Optimization of the Configuration of Cross-Beam System
Dimensional Structure Depending on the Specified

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Abstract. This article presents an analysis of cross-beam systems made of wood-composite materials made of glued wood, highlights their positive aspects, including a significant reduction in the weight of the structure, as well as disadvantages that prevent the spread of this technology in Russia. The experience of calculation and construction of structural plates in Russia is considered. The most progressive method of arrangement of the core structure is determined experimentally. The possibilities of using cross-beam systems for the construction of public buildings and structures are considered.

1. Introduction

Wood is one of the first building materials that was used by man, but today this material is still in demand. Now the ideas of energy saving are gaining more and more popularity, and the construction of environmentally friendly materials, which allows to reduce future operating costs as much as possible, is becoming more relevant than ever. Modern wood materials not only reduce construction time, but also energy consumption, due to their low thermal conductivity, and facilitate construction, thereby reducing the load on the lowest structures. In addition, wood is the only renewable building material that allows completely waste-free production.

The first to implement the idea of building large-span and high-rise buildings using LVL wood were the Scandinavian countries, where wood is still the most common building material, but the wide possibilities of using this material in the construction of buildings with complex characteristics allow us to implement more and more of the most daring projects. Europe, striving to solve environmental problems, takes a leading position. In an increasing number of European cities, multistorey buildings are being built using wood materials as enclosing and supporting structures. Russia's largest dome of wooden structures with a diameter of 90 m is the dome of the aquapark in St. Petersburg, the largest domes of spatial wooden structures with a diameter of 143 meters, built by the European energy concern Enel, for its warehouses, and the world's tallest headquarters office will be built entirely of wooden composite materials in Sydney, for Atlassian its height will be more than 180 meters.

There is still an ambiguous attitude to wood structures in our country: the most affordable eco-friendly material, Russia is the country of the most unsurpassed wood masterpieces. The method for calculating
spatial cross-rod systems belongs to scientists of the Soviet school of engineering A. A. Gvozdev, P. L. Pasternak and V. Z. Vlasov. The method developed in the early 20th century, when in connection with a large consumption of metal, found an alternative way, in Russia in the first in the world in Arkhangelsk was built multistorey building entirely of wooden structures, but that a court order was dealt with, to this day there are strict restrictions on the use of wood in construction.

Spatially-rod structures have long been widely used, they are much less material-intensive and weigh much less than continuous structures. At the same time, the spatial structure better accepts loads, structural floor slabs, and is able to reduce uneven stresses during the construction of buildings with an irregular grid of columns, which allows its use even in earthquake-prone areas, the absence of intermediate supports and partitions ensures a free layout.

2. Methods

One of the varieties of space-rod structures, structural plates formed by the upper and lower belts of cross shapes, and having racks at the nodes of the intersection of trusses, are also widely used, but the main developments in the research of structural plates in our country were carried out mainly for metal structures, or structures with a slight inclusion of non-metal elements.

Cross-beam or cross-rod systems are used not only in construction, but are also widely used in engine building, shipbuilding, and aircraft construction.

The technology has a number of advantages: it allows you to cover large spaces, structures are manufactured in the factory, most of the work can be performed before lifting to a height, it is not material-intensive, allowing significant savings in metal—all this contributes to expanding the scope of application, allowing you to use such design solutions as coatings and ceilings of industrial buildings, warehouses, in rural construction, where the use of metal may be limited.

Nonmetal versions of cross-rod systems from separate rectilinear elements, prefabricated, with the device of inserts "half-wood", and monolithic with a nail clamp, were developed and implemented in the application of the Volokolamsk experimental plant of building structures and the laboratory of wooden structures of Central research Institute of building structures in Volokolamsk. Forces in the stretched zone of the cross—rod system are perceived by cross-shaped metal cores and high-strength bolts, and in the compressed zone—by a frontal stop. The structures can’t be considered perfect, according to their own tests, most of the materials in the structure do not work together, and in part of the section due to weakening, significant stress concentrations occur that reduce the load-bearing capacity, and there is a need for additional reinforcement of elements in areas of concentrated transmission of longitudinal forces.

In comparison with an all-metal structural plate, replacing belts and compressed elements with wooden ones, and stretched elements with wooden ones reinforced with high-strength steel rods, when the forces arising in the coating are perceived by steel nodes, reduces the total weight of the metal by 65-75%.

Main advantages of glued wood: at low weight, it has a high load-bearing capacity, high accuracy and dimensional stability, uniform structural composition, no cracks or twisting compared to solid wood, low thermal conductivity, and C02 neutrality.

For a long period of time, the development of classical methods for calculating statically indeterminate systems that lead to the solution of a large number of systems of linear equations was hindered by computational difficulties.

Given the lack of experience in the field of research, manufacture and operation of such structures, the proposed topic is very relevant.

The purpose of the study is to clarify the optimal design solution, spatial configuration and calculation of wooden structures, when changing parameters.

Objectives of the study are: selection of the optimal solution the cross-coating systems with orthogonal and diagonal arrangement of beams of wood of different breeds through research in software construction,
and evaluation of bearing capacity and stress-strain state of design of flexible elements of composite sections.

Taking into account that different types of wood have different indicators of elastic modulus and shear modulus, and the forces must be fully perceived by the cross-section, so that the bar reinforcements of stretched rods could take a minimum cross-section sufficient for this load, the study was conducted by experimental and theoretical studies of stability and verification of calculation models using the finite element method, taking into account displacements. The numerical experiment was carried out using the computational and graphical robot complex, which allows determining the stress-strain state of structures from dynamic and static influences, and performing a number of functions for designing structural elements.

For the design scheme, we adopted beam structures with orthogonal and diagonal arrangement of beams in the form of a space-rod model of the General form 48x48m, which is located in the XOY plane, consisting of rods rigidly conjugated to each other at nodes (Fig. 1). The hinge support of the structure on the pillars is set by superimposing connections in the direction of the X, Y, and Z axes.

Structures with different configurations were calculated under the same conditions, with the same load of 10kn, followed by a gradual reloading in steps of 5kN, until the moment of loss of stability, which allowed us to determine the critical force.

The main unknown quantities are the movements and rotations of the nodes of the design scheme. Based on this, the idealization of the design is embodied in a form adapted to the use of this method, in the form of a certain set of standard-type bodies that are attached to the nodes.

The condition of non-monolithic coupling of cross-beam systems made of wooden elements with coating elements is implemented by setting the coating plate thickness of 1 mm. In this case, the coating performs only the functions of transferring the load to the structure, and at the same time will not participate in its overall operation (Fig. 2).

For greater clarity, the design model was loaded on a span of ½, while depending on the stress-strain state (VAT) of the design cross-section, the stresses over the entire cross-section area did not exceed the

Figure 1. Visualization of the design model of the beam structure in the ROBOT program using the example of an orthogonal and diagonal 48x48m scheme.
design resistance $\sigma \leq \frac{R_y}{\sqrt{2}}$, according to the first group of limit States, i.e. the structures were designed for strength and stability.

For the experiment, we selected existing composite cross-section beams made of LVL beams with cross-section material [6, 7]:

- oak/birch/oak (modulus of elasticity – 14300/18 300/14 300 MPa; Poisson's ratio – 0.41/0.45/0.41. The shear modulus – MPa 1380/1510/1380);
- oak/birch/pine/birch/oak (modulus of elasticity -14300/18 300/12 100/18 300/14 300 MPa; Poisson's ratio– 0.41/0.45/0.41/0.45/0.41; shear modulus-1380/1510/1210/1510/1380 MPa);

And for comparison, the indicators of a solid oak beam were used.

The same sections were set:
- Belts – 100x250mm
- Racks – 50x100mm
- Braces – 100x225mm

Figure 2. loading Diagram for an orthogonal and diagonal beam system.
Beam 2:

Load-applied to the surface of the coating, equivalent to 1.86 kPa.
Static calculation is performed in the robot calculation and graphics complex. the stretching forces are given with a sign (-), and the compressing forces are given with a sign (+).
Nx cards for rods. Load per ½ span (10 kN)
With an orthogonal scheme

Beam 3:
Table 1. Calculation results.

|          | EX(kN) | FY(kN) | FZ(kN) | MX(kNm) | MY(kNm) | MZ(kNm) |
|----------|--------|--------|--------|---------|---------|---------|
| MAX      | 193.37 | 0.11   | 0.83   | 0.02    | 1.02    | 0.27    |
| Rod      | 793    | 726    | 855    | 725     | 757     | 238     |
| Knot     | 140    | 217    | 282    | 305     | 138     | 145     |
| Loading  | 1      | 1      | 1      | 1       | 1       | 1       |
| MIN      | -71.35 | -0.19  | -0.83  | -0.02   | -1.07   | -0.30   |
| Rod      | 227    | 238    | 848    | 750     | 530     | 238     |
| Knot     | 135    | 144    | 275    | 73      | 39      | 144     |
| Loading  | 1      | 1      | 1      | 1       | 1       | 1       |

Max force: **-193.4 kN**; Max movement: **-5.5 cm**

Figure 3. Beam 2: the Weight of this structure is 54,112 kg.

Table 2. Calculation results.

|          | EX(kN) | FY(kN) | FZ(kN) | MX(kNm) | MY(kNm) | MZ(kNm) |
|----------|--------|--------|--------|---------|---------|---------|
| MAX      | 248.95 | 0.17   | 1.36   | 0.03    | 1.92    | 0.42    |
| Rod      | 833    | 726    | 855    | 725     | 825     | 726     |
| Knot     | 280    | 217    | 262    | 305     | 104     | 217     |
| Loading  | 3      | 3      | 3      | 3       | 3       | 3       |
| MIN      | -102.65| -0.17  | -1.19  | -0.03   | -1.58   | -0.42   |
| Rod      | 550    | 788    | 850    | 735     | 747     | 788     |
| Knot     | 159    | 238    | 278    | 242     | 170     | 238     |
| Loading  | 3      | 3      | 3      | 3       | 3       | 3       |
Max force: -248.05 kN; Max movement: -4.9 cm

Figure 4. Beam 3: the Weight of this structure is 51,029 kg.

3. With a diagonal scheme

| Table 3. Calculation results. |
|-------------------------------|
| | FX(kN) | FY(kN) | FZ(kN) | MX(kN.m) | MY(kN.m) | MZ(kN.m) |
| Max | 116.21 | 0.26 | 0.88 | 0.01 | 1.65 | 0.46 |
| Rod | 1642 | 18 | 383 | 1240 | 63 | 18 |
| Knot | 91 | 12 | 231 | 216 | 39 | 12 |
| Loading | 1 | 1 | 1 | 1 |
| MIN | -61.06 | -0.34 | -0.88 | -0.01 | -1.65 | -0.58 |
| Rod | 1776 | 239 | 63 | 1233 | 383 | 228 |
| Knot | 50 | 144 | 39 | 48 | 231 | 144 |
| Loading | 1 | 1 | 1 | 1 |
Max force: **-116,21 kN**; Max movement: **-3,6 cm**

**Figure 5.** Beam 2: the Weight of this structure is 34,176 kg.

**Table 4.** Calculation results.

|                | **FX(kN)** | **FY(kN)** | **FZ(kN)** | **MX(kNm)** | **MY(kNm)** | **MZ(kNm)** |
|----------------|------------|------------|------------|-------------|-------------|-------------|
| **MAX**        | 122.59     | 0.29       | 0.99       | 0.06        | 1.84        | 0.51        |
| **Rod**        | 1642       | 18         | 383        | 1240        | 63          | 18          |
| **Knot**       | 91         | 12         | 231        | 216         | 39          | 12          |
| **Loading**    | 1          | 1          | 1          | 1           | 1           | 1           |
| **MIN**        | -64.53     | -0.37      | -0.99      | -0.06       | -1.84       | -0.63       |
| **Rod**        | 1776       | 238        | 63         | 1233        | 383         | 238         |
| **Knot**       | 50         | 144        | 39         | 48          | 231         | 144         |
| **Loading**    | 1          | 1          | 1          | 1           | 1           | 1           |

Max force: **-122,59 kN**; Max movement: **-3,2 cm**

**Figure 6.** Beam 3: the Weight of this structure is 31,726 kg.
4. For comparison, the results of the study of solid oak beams are presented
For the orthogonal scheme: Max force: -104.8 kN; Max displacement: -8.3 cm
For diagonal design: Max force: -97.65 kN; Max displacement: -5.3 cm

|                  | EX(kN) | FY(kN) | FZ(kN) | MX(kN.m) | MY(kN.m) | MZ(kN.m) |
|------------------|--------|--------|--------|----------|----------|----------|
| MAX              | 97.65  | 0.25   | 0.84   | 0.01     | 1.29     | 0.44     |
| Rod              | 1705   | 23     | 383    | 1206     | 63       | 23       |
| Knot             | 187    | 15     | 231    | 216      | 39       | 15       |
| Loading          | 3      | 3      | 3      | 3        | 3        | 3        |
| MIN              | -59.09 | -0.32  | -0.80  | -0.01    | -1.57    | -0.54    |
| Rod              | 2649   | 276    | 1266   | 1051     | 383      | 278      |
| Knot             | 32     | 168    | 237    | 72       | 271      | 168      |
| Loading          | 3      | 3      | 3      | 3        | 3        | 3        |

Figure 7. Diagram of movements depending on the material of the structure (orthogonal and diagonal) when loading $1/2$ span.

Based on the presented results, it is clearly seen that by changing the cross rod system from orthogonal to diagonal, it is possible to significantly reduce the forces on the structure, thereby reducing weight, and deformation (displacement), but at the same time increasing the maximum moment acting on the structure by 18%

5. Conclusions
The calculation of a spatial cross-beam system loaded with a stamp load for $1/2$ span, with a constant elastic modulus $E = 14300$ MPa in accordance with the set of rules (SP 64.13330.2011) and a variable
elastic modulus.

The obtained deflection values are analyzed and compared with the limit value for this design. The maximum deflection values under the applied load do not exceed the permissible values. The study was conducted without taking into account the malleability of nodal connections.

From this we can conclude that the set of parameters: stress, displacement and weight, with the maximum loading of the rods in the spatial structure the most effective use of the diagonal truss system, it is 39.9% more efficient design with orthogonal position of the belts. The structure is also influenced by the composition of the material (solid wood, beam 2 (oak, birch), beam 3 (oak, pine, birch)). According to research, Beam 3 is more profitable to use than solid wood and beam 2 in terms of weight, maximum moments and movement of the structure.

The study confirms the need to clarify the calculations and account for wood creep. The data from the experiment may be of a recommendatory nature.

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