Local deformation and strength characteristics of S-shaped reinforcement in wood

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Abstract. Reinforced wooden beam structures under the influence of critical loads are subject to brittle fracture, which is dangerous when operating beams in buildings. To solve this problem, reinforcement of wooden beams for civil and industrial buildings was invented using steel rope as a reinforcing element. The rope is located in the stretched area of the beams along the original S-shaped trajectory. Numerical studies of the deformation of the reinforcement model using the LIRA program are performed. Based on numerical studies, samples were made for testing for pulling S-shaped anchoring elements from solid wood. The analysis of deformation - strength characteristics based on the results of tests on a tensile testing machine glued curved rods. A triple increase in the ductility of the deformation in the zone of destructive loads was revealed. The main problems of this type of reinforcement are the appearance of stress concentrators in areas with a small radius of curvature of the reinforcement. As a result of the study, the optimal trajectory of the reinforcement insert was determined with the aim of obtaining higher strength and deformation characteristics - with a reduced oscillation amplitude. The possibility of using structures in the form of safety elements has been established, which allows to increase the destruction time of beam systems when exceeding the permissible load.

1. Introduction

Turn of the twenty-first century was marked by the recognition of wood as a structural construction material suitable for high-rise construction [1-4]. Designs for the wooden building, setting records, are being developed and carried into effect throughout the entire world- in Sweden, Finland, USA, Japan, Norway, Canada, China. Notable examples of such objects are the building of the Mjøstårnet hotel with a height of 85.4 on the shore of Norwegian Lake Miesa, the building of the Brock Commons University dormitory in Canada (53 meters) or the building in Bergen (Norway) 51 meters high [5-7]. The tendency to use wood where it seems impossible and impractical forms special requirements for the constructive units that compose the bearing construction of the record-breaker buildings [8].
Experience in erecting such buildings has shown that the main load-bearing elements in such structures are wooden beam systems made from solid and glued wood. This material is expensive and difficult to process [9-12]. Therefore, the issues of saving timber during the constructing of building structures are relevant today. There are various methods of wooden beam systems modernization [13-18]. The most common methods include: introduction of steel plates into the solid wood in the node connections and along the beam length, reinforcing the wooden beams using hot-rolled steel reinforcement, modernizing wood by impregnating with various reinforcing and preserving compositions, gluing on carbon fabrics on the beams and many others [18-25].

Distinctive vulnerabilities in the operation of the modernized beam structures such as the tendency to unstable failure, putrescibility and biodeterioration, the need for reinforcing the beams support zones, issues of protection against fire exposure in case of fire and earthquake resistance have been ascertained by the numerous studies of the leading scientific associations [26-31].

There are several ways to avoid the negative impact on the strength and deformability of these factors. The first way is to increase the structures cross-sections that will lead to an increase in the cost of construction and the weight of the building, which will affect the foundation and the building base [32-35]. The second way is to apply the effective methods of reinforcement mentioned above. This method leads to an increase in the structure fabrication, however, it gains strength and significant savings of wood as the main material through the use of more durable inserts in the body of the structure [36-39]. Methods of reinforcing wood are improved with every passing year. In 2017, Koshcheev A.A. in a number of scientific articles, proposed method of reinforcing wooden beams - using steel wire reinforcement along an original curved trajectory [17].

The principle of the method of reinforcement is the use of steel wire reinforcement in the wooden beam tension area, located in the solid wood along the original S-shaped trajectory. The curved arrangement of the reinforcement should provide an increase in the length of the reinforcing bar in the wood mass per linear meter of the structure. Thereby, an increase in strength and a decrease in the structural deflection should arise. The double-lay steel wire rope is 2.8 times stronger than reinforcing bars of the comparable cross section; therefore, its use is potentially more cost-effective [40-41]. In previous author's scientific works, numerical studies of this type of reinforcement have been carried out, assumptions on the optimal trajectory for inserting a groove for reinforcing in solid wood have been made [16,17,33]. However, it is impossible to claim about the feasibility and effectiveness of using steel wire reinforcement in wooden beams without analyzing the experimental data on this reinforcement method.

The purpose of this research is to test the behavior of the steel wire rope in solid wood under tensile load on the basis of testing samples of glued segments with this type of reinforcement and to form the optimal trajectory for the reinforcing insert, giving the maximum increase in strength per square millimeter of the steel cross section in wood.

The objective of the present research is: to analyze the stress-strain state of the reinforcement along the S-shaped trajectory on the basis of the full-scale study of the samples of the steel cable elements glued into the wood; comparing the results with the data of the numerical experiment - modeling the deformation of a sample on the Lira 10.10 program, which operates by the finite element analysis; draw conclusions about factors affecting the strength of the glued joint; giving recommendations on the trajectory of further studies of this type of reinforcement.

2. Methods

Two series of samples with curved gluing of the double-lay steel wire rope in wood have been used as experimental. In the first series, the wire rope has been located on the sawn wood edge of the timber strip, in the second - in the middle of a solid wood made up by gluing two halves of the timber strip.

The first step of the experiment has been a numerical calculation on the Lira 10.10 program, which completely repeats the full-scale experiment in the field of the cross sections geometric characteristics and the materials strength characteristics.

Parameters of the numerical experiment:
The wood mass has been formed as an orthotropic 3D object of the intended size and shape: with the width of 100 mm, the depth of 100 mm, and the length of 360 mm. The body has been divided into small prisms with the subinterval of 5 mm for the implementation of the calculation by the finite element method. The element properties: Modulus of wood elasticity along the fibers has been 10000 MPa; across the fibers has been 400 MPa, the shear modulus relative to the axes directed along and across the fibers has been 500 MPa. The wood Poisson's ratio across the fibers - 0.45, along the fibers-0.018. The reinforcing material has been set in the form of an elastic bar with a cross section of the «Steel rope LK-O construction 1x7 + 1 according to GOST 3062-80» type of 1370 marking group with a profile of 6.2 mm. The core of the steel wire rope has been fixed from below by rigid restraint, the movement of the wood mass along all axes except the vertical one has been additionally limited, so that the geometric diagram of the numerical experiment has been statically unchanged. The load of 10 kN has been applied to the upper bar.

The flow diagram is shown in Figure 1. As a test sample, the author has proposed to carry out a symmetrical gluing of the steel wire into a groove made in wood by a milling cutter. This design of the sample is related to the distinction of the load application by the tensile testing machine - it is necessary to ensure the fixation of the element in the clamps, which are located on the 1 axis.

![Figure 1. The flow diagram on pulling out rods glued along the curved trajectory](image)

Let's describe the basic conditions for conducting a full-scale experiment:

The basic material is pine winter cutting wood of the first grade, dried in constant humidity testing room with the constant humidity of 23%.

The reinforcing material is steel wire rope with zinc coating. The diameter of the cable is 6 mm, the thickness of the zinc coating is 50 microns, the steel wire rope is the double-lay steel wire rope with a flexible carbon fiber core.

The adhesive composition has been an epoxy resin of the ED-20 type (based on epoxy, PEPA hardener). To make compensation for the arising temperature deformations and increase the strength properties, ground quartz of 0.2 mm fraction has been used as an aggregate. Quartz has been prepared - dried on a gas burner to eliminate the humidity effect on the resin polymerization.

The source of tensile load has been the REM – 100 – A – 1 electromechanical tensile testing machine, manufactured in accordance with GOST 28840, STO 75829762-001, listed on the State Register of Measuring Instruments of the Russian Federation No. 57528-14. The machine is designed to create a normalized value of the force during physical and mechanical tests on samples of various materials. It is equipped with a two-column module that presets force and an automated measurement and control system that allows testing according to standard conditions due to the special software -
«MTest REM-2.15», which makes it possible to determine the actual load on the sample more accurately. The external conditions of the experiment - the relative humidity in the room has been 42%, the room temperature - 23 degrees Celsius.

Description of the sample manufacturing process:

Samples for full-scale tests are made up in several stages. The first stage is the preparation of the initial materials that are used in the experiment. Massive wood-working is carried out with a Bosch GHO 40-82 C planer with the carbide tip at 30,000 rpm. Thus, surface preparation is performed for milling and for further gluing of the wooden board halves to form a centered gluing of the reinforcing bar.

The next step is milling the groove for gluing. The working machine tool is a Makita 3612C milling cutter, the grooving milling cutter with 8 mm groove with multiball bearing, to enable milling of the selected trajectory according to the template. The milling spindle rotates at 12,000 rpm to form the desired degree of the surface roughness.

When the wood samples are ready, proceed to the preparation of the steel wire rope for gluing. Only zinc-coating steel wire ropes are suitable for this operation. This is due to the absence of a greasing that protects against corrosion, which can lead to the delamination of the adhesive composition from the body of the steel wire rope. Nevertheless, even in the absence of greasing, steel is treated with acetone to degrease the surface and for the better adhesion with glue. Gluing of the reinforcing elements is carried out in two stages: first, the reinforcing bar itself is glued with brush and put into the solution, then the groove made in the wood is filled and the steel wire rope is placed into this groove. Excess glue is poured out of the groove and removed with a spatula.

After gluing the steel wire rope into the groove, manufacturing the samples with open gluing is considered to be complete – the samples are left for 20 days to ensure complete curing of the glue. The second series of samples, where the reinforcement should be centered, is prepared for gluing with the...
second half of the solid wood. ED-20 glue without sand as an aggregate is applied with a brush to the
planed surface. Two halves of the sample are combined with each other and are compressed with a
pipe clip Irwin with a compression force of 250 kg and are also aged 20 days until they gain full
strength.

Figure 4. Glueing of samples induced by clamps

Thereby, with the purpose of studying the behavior of the steel wire rope glued into the wood along
the S-shaped trajectory, 2 series of samples in threes in each series with open and centered gluing
have been made.

Figure 5. Appearance of manufactured test samples

3. Results and Discussion
Results of the numerical experiment.

The numerical calculation performed on the Lira 10.10 program allows to carry out analysis of the
work strain according to the following parameters: deformation, stress isofield in the wood mass and
stress diagrams in the steel wire rope. To perform this analysis, element calculations have been
performed in one workspace for the adequate display of the stresses color schemes.
Figure 6. Virtual experiment on pulling out a curved bar. Results of tensile stresses in the wood mass (red is the tensile zone, blue is the compressive zone)

Figure 7. Virtual experiment on pulling out a curved bar. Results of shearing stress in the wood mass (red - positive, blue - negative)

Figure 8. Virtual experiment on pulling out a curved bar. Results of the tensile forces in the reinforcing element (red - positive, blue - negative)

Results of the full-scale experiment are represented by the graphic data - changes in the shape of the reinforcement sample under the action of tensile load allow us to control the sort and the type of deformation, presence of ruptured grains at the place of the greatest shearing stress. The software of the tensile testing machine allows to develop the diagram of the stress-strain behavior for the investigated insert based on the dependence of deformations from the load applied to the sample.
Calculations on the Lira 10.10 program have shown that the stress-strain state that the wood experiences during deformation is much more complicated than the stress with the direct gluing of the bars. Local stress concentrators are visible on the first “waves” of the S-shaped reinforcement trajectory - it is at these points that failure occurs in the first turn. In addition, it can be seen on the obtained epure of the tensile forces in the reinforcement bars, that the gluing strength is mainly ensured by the first reinforcement wave - subsequent waves are less involved.
modeling is based on the elastic stage of the structure, so the calculation does not show that the next one is included in the work after the first wave deformation etc. until the waves of the reinforcement end.

Results of the full-scale experiment turned out to be somewhat unexpected for the author of the article. It was assumed that a steel cable firmly glued to the wood would be pulled out of the mass by brittle fracture and the nature of the rupture would be immediate under the maximum load. However, the nature of the deformation that is highly visible on the photo and the graph of the deformations dependence on the acting forces suggest that the deformation is plastic and takes place in a long time interval without significant change in rigidity.

![Figure 11. Curve of the stress-strain behaviour of the tested reinforcement samples](image)

4. Conclusions
Proceeding from the results of the experiments, we can conclude that there are prospects for further development of wooden reinforced structures. The main result of this experiment is the conclusion about the plastic deformation of the samples with S-shaped reinforcement gluing. This property allows us to use this type of reinforcement together with the linear steel wire reinforcement as safety systems for structures and beam systems of particular importance. Plasticity of the deformation will significantly increase the time of the construction failure under the extreme loads, which will allow to evacuate people from the building or diagnose irreciprocal structural failure in time and take measures to strengthen the elements of buildings and structures. Furthermore, based on deformation curve, this type of reinforcement possesses increased stiffness in the elastic zone of the deformation in comparison with the reinforcement samples along a straight trajectory. But there are also negative factors. The main one is localized tensioning surges in the wood at the reinforcement flexion. As a result the steel wire rope is included in the work only at the beginning of the gluing and the wood begins to collapse at this point, which entirely reduces the strength of the connection.

The author of the article considers that the main direction in the development of this reinforcement technology is an attempt to obtain some optimal reinforcement trajectory by gradually reducing the amplitude of the S-shaped wave in order to preserve the plasticity of the deformation during failure, to put into operation a steel wire rope along the entire length of the gluing in the wood and to increase the tensile strength of wooden beams where this reinforcement will be applied.
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