation of samples from the applied load were recorded.

As a result, we obtained the following empirical dependencies, found from the graphs of the influence of each amplification factor:

\[ f(r) = 0.506 \cdot \ln a + 0.949 \]  \hspace{1cm} (1)

\[ f(c) = -0.0087 \cdot u^2 + 0.0731 \cdot u + 0.8827 \]  \hspace{1cm} (2)

\[ f(t) = 0.0061 \cdot t^2 + 0.0186 \cdot t + 0.9889 \]  \hspace{1cm} (3)

Thus, based on the found partial equations of each variable, an empirical dependence is obtained that takes into account the influence of each design factor on the strength of the prototypes.
The adequacy of the obtained empirical formulas is not in doubt, since, obtained by calculation according to these formulas, the destructive load differs from the experimental one by no more than 5%. The resulting multi-factor formula is designed to determine the strength depending on any combination of three variable factors. Substituting the appropriate parameters of factors, we get the corresponding value of the destructive load. The reinforcement with the best strength characteristics was used for the experiment.

Tests of prototypes were carried out with a short-term load [37]. Samples for experimental studies were performed according to the norms. Geometric dimensions were measured using an electronic caliper. The samples were weighed on a laboratory electronic balance. The moisture content of wood was measured by a moisture meter and was 12% with a possible error of ±2%. The temperature and humidity of the environment were determined by a portable weather station. The air temperature in the room was in the range of 18...22 °C, and the relative humidity was 50-60%.

All tests were carried out in series, the strength indicators of wooden and reinforced samples were determined according to the variable parameters of the methodical grid. The coefficient of reinforcement was changed by the number of layers of adhesive composite on the corresponding wooden samples. The CNT concentration varied by the percentage of mass parts of nanotubes to the total weight fraction of the adhesive composition. The curing temperature of the reinforced samples was at room temperature of 20 °C ± 1 °C, additional heating of the samples was performed in a drying test chamber "heat/cold/moisture".

The samples were tested for compression across the fibers (crumpling) in accordance with the requirements of regulatory documents. Samples for compression tests across the fibers were made in the form of a rectangular prism with a base of 20x20 mm and a length along the fibers of 30 mm (figure 2).

![Figure 2](image-url)

**Figure 2.** a) Geometric dimensions and loading scheme of the wood sample for compression tests across the fibers. b) General view of the experimental test specimen in compression across the grain

The constant speed of loading or the constant speed of movement of the machine's traverse was such that the conditional strength limit was reached in (1.5±0.5) minutes after the start of loading.

When using the MI-50 testing machine, the machine was tested with a uniform loading speed (1000=200) N/min, provided that the conditional strength limit of the sample was reached within the specified time interval.

The tests were conducted in the laboratory of building constructions named after V. Yu Shuko on the basis of the Vladimir state University. The wood type is pine. Designation of test samples: W – wooden sample; C1, 3, 5 (c-t) - wooden sample with surface reinforcement composite in 1, 3 and 5 layers, respectively (CNT concentration – curing temperature).

A series of tests was performed on samples in the following sequence:
1. Before testing, the samples were weighed, their humidity and geometric dimensions were measured in three planes.
2. Samples for cross compression were placed on a fixed plate of the test machine and the traverse was lowered close to the sample.
3. Compression of the corresponding samples was performed.
4. According to the data on the display of the test machine, the values of the destructive load $P$ (N) and the corresponding deformations of the sample were recorded.

We performed the construction of diagrams to visualize the results of the experiment.

3. Results and discussion

The General view of the prototypes at the time and after testing is shown in figure 3. During the tests, the dependence of normal compressive stresses on the applied load is constructed (figure 4).

![General view of the test (a, c) and tested (b, d) prototypes for compression across the fibers](image)

Figure 3. General view of the test (a, c) and tested (b, d) prototypes for compression across the fibers

![The dependence of "load – normal compressive stresses" in the compression tests across the grain](image)

Figure 4. The dependence of "load – normal compressive stresses" in the compression tests across the grain (blue is the first test series, gray is the second series, red is the third series, yellow is the fourth)
Data on test results are summarized in the table 1.

Table 1. Test results of experimental wooden and reinforced specimens.

| Sample marking | Breaking load, kN | Increasing the strength of, % |
|----------------|------------------|-----------------------------|
| W              | 2.09             | -                           |
| W1(0.5-20)     | 2.28             | 11                          |
| W1(0.3-40)     | 2.59             | 9                           |
| W1(0.1-60)     | 2.51             | 15                          |
| W3(1.0-20)     | 2.77             | 16                          |
| W3(1.0-40)     | 2.85             | 13                          |
| W3(1.0-60)     | 3.35             | 28                          |
| W5(1.0-20)     | 2.86             | 17                          |
| W5(1.0-40)     | 3.6              | 30                          |
| W5(1.0-60)     | 3.9              | 39                          |

Thus, when testing prototypes, the rational concentration of CNT – 0.3 % and the curing temperature of the composite equal to 60 °C were determined.

Experimentally, it was found that the destruction of wooden samples was of a brittle nature, in contrast to samples with surface reinforcement, which were characterized by a plastic nature of destruction. Also, when the reinforced samples were destroyed, the separation of the composite from the wood was not detected.

4. Conclusions

As a result of experimental studies, the following conclusions can be drawn.

1. The installation and tool base for testing are presented. The method of conducting an experimental study is described.
2. The experiment was planned to determine the rational composition of the composite. A methodical grid of three-factor experiment experiments has been developed. This research scheme allows you to obtain results with a margin of error, which reduces the number of tests performed.
3. The degree of influence of the reinforcement coefficient, the concentration of nanotubes and the curing temperature of the CNT-based composite on the strength of experimental samples was revealed. We obtained an empirical dependence that allows us to determine the destructive load of the sample depending on the above factors.
4. The values of the strength properties of the prototypes were determined on the basis of experimental studies. It was found that the strength limit of reinforced samples in comparison with wooden ones increases when tested for compression across the fibers to 39 %.

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