The effect of eccentricity on the strength characteristics of glued rods made of steel cable reinforcement in solid wood

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Abstract. The article is devoted to the study of the behavior of glued rods made of hot-rolled steel reinforcement and steel cables in a solid wood based on experimental tests of beam elements. The influence of eccentricity on the deformation - strength characteristics is studied with a straight-line gluing of reinforcing rods. The comparative analysis of the deformability indices of the centered and lateral gluing performed by milling with fillet groove U - shaped milling cutters was carried out. The technology of manufacturing samples, which consists of preparing wood, milling and pasting rebar into the groove, were described. The diagrams of deformation - strength characteristics of samples of various types were obtained and correlated. The conclusions were drawn about a local increase in strength in the case of using a steel cable as reinforcement and the negative effect of eccentricity on the strength of the adhesive joint during tensile tests. A visual analysis of the damage occurring during the test showed that in the manufacture of full-scale structures, glued rods should be closed with an array of wood. The conclusions were drawn about the optimal depth of milling of grooves for reinforcement, taking into account the use of adhesive compositions on epoxy resin filled with quartz sand - 1.5 depth of reinforcing bar diameter.

1. Introduction

Construction industry, which is actively developing in the present-day conditions, creates demanding requirements for the reliability and durability of structures made from various materials. Invention technologies have been improved, new constructional materials and products that were not previously used in the construction industry as structural ones like carbon fiber, high-strength alloys, new types of concrete have been invented [1-8]. However, the trend to use the materials of natural origin such as wood, metal, concrete with various aggregates, ceramic materials, remains dominant in architecture and design [9-14]. This is due to the commitment to the ecological compatibility and visual aesthetics of the surrounding space. Along with this, technological progress leads to the increased requirements for the service parameters of buildings and structures. For example, the requirements for the span length of buildings are growing - this demands greater rigidity and strength of beams [14-17]. A man
masters construction in seismic regions - requirements for increasing plastic properties of destruction and reliability of structures are growing. Increase in the architectural volume steps up the fire safety requirements that also has an effect on the increase of the structural section [17-22].

The trends discussed above lead to the need for the increased strength and rigidity of building structures, especially from a material such as wood. The strength of the solid wood beams is sometimes not enough to form the necessary architectural forms - large spans of buildings, long curved elements, etc. Development of technologies for perfecting wooden structures today has been formed in several ways.

The most common way to increase the quality indicators of wooden beam structures today is the use of glued wood. Beams of this class can consist of glued laminated timber of various thicknesses, from calibrated bars to thin lamellas. The main advantage of glued wood is its increased strength and rigidity, the ability to manufacture long size and curved structures [23-25]. However, due to the fact that wood remains the main supporting element in such beams, many of its drawbacks such as rotting, defects, creep during prolonged deformation, low outward flow of high-quality lumber from roundwood - still impose some limitations on the applicability of these structures in particular essential buildings and facilities [26-29].

The second popular method of wood modification is the use of various types of reinforcement. At the end of the 20th century, scientific communities in various countries of the world were engaged in this area. For example, in Russia, in a number of scientific institutes such as TsNIISK named after V.A. Kucherenko, NArFU named after M.V. Lomonosov and others, wooden beams with various types of transverse and longitudinal reinforcement were developed - using steel reinforcement and steel glued bars [35,36]. Also a school of reinforced wooden structures under the guidance of V. Shchuko appeared at Vladimir State University. Among others, developments on the problem related to the subject of this work - strengthening the support zones of wooden long-span beams were carried out [36]. Today, research in this direction continues and leads to the creation of the different types of beam reinforcement - using carbon fiber, carbon fabric, the introduction of epoxy adhesives in wood mass [9,10]. Invention of wood reinforcement has made it possible to use inferior wood in building structures, to reduce the consumption of lumber by reducing the cross-section of structures, to increase strength and stiffness in combination with a small installation weight.

In the leading scientific works of the researchers, the main drawbacks and problem areas of wood structures have been identified - an increased tendency towards the brittle failure in the area of the maximum bending moments and in the supporting zones [30-36], problems of corrosion resistance, strength under dynamic effects such as wind gusts, seismic effects, specific nature of the structural failure under the action of loads exceeding the maximum allowable [37-41]. Number of these problems are being solved by the effect of the differences in the reinforcing material and wood elastic moduli. This property, if the selection of reinforcement sections is correct, allows to use the entire range of the reinforcement bearing capacity until the wood strength is exhausted [42-43]. On the basis of the presented research, brittle fracture will not occur until the maximum permissible load is exceeded one and a half times. However, with a further increment of load, the brittle fracture is inevitable. Based on these conditions, in 2017 a method of reinforcing wooden beams was proposed at Vladimir State University – the method of steel wire rope reinforcement in the tensile region along the original curvilinear trajectory [17]. The proposed method of reinforcement allows to increase the length of reinforcement along the beam plane surface, to include a larger wood mass in the work. Based on the numerous experiments on the SCAD program, it has been proved that this method is posited to increase the strength of beams as compared to the use of hot-rolled steel reinforcement, which is filarially located. However, the results of the numerical experiment have made it impossible to take into account the work of the glued joint that connects the reinforcing material with wood. Therefore, it has become essential to carry out full-scale experiments to prove the effectiveness of this type of reinforcement in practice.
2. Methods
As the first step of the full-scale experimental research, it was decided to analyze the work of the direct glued bars in wood. Samples with wire cable reinforcement were in question. It was expected to find out whether the work of the wire cable in the adhesive composition, that is connected to wood, is similar to the so far investigated specific performance features of hot-rolled steel reinforcement of the comparable cross-section diameters under the same conditions [16,17,34,36].

Based on the results of the numerical investigations, it has become possible to formulate the behaviour pattern of the wire cable under load, that can lead to the unpredictable work together with the adhesive composition in a wooden beam:
1. Reduction of the wire cable cross-sectional area under the tensile loads - this phenomenon can lead to cracking of the adhesive layer around the reinforcing element and, as consequence, to stress reduction;
2. Presence of the transportation lubricant on the reinforcing products can lead to poor adhesion with the adhesive composition in the absence of the removing grease process;
3. The strongly pronounced surface relief of the wire cable, arising due to the presence of twisted elements, can improve adhesion and neutralize the negative consequences of the above-described properties;
4. The wire cable possesses high-strength provided its cross-sectional area equals to the undisturbed steel reinforcement cross-sectional area - this quality, when tested successfully, can create economic benefits over reinforcing with undisturbed steel members.

To study out the influence of these factors on the operation of the adhesive joint, it was proposed to conduct an experiment on tension using samples of two symmetrically glued bars.

**Figure 1.** The scheme of the experiment on pulling bars

Experimental setting:
The test piece material is wood, it’s the first board pine, dried in the room with 20% of moisture, and the samples have been prequalified for knots.

The reinforcement material is double splice joint wire cable of the Lk-O type with a zinc coating with a diameter of 6 mm. The cable fixing material in the tensile testing grip is a copper tube with a diameter of 8 mm.

Glue composition - Epoxy resin ED - 20, PEPA hardener, aggregate - ground quartz with 0.2-0.5 mm fraction, precleaned and dried by heating to 150 degrees Celsius. Relative moisture content during preparation and solidification of the adhesive mixture - 30%; Relative moisture content when testing samples - 60%.
The sample manufacturing process consists of several stages. The first stage is wood preconditioning that includes drying to a stable moisture content, preliminary marking of the milling line, surface preparation - processing with the power planer and milling using a fillet groove U-shaped cutter with a diameter of 8 mm.

The second stage is the preparation of glue and gluing in the bar. The glue composition in this research work consists of two-component resin and quartz sand, the blending ratio is maintained in accordance with the recommendations of TsNIISK named after V.A. Kucherenko - 150 weight parts of quartz sand per 100 weight parts of resin. As a result we get non-transparent fluidal adhesive composition. Mixing is carried out on the electronic scales. Next, samples are prepared - wire cable bars are degreased with acetone. After this procedure, the core is pasted into the prepared groove. The glue is applied in two stages – at first the groove is poured over, then the core is brought down and the full filling is performed until the groove is filled. This ensures the filling of all air voids and their absence in the adhesive layer.

The third stage is hardening of the samples to solidification which usually takes 5-6 days to ensure complete polymerization of the adhesive composition. Manufactured samples are transferred to the testing laboratory where the tensile testing machine is located.

For the full-scale study of the adhesive interlayer behavior with a new reinforcing material, two types of samples have been made - with a centered rebar connection and with the rebar located near the external plane of the wood. This arrangement of the connection is due to the task of investigating the negative effect of the eccentricity of the load application, since in a real beam structure the reinforcement is located on the lower side of the beam that experiences tensile stresses and is cleaned with a thin wooden plate to ensure fire resistance. For the objectiveness in evaluating the results obtained, 2 series of samples have been made up, 3 in each series - with and without center adjustment, with a wire cable as a reinforcing material.

![Figure 2. Milling work and hardening of samples under the load after gluing](image)
Alongside with the experiment, the numerical simulation of the above tests has been performed to compare the results with the full-sized results. For the numerical simulation, a stationary simulation test program for building structures Lira 10.10 has been used. The following stages of the mathematical model formation of a wooden beam have been completed:

1. The geometry of the wood mass as an orthotropic object with the following parameters has been formed: Modulus of wood elasticity along the fibers - 10000 MPa; across the fibers – 400 MPa, the shear modulus relative to the axes directed along and across the fibers is 500 MPa. The Poisson's ratio of wood across the fibers is 0.45, along the fibers - 0.018.
2. The introduction of a spatial bar into the wood mass, imitating the operation of steel reinforcement, and wire cable with a cross section of 6 mm, has been completed. The end of the lower bar has been fixed with a rigid restraint, the load of 10 kN has been applied to the upper rod.
3. To ensure the indeterminateness of the system, the limitation of the wood mass towards the current load has been fulfilled.

3. Results and Discussion
To create a complete picture of the tests, we present the results of the numerical experiment that will be presented in the form of a diagram of strains and stress isofield and then compare them with the full-sized data. To analyze the stress - strain state of the samples under investigation, 2 computations have been performed in one working space - in this case, the resulting isopoles would graphically reflect the color-correct picture of the forces, deformations and stresses.
Figure 5. Epure of the longitudinal force $N$ and the bending moment $M$ that occur in the cable during the deformation. The calculation shows that with the centered gluing, the moment in the bar is 0.

The results of the experimental part can be analyzed using the visual method of deformation control - the presence of wood stitches in places where the fibers are torn by the action of normal and shear stresses. The second group of data is the graphs of the dependences of the resulting deformations on the applied forces obtained during the experiment, which will allow us to draw conclusions about the nature of the destruction of the glued joint of wood and wire cable.

Figure 6. The experimental full-scale procedure - fixing the samples on the tensile testing machine, the results of the applied force - splintering on the centered and side connection

The experimental results form a number of important conclusions necessary for the further research on the reinforcement technology. Firstly, on the basis of the visual analysis of the samples nature of deformation — the destruction of both types of connections occurs along the main material of the product — wood. This conclusion should be recognized as positive, since the wood destruction in this experiment suggests that all the
negative features of the wire cable don’t lead to the destruction of the adhesive layer. Previous experiments have shown that the ordinary hot-rolled reinforcement in wood develop the same attitude.

**Figure 7.** Diagram of the dependence of the sample deformation on the applied forces for the side connection (with eccentricity)

**Figure 8.** Diagram of the dependence of the sample deformation on the applied forces for the side connection (with eccentricity)
Secondly, analyzing the deformation characteristics graphs, we can conclude that the presence of eccentricity, when gluing reinforcing bars, leads to a significant decrease in the bearing capacity of the adhesive joint. The main reason for the decrease in strength is the appearance of bending forces in the reinforcing bar and the occurrence of shear stresses in the wood due to this. These findings should be followed by the negative factors that must be considered when creating the following samples. A partial solution to this problem can be expressed in the creation of a protective layer of wood on the reinforced side of the beam. This will not only increase strength, but also ensure compliance with fire safety requirements and increase the aesthetic perception of the building structure due to the absence of steel elements on the outer surfaces of the beams.

4. Conclusions
Based on the results of the experiments, we can conclude that the use of the wire cable reinforcement is a possible method of reinforcing wood. However, in further tests of this type of reinforcement, the negative effect of the location of the reinforcement eccentricity in the wood mass should be taken into account. According to the preliminary calculations, the location of the reinforcement near the lower side of the beam will reduce the bearing capacity of the adhesive joint by 30%. Therefore, it is necessary to provide for a change in the geometry of the cable location in the wood mass in such a way as to compensate for the loss of the bearing capacity of the adhesive joint by increasing the length of the reinforcement per meter of building structure. This solution can be implemented due to the flexibility of the wire cable - the use of the s-shaped reinforcement technology, which is described in other works of the team of authors of the article.

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