Innovate designs of wooden beams for buildings and structures in the arctic zone of Russia

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Abstract. The possibility of using wooden beams for ceilings and coatings in buildings and structures in the Arctic zone of Russia is studied. The innovative developments of wooden beams reinforced by steel elements and composite materials, protected by patents, their advantages, and the peculiarities of the proposed structures are analyzed. The load-carrying capacity calculations of several beam variants according to the existing methods, including the use of calculation complexes, are performed. The main advantages and directions of the rational application of innovative beams in the load-bearing elements of buildings and structures are revealed and confirmed. A comparison of material intensity, the labor intensity of manufacturing, and the reliability of operation of innovative and traditional load-bearing structures have been carried out.

1 Introduction

The search for new, more rational structural solutions for buildings and structures in the Arctic zone of Russia is an urgent task in the XXI century. The main requirement, in this case, is to ensure the necessary reliability of the building or structure with minimal material and labor intensity of manufacturing, low operating labor costs, as well as sufficient durability. In this case, various hybrid structures using steel, concrete [1], or wood are rational. Wooden girder structures are increasingly used in covering civil and industrial buildings, as well as some structures. Due to the flammability and susceptibility to biological corrosion, wood is not often used [2]. However, with the development of the methodological basis for the calculation of wooden structures [3] effective protective coatings and impregnations of wood durability of wooden structures increases significantly and their use can now be justified for several objects, including transport [4] and in low-temperature conditions [5]. In addition, as experimental studies [6] show, the strength and frost resistance of glued wooden structures at low temperatures when using high-quality adhesive compositions is quite sufficient, and the strength of wood when freezing moisture temporarily increases. To increase the load-bearing capacity and reliability of floors and coverings using wood, it is rational to use glued wooden beams, the designs of which are currently quite diverse [7-8]. Basically, in ceilings, coatings of buildings and structures, wooden beams consisting of a package of glued planks, in which reinforcing elements consisting of

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longitudinal horizontal rods and transverse inclined rods are glued. The main disadvantage of most of such solutions is, as a rule, a high labor intensity of making them, which is caused by making the system of grooves and boreholes of complex configuration in the glued package for reinforcing elements, as well as low durability associated with corrosion wear of reinforcing bars. Rationale, in this case, maybe the use of composite materials on a polymer basis as reinforcement of wooden beams [9-13], as well as the use of a better design of steel reinforcement [7].

2 Methods

We used analytical methods of calculation given in the modern norms of wooden structures design and scientific and technical literature, as well as methods of numerical simulation of structures using the design-computing complex SCAD.

3 Outcomes

We propose the use of innovative reinforced wooden beams with steel elements (Fig. 1) or composite materials (Fig. 2,3).

Fig. 1. General view of a wooden beam reinforced with steel elements (patent RU 2633721). 1-support, 2-package of glued planks, 3-C-shaped toothed strips, 4-paired frames, 5-longitudinal upper rods, 6-longitudinal lower rods, 7-inclined rods, 8-teeth, 9-holes, 10-dowels.

The beam according to the first variant reinforced with steel elements (Fig. 1) and includes a package of glued planks to the side surfaces of which using steel C-shaped toothed strips are fixed the paired frames consisting of longitudinal upper bars, longitudinal lower bars, and inclined bars, such as steel of circular, square and circular periodical section. The C-shaped toothed strips are rigidly connected with the paired frames by fixing the longitudinal upper rods, longitudinal lower rods, and inclined rods to the C-shaped toothed strips, for example, by measuring welding (Fig. 1, c). This structural solution of the beam is patented by the author and will reduce the complexity of manufacturing and increase the load-carrying capacity of the wooden beam, in particular, on the action of transverse forces, as well as reduce the material intensity of the wooden beam.
The attachment of paired frames with C-shaped toothed strips on the outer surfaces of a package of glued boards eliminates additional labor-intensive operations of arranging grooves and slots in the wood of a wooden beam, installation of reinforcement rods in them, including with their bending, gluing of reinforcement elements and wood, which leads to a significant reduction in labor intensity of production. Additionally, glue saving is ensured.

Fig. 3. General view of a wooden beam reinforced with composite (patent RU 197463). 1-Girder, 2-package of glued boards, 3-glue joint, 4-reinforcing elements
The longitudinal upper and lower bars of the paired frames, due to their attachment to the C-shaped toothed strips, work together with the wood of the laminated board package, which leads to a reduction in the bending moment from external forces and, consequently, to an increase in the load-bearing capacity of the beam.

The inclined rods are rigidly attached to the C-shaped notched strips and the longitudinal upper and lower rods of the paired frames and work together with the wood of the glulam board package. Under the action of external load on the wooden beam, tensile forces arise in the inclined bars and ensure the perception of some of the transverse forces, which leads to a reduction of transverse forces in the wooden beam and, consequently, to an increase in the bearing capacity. The presence of tensile forces in the inclined bars makes it possible to fully utilize the strength properties of steel and therefore reduce the cross-sectional area of the bars, which also leads to an increase in the load-bearing capacity of the beam.

The C-shape of toothed strips allows fixing the designed position of paired frames when they are attached to the package of glued planks. The presence of teeth on the vertical parts of the C-shaped toothed strips attached to the side surfaces of the package of glued planks provides the perception of shear forces between the paired frames and the wood, allows you to abandon several technological operations in the manufacture of the wooden beam, which will reduce the labor intensity of manufacturing. The presence of holes on the horizontal parts of the C-shaped toothed strips adjacent to the horizontal planes of the package of glued planks allows to ensure their fastening with dowels, and the absence of teeth on these parts allows to perform fastening of paired frames to the package of glued planks without deformation of these sections of C-shaped toothed strips, which generally reduces the labor intensity of manufacturing. The C-shape of toothed strips with the placement of teeth only on their vertical parts adjacent to the side surfaces of the package of glued boards allows the use of simple and effective technical means in the form of clamps or jacks for assembling a wooden beam, which also reduces the labor intensity of its production. Increasing the width b of the C-shaped toothed strips by the epicure of shear stresses arising in the wooden beam from the external load, from the middle of the wooden beam to its supports allows to ensure the alignment of their values in the C-shaped toothed strips' connections with the wood of the glued wooden board package along its length of the wooden beam and, as a outcome, reduce steel consumption of the C-shaped toothed strips.

In the upper longitudinal rods of paired frames, under the action of external loads, compressive forces arise, the magnitude of which increases from the foot of the wooden beam to its middle. The bearing capacity of the longitudinal rods, which work in compression, is determined by the limiting condition due to the stability of their shape. The reduction of pitch S of the C-shaped toothed strips from the supports of the wooden beam to its middle by the epicure of the compressive forces in the upper longitudinal bars of the paired frames allows to decrease the value of their design lengths left, and consequently, to increase the stability factor in the central compression from the supports to the middle of the wooden beam, which finally leads to the reduction of steel consumption for C-shaped toothed strips and allows to reduce the material consumption of the wooden beam in general.

The beam according to the second variant with composite reinforcement (Fig. 2) consists of two packages of glued planks symmetrically along the width of the beam, joined with tie rods and wooden strips along the length. The packages of glued planks are provided with reinforcing elements in the form of longitudinal and transverse plates of composite material, for example, carbon plastic, capable of taking tensile, compression, and shear forces while ensuring their stability, which was established experimentally [14]. Reinforcing elements are glued to the inner surfaces of the laminated board package, with the longitudinal plates having variable thickness along the section height and span of the wooden beam, and the transverse plates having variable thickness along the span of the wooden beam. Changing the
thickness of the reinforcing elements can be achieved by layer-by-layer gluing several longitudinal and transverse plates (laminates) on top of each other.

Wooden strips are fixed to the halves with dowels, such as self-tapping screws, nails, and blind blocks, and ensure that the packages of glued planks of the wooden beam work together. This structural solution of the beam is patented by the author and will reduce the complexity of production, and increase the load-bearing capacity and durability of the wooden beam. The effectiveness of such designs already has some justification in both domestic and foreign studies [15,16].

Reinforcing elements of such a beam are glued to the surfaces of glued board packages, which makes it possible to avoid labor-intensive operations of grooving or boring in the wood and leads to a reduction of the labor intensity of the wooden beam manufacturing. Reinforcing elements are made of composite material whose properties can be varied, which improves the efficiency of the beam, avoids corrosion wear of the material and, as a consequence, increases the reliability and durability of the wooden beam. The reinforcing elements are located inside the cross-section of the wooden beam composed of two packages of glued planks and are covered with wooden strips, which protect the reinforcing elements from high temperatures and solar radiation and, consequently, increase the longevity of the wooden beam as a whole.

Reinforcing elements are glued to the wood between the packages of glued boards, work together with them, and can work not only in tension but also in compression and shear. The longitudinal plates have a variable thickness along the section height and span of the wooden beam by the distribution of normal stresses in the beam from the calculated load, and transverse plates have a variable thickness along the span of the wooden beam following the distribution of transverse forces in the beam from the calculated load, which leads to an increase in the carrying capacity of the wooden beam.

In traditional timber beams with transverse steel reinforcement or bends, the load-bearing capacity of the beam for the action of the transverse force is not increased, and the transverse reinforcement is designed solely to absorb shear forces between the layers of the glued plank package. In the case of composite material plates, it is possible to increase the shear load-bearing capacity of the beam by continuous reinforcement.

The wooden slats located on the upper planes of the glued board packages can be made of hardwood and be support platforms for the distribution of large concentrated forces applied to the beam, which leads to an increase in the bearing capacity of the wooden beam on the action of local stresses.

The beam according to the third variant with composite reinforcement (Fig. 3) consists of a package of glued planks joined together by adhesive joints. The packages of glued boards are provided in the glued joints with reinforcing elements in the form of fibers of composite material, for example, carbon fiber or fiberglass. The reinforcing elements are evenly distributed along the width b of the glued board package and unevenly along the span L and the cross-section height h of the wooden beam (Fig. 1). Reinforcing elements are located along the whole height of a package of planks at the supporting part of the wooden beam 1 with the length L1≈0,15 L (Fig. 2) and in the outermost layers of the glued package of planks in the middle part along the span of the glued wooden beam 1 with the length L2≈0,15 L, L3≈0,4 L (Fig. 3).

Reinforcing elements are glued into the package of glued boards 2 in the glue joints 3 along the entire length of the glued wooden beam, working together with them, which leads to an increase in the carrying capacity of the glued wooden beam. The reinforcing elements are made of composite material, which avoids corrosive wear of the material and consequently increases the longevity of the glued wooden beam as a whole. The reinforcing elements are located inside the glued package of boards, protected by adhesive seams, which protect the reinforcing elements from high temperatures and solar radiation and, as a
consequence, increase the longevity of the glued wooden beam. Reinforcing elements are placed along the full height of the board package at the supporting section of the glued wooden beam with the length L1-in accordance with the distribution of lateral forces in the beam from the action of design load, and in the extreme layers of the glued package of boards in the middle part along the span of the glued wooden beam with the length L2, L3-in accordance with the distribution of normal stresses and bending moments in the beam from the action of design load, which leads to the higher carrying capacity of the glued wooden beam.

Reinforcing elements of fiber are placed by laying in the glue joints without additional technological operations, which also reduces the labor intensity of glued wooden beams, especially compared to the manufacture of counterparts.

The dimensions of the cross-section of the packages of glued boards, the material and thickness of the reinforcing elements, the material and thickness of the wooden strips, and the diameter and pitch of the tie rods and dowels are determined by calculation.

To select the cross-section of the innovative wooden beam, the options of rafters of the span L=18m, under the snow load for the V-th region of the Arctic zone of Russia were considered. Reinforcement of the innovative beam according to Option 1 - longitudinal rods 4d30 A300, transverse reinforcement - plates 100x3-6 mm. Reinforcement of the innovative beam according to Option 2 - carbon fiber-reinforced plastic plates 2-5 mm thick with the elastic modulus E = 150 GPa. Glulam beams without reinforcement and with steel rod reinforcement were considered alternatives. Calculation of beams was carried out with the help of the design-computer complex SCAD according to the plate-and-string scheme to analyze the stress-strain state of wood and reinforcing elements.

The outcomes of beam calculation, their design solution, and comparative analysis are summarized in Table 1. Reduction of the material intensity of innovative beams, a more uniform distribution of normal and tangential stresses in a package of glued planks is established.

**Table 1. Comparative analysis of the structural design of wooden beams.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Wooden girder</th>
<th>Reinforced wooden beam with steel reinforcement</th>
<th>Reinforced innovative wooden beam Option 1 - with steel reinforcement</th>
<th>Reinforced innovative wooden beam Option 2 - with composite reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cross section</td>
<td>1,3x0,3 m (h x b)</td>
<td>1x0,3 m (h x b) + 8d25 A400</td>
<td>1x0,24 m (h x b) + 4d30 A300, plates 100x3-6 mm</td>
<td>1x0,3 m (h x b) + -100x30 mm</td>
</tr>
<tr>
<td>2. h/L</td>
<td>1/14</td>
<td>1/18</td>
<td>1/18</td>
<td>1/18</td>
</tr>
<tr>
<td>3. Reinforcement consumption, t</td>
<td>-</td>
<td>0,3</td>
<td>0,4</td>
<td>-</td>
</tr>
</tbody>
</table>
4 Conclusion

The use of innovative reinforced wooden beams is proposed in several variants. According to Variant 1, the beam consists of a package of glued planks, to the sides of which, using C-shaped toothed strips, paired steel frameworks consisting of longitudinal upper rods, longitudinal lower rods, and inclined rods are attached. The C-shaped toothed strips are rigidly connected to the paired frames by attaching the longitudinal upper rods, longitudinal lower rods, and inclined rods to the C-shaped toothed strips. This structural solution of the beam will make it possible to reduce labor intensity and increase the load-carrying capacity of the wooden beam, in particular, on the action of transverse forces. The consumption of reinforced beam timber can be reduced by up to 35% while maintaining the stiffness and load-carrying capacity of the beam. According to variant 2, the beam consists of two symmetrical packages of glued planks along the beam width, joined together along the length by tie rods and wooden strips. Packages of glued boards are provided with reinforcing elements in the form of longitudinal and transverse plates of composite material. According to embodiment 3, the beam consists of a package of glued boards joined together by adhesive joints. The packages of glued boards are provided with reinforcing elements in the form of fibers of composite material such as carbon fiber or fiberglass in the glutinous joints. Beams have been researched using software-computer complex SCAD, based on the method of finite elements. Comparative theoretical research of the stress-strain state of wooden beams has been made based on the outcomes of automated and manual calculations by the existing norms. Rational parameters of reinforcing elements and their arrangement in a beam have been determined. The application of composite plates (laminates) makes it possible to distribute tensions along the cross-section of the wooden beam more evenly and avoid considerable stress concentration in the wood. Increased stiffness of the innovative beams as compared with the traditional wooden beam or reduction of its cross-section height is up to 30%, and reduction of material intensity in terms of wood consumption is up to 40%. The proposed wooden beams are less labor- and material-intensive with increased reliability and durability, which can be very relevant in the Far North and the Arctic zone of Russia.

References

1. V. Veselov, Application of Steel-Concrete Beam Structures in Transport Construction. Lecture Notes in Networks and Systems, 402, 269 doi: 10.1007/978-3-030-96380-4_30


