Testing wood-composite reinforced specimens for shearing along fibers

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Abstract. With the development of chemical technologies, new building materials and products based on them appear. Such materials are used both in the production of new structures and in the strengthening of existing elements. A method of strengthening with glass and carbon fabrics has proven itself in reinforced concrete structures. We have developed a method for reinforcing high wood-glued beam structures with a polymer composite in the support zones. The composite consists of fiberglass impregnated with epoxy. To increase the strength, carbon nanotubes are included in the polymer composition. To confirm the effectiveness of this amplification, it is necessary to carry out numerical and experimental studies. In order to save labor costs, planning a multivariate experiment and machine tests of standard samples with and without amplification is first carried out. As a result of the test for chipping along the fibers of prototypes, it was found that the tensile strength of reinforced samples compared to wooden ones without reinforcement increased by 49%, which is the optimal value for full-scale tests.

1 Introduction

Wood is widely used in the construction industry [1-4]. The most common wooden and wood-glued bending structure is a beam. In such structures, the maximum stresses occur in the tension and compression zones of the beam under the action of the maximum bending moment [5-7]. In the classical solution, when loading with a uniformly distributed load, the destruction of the beams occurs in the middle of the span. For this reason, many beam reinforcement solutions aim to reduce the influence of normal stresses in the span [8], while the reinforcement of the support zone is erroneously ignored.

Under the action of a uniformly distributed load on the support of the beams, a shift occurs along the fibers, surface compression from the support reaction, and tension at an angle to the fibers. It should be noted that wood destruction occurs faster during operation in the supporting zones, which exacerbates the complex stress state.

As a result, defect centers and the first signs of failure often occur outside the region of maximum stress in the span. The nature of the failure in the form of shear can be typical for inserts of glued beams [9] in cross systems, multilayer high beams made of wood, etc. The strength of beam supports should be evaluated as the strength of anisotropic bending

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elements [10-16], using the criteria for wood strength under complex stress conditions. The feasibility of evaluating laminated timber beams at an angle to the fibers also arises near concentrated forces that increase the forces of support reactions, in areas with steep undercuts, especially at flared edges, and in curved areas at bends that reduce the curvature of the element.

From the above, it can be concluded that wood is susceptible to stresses in the support zones due to the structure's anisotropy; in some cases, the support zone of the beam structure needs to be strengthened. Classical reinforcement methods are used to reinforce beam structures [17, 18] on supports, such as increasing the section with overlays, installing stiffeners, and gluing reinforcing bars. There are also methods for strengthening the supporting sections of beam structures with polymers, wood impregnation, and installation of external fabric reinforcement. To increase the compressive strength across the fibers of the support zones, wooden prisms with vertically arranged fibers, spacer plates, etc., are installed. The authors have developed a reinforcement method involving the creation of a shell of epoxy resin (ED-20) and fiberglass impregnated with carbon nanotubes (CNTs) on the beam supports [19, 20]. The number of layers in the shell varies from one to five.

Strengthening the support zones of timber beams using fiberglass or adhesive compositions based on nanotechnologies requires special studies, including experimental ones [21–28]. The object of study is wood reinforced with polymer composites consisting of fiberglass, epoxy resin, and carbon nanotubes. The subject of the study is the shear strength along the fibers of the polymer-wood composite.

The objectives of the study are as follows:

1. Determine the ultimate strength and breaking load of experimental wood samples with surface reinforcement.
2. Show that the tensile strength of the sample depends on the reinforcement ratio, the concentration of carbon nanotubes, and the curing temperature of the composite.
3. Determine the failure behavior of the tested wooden and reinforced specimens.

2 Methods

An experimental study of the physical and mechanical properties of wooden and reinforced samples [29] subjected to shear along the fibers was conducted using a testing machine MI-50U.

Before experimenting, it must be planned. The main goals of experiment design are to minimize the number of tests that need to be performed and maximize the accuracy of measurements while maintaining the statistical reliability of the results [30].

The methodical grid of the experiment to determine the rational reinforcement of glued beams consists of three options, each of which is based on a combinatorial block developed for three influencing factors. Epoxy resin ED-20 was chosen as the constant factor. Reinforcement ratio, CNTs content, and polymer cure temperature were variable factors.

At least three different values or variations should be given to determine the influence of each factor. The most uniform is to cover all possible combinations of influencing factors in the range of the table with a minimum number of tests.

Such an experimental scheme makes it possible to reduce the number of experiments from 27 to 9, with an acceptable decrease in the accuracy of the dependences of both secondary factors of strength and deformability on the primary factors of interest: "a" is the reinforcement coefficient, "u" is the quantitative composition of CNTs and "t" is the curing temperature composite.

Factor "a" examines the effect of layers of composite reinforcement on the strength of reinforced timber beams, which varies between 1, 3, and 5 layers. The "u" factor studies the effect of the concentration of carbon nanotubes in the adhesive composition on the strength of reinforced wooden beams, which is in the range of 0.1 ... 0.5%. The "t" factor varies in the range of 20…60°C, investigating the effect of the composite curing temperature on the strength of reinforced wooden beams.

It is important to find an empirical formula that considers these factors' influence. The strength properties of the test model were investigated using specimens with surface reinforcement. During the test, the deformation of the sample under the applied load is recorded.

As a result, the following empirical dependencies were found in the influence diagrams for each factor:

$$f(a) = 0,506 \cdot \ln a + 0,949 \quad (1)$$

$$f(u) = -0,0087 \cdot u^2 + 0,0731 \cdot u + 0,8827 \quad (2)$$

$$f(t) = 0,0061 \cdot t^2 + 0,0186 \cdot t + 0,9889 \quad (3)$$

The resulting partial equations for each variable give empirical relationships that calculate the effect of each structural element on the strength of the prototype:

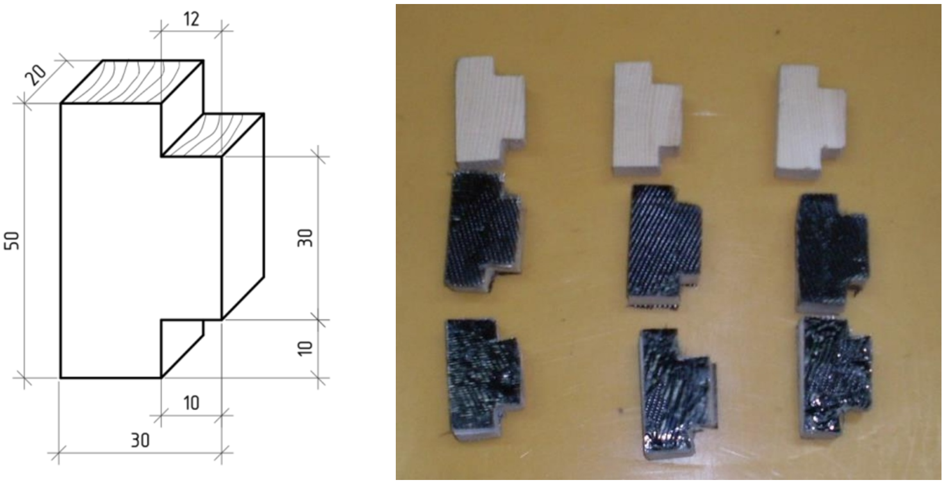
$$P = \Delta_{av} \cdot f(a) \cdot f(u) \cdot f(t) \quad (4)$$

The resulting multi-factor equation is designed to determine the strength by combining three variable factors. Changing the corresponding parameters of the factors gives values corresponding to the breaking load. In the experiment, reinforcement with the best strength characteristics was used.

The samples were tested under short-term loads. Samples for experimental tests were prepared following the standard. The geometric dimensions were measured using electronic thickness gauges. The weight of the samples was measured using an electronic laboratory balance. The moisture content of the wood was measured with a hygrometer and was 12% with a possible error ± 2%. Air temperature and humidity were measured using a portable weather station. The air temperature in the room fluctuated between 18-22 °C, and the relative humidity was 50-60%.

All tests were carried out sequentially, and the strength values of wooden and reinforced samples were determined per various parameters of the methodological grid. The reinforcement ratio was varied by the number of layers of composite adhesive in the respective wood samples; the CNTs concentration was varied by the ratio of the mass fraction of nanotubes to the total weight fraction of the adhesive composition. Reinforced samples were cured at room temperature 20 ± 1 °C, and additional samples were heated in a laboratory oven.

The test piece is placed in the shear test fixture. The movable support is in contact with the sample. The load on the sample is applied through a pressure prism with bearings. The shape and dimensions of the sample are shown in Figure 1.



a *b*

Fig. 1. Specimens for chipping test along fibers: (a) schematic representation of sample with specified dimensions, mm; (b) general view of prepared samples

The sample was loaded uniformly at a constant speed (4±1 kN/min) of loading or a constant speed of movement of the loading head of the machine (4 mm/min). The speed was such that the sample was destroyed after 1.0 ± 0.5 minutes from the moment of loading.

The tests were carried out in the laboratory of composite building structures of the interregional multispecialty and interdisciplinary center for the collective usage of promising and competitive technologies in the areas of development and application in industry/mechanical engineering of domestic achievements in the field of nanotechnology based on Vladimir State University. The type of wood was pine. Name of samples: W - wooden sample, C1,3,5(u-t) – wood samples with surfaces reinforced with 1, 3, and 5 layers of composite, respectively (CNTs concentration – curing temperature).

A series of tests were carried out on the samples in the following order:

1. Before testing, the samples' weight, moisture content, and geometric dimensions were measured.
2. Samples for chipping were fixed in the installation according to GOST, installed on a fixed plate of the testing machine, and the traverse was lowered close to the sample.
3. Cleaving of samples was carried out.
4. The value of the breaking load F (N) b and the corresponding deformation of the sample were recorded on the display of the testing machine.
5. Performed a graphical representation of the experiment's results in the form of diagrams.

3 Results and Discussion

The general view of the sample during and after the test is shown in Figure 2. During the tests, the diagrams "load - shear stresses" (Figure 3) and "load - relative deformation" (Figure 4) were built.

The test results are summarized in Table 1.

Therefore, according to the prototype test results, a reasonable CNTs concentration of 0.3% and a composite curing temperature of 60 °C were determined.

https://doi.org/10.1051/e3sconf/202340103001

Fig. 2. General view of test and tested prototypes for shearing along the fibers.

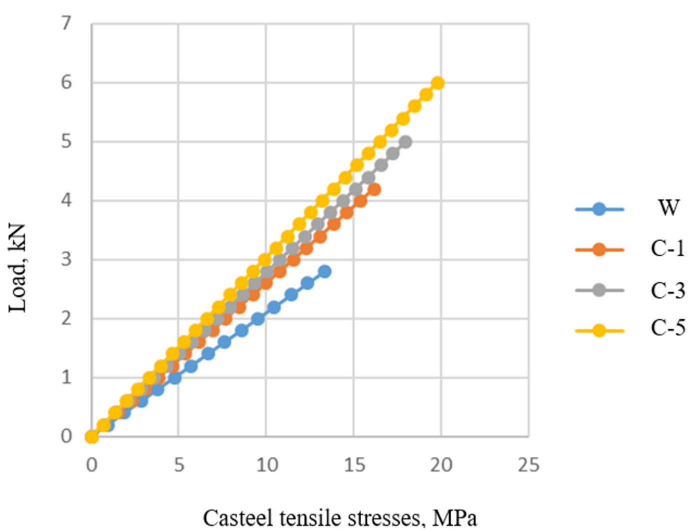


Fig. 3. Load-shear stress diagram for shearing along fibers.

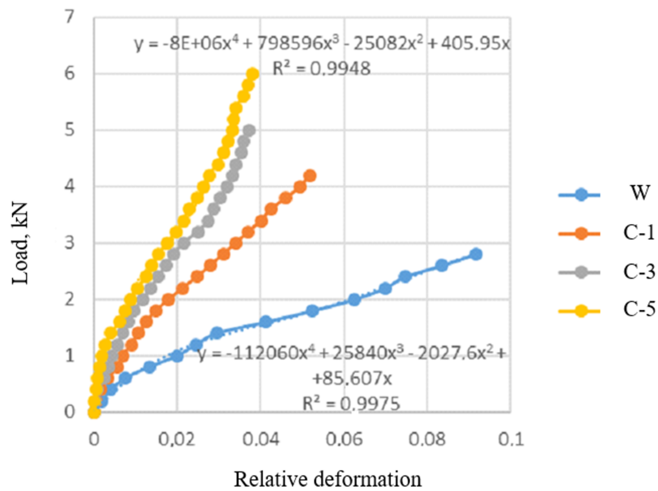


Fig. 4. Diagram "load - relative deformation" during tests for shearing along fibers.

Table 1. Test results of wooden prototypes and reinforced samples

Sample marking	Breaking load, kN	Redistribution of strength, MPa	Strength increase, %
W	2.78	13.33	-
C1(0.5-20)	3.23	14.22	7
C1(0.3-40)	3.87	15.54	16
C1(0.1-60)	3.7	15.21	14
C3(0.3-20)	4.11	16.0	20
C3(0.1-40)	4.24	16.27	22
C3(0.5-60)	5.01	17.78	34
C5(0.1-20)	4.39	16.64	24
C5(0.5-40)	5.53	18.79	41
C5(0.3-60)	6.01	19.8	49

The results experimentally showed that the failure of wooden samples was brittle, while the failure of samples with surface reinforcement was ductile. During the destruction of reinforced samples, no separation of the composite and wood was observed.

4 Conclusions

Based on the results of the experimental study, the following conclusions can be drawn:

1. The installation and instruments for testing are presented. The technique of experimental research is described.
2. Experimental planning was applied to determine the logical composition of the composite material. A methodical experimental grid of three-factor experiments has been developed. Such a research plan allows you to obtain results within the margin of error and reduce the number of tests.
3. The degree of influence of the reinforcement factor, the concentration of nanotubes, and the curing temperature of composites based on CNTs on the

strength of the samples have been established. The above factors give a rule of thumb that allows you to determine the load on the sample at failure.

4. The values of the strength characteristics of the samples were determined based on experimental studies. The results showed that the tensile strength of reinforced specimens, compared to wooden specimens, increases when tested for shearing along the fibers up to 49%.

5 Funding

The research was carried out within the state assignment in the scientific activity of the Ministry of Science and Higher Education of the Russian Federation (theme FZUN-2020-0015, state assignment of VlSU). The study was carried out using the equipment of the interregional multispecialty and interdisciplinary center for the collective usage of promising and competitive technologies in the areas of development and application in industry/mechanical engineering of domestic achievements in the field of nanotechnology (Agreement No. 075-15-2021-692 of August 5, 2021).

References

1. Y. Qi, H. Fang, H. Shi, W. Liu, Y. Qi, and Y. Bai, Constr. Build. Mater. **156**, 532 (2017)
2. D. A. García, R. Sampaio, and M. B. Rosales, J. Brazilian Soc. Mech. Sci. Eng. (2016)
3. A. Y. Naychuk, in *Adv. Mater. Res.* (2013)
4. M. Khelifa and A. Celzard, Compos. Struct. **111**, 393 (2014)
5. S. I. Roschina, M. S. Lisyatnikov, M. V. Lukin, and M. V. Popova, Mater. Sci. Forum **931**, 226 (2018)
6. V. Repin and V. Grinyov, 1230 (2022)
7. Y. J. Kim and K. A. Harries, Eng. Struct. **32**, 3225 (2010)
8. H.-Z. Zhou, E.-C. Zhu, and G.-C. Zhou, Jianzhu Cailiao Xuebao/Journal Build. Mater. **16**, 913 (2013)
9. S. I. Roschina, M. S. Lisyatnikov, V. I. Melekhov, B. V. Labudin, and M. V. Lukin, Izv. Vyss. Uchebnykh Zaved. Seriya Teknol. Tekst. Promyshlennosti **2016-Janua**, (2016)
10. J. Zhang, Q.-F. Xu, Y.-X. Xu, B. Wang, and J.-X. Shang, J. Zhejiang Univ. Sci. A **13**, 491 (2012)
11. R. Sardiko, K. Rocens, J. Iejavs, V. Jakovlevs, and K. Ziverts, in *IOP Conf. Ser. Mater. Sci. Eng.* (2017)
12. Y.-F. Li, Y.-M. Xie, and M.-J. Tsai, Constr. Build. Mater. **23**, 411 (2009)
13. A. S. Ribeiro, A. M. P. de Jesus, A. M. Lima, and J. L. C. Lousada, Constr. Build. Mater. **23**, 2738 (2009)
14. F. Pichelin, M. Nakatani, A. Pizzi, S. Wieland, A. Despres, and S. Rigolet, For. Prod. J. **56**, 31 (2006)
15. M. Lukin, E. Prusov, S. Roshchina, M. Karelina, and N. Vatin, Buildings (2021)

16 A. Lukina, M. Lisyatnikov, V. Martinov, O. Kunitskaya, A. Chernykh and S. Roshchina, Architecture and Engineering (2022)

17. A. D. Pavlenko, V. A. Rybakov, A. V Pikht, and E. S. Mikhailov, Mag. Civ. Eng. **67**, 55 (2016)
18. M. Autengruber, M. Lukacevic
19. S. Roschina, A. Gribanov, M. Lukin, M. Lisyatnikov, and A. Strekalkin, in *MATEC Web Conf.* (2018)
20. A. A. Koshcheev, S. I. Roshchina, M. V. Lukin, and M. S. Lisyatnikov, Mag. Civ. Eng. **81**, (2018)
21. N. Vatin, A. Sinelnikov, M. Garifullin, and D. Trubina, *Simulation of Cold-Formed Steel Beams in Global and Distortional Buckling* (2014)
22. A. Borri, M. Corradi, and A. Grazini, Compos. Part B Eng. **36**, 143 (2005)
23. M. R. M. Asyraf, M. R. Ishak, S. M. Sapuan, N. Yidris, and R. A. Ilyas, J. Mater. Res. Technol. **9**, 6759 (2020)
24. G. C. Foliente and T. E. McLain, J. Struct. Eng. (United States) **118**, 2407 (1992)
25. J.-F. Bocquet, A. Pizzi, A. Despres, H. R. Mansouri, L. Resch, D. Michel, and F. Letort, J. Adhes. Sci. Technol. **21**, 301 (2007)
26. A. D’Ambrisi, F. Focacci, and R. Luciano, Compos. Struct. **108**, 720 (2014)
27. F. J. Keenan, For. Prod. J. **24**, 63 (1974)
28. Y.-F. Li, M.-J. Tsai, T.-F. Wei, and W.-C. Wang, Constr. Build. Mater. **62**, 118 (2014)
29. A. M. P. De Jesus, J. M. T. Pinto, and J. J. L. Morais, Constr. Build. Mater. **35**, 817 (2012)
30. D. Shi, X. Hu, H. Du, Y. Meng, and Z. Xie, Fire Saf. J. **130**, 103594 (2022)