Investigation of Wooden Fire-Resistant Plate with Spatially Structure

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Abstract. The cross-rod system under consideration is widely used in various fields: industrial and civil construction, aircraft and shipbuilding. There are a large number of methods for calculating these structures’ types, based on differential dependencies system of the 4th order, describing the bending of a flat covering. However, the main reason in solving problems for calculating cross-rod systems is the complexity of mathematical calculations and a large amount of labor, since the system is statically indeterminate. It leads to a large number of linear equations’ systems solution with boundary conditions. The use of computers in the calculation of cross-rod systems allows you to make both dynamic and static calculations of building structures with high accuracy. At the same time, simplified ideal schemes are used in the calculation of structures, where the elements are connected to each other either rigidly or pivotally. In real designs, the connections are elastic and cannot always be replaced with ideal analogues, used in the design schemes. The use of ready-made laminated structures allows reducing not only the cost of production, labor intensity and construction in general, but also the totality of all factors, such as the timing of construction and installation work on the reconstruction and overhaul of buildings and structures.

1. Introduction

Wood has a low coefficient of thermal conductivity, which significantly increases the energy efficiency of the structure as a whole. The use of wooden structures reduces logistics costs due to their transportability. In addition, due to the increased factory readiness and prefabricated wooden structures, the speed of construction increases. In general, the construction of buildings made of timber in Northern latitudes is a promising direction due to technical, aesthetic and geometric characteristics of the structure [1-3].

The suggested technological solution is a multilayered structure consisting of a cross-rod, a wooden frame (Figure 1), which cells are filled with basalt mineral wool plates with a density of not more than 50 kg/m³ to beams height to prevent formation of air gap, in order to ensure the impossibility of fire propagation in a structure interior. For gluing the frame, a special fire-fighting two-component glue is used, which increases in volume, exposed to high temperatures and direct flame exposure, forming a coke cap between the glued layers, which prevents further spread of fire and impact on the overlying layers of the structure. A cement-chip panel with a thickness of 12.5 mm is arranged, followed by a waterproofing coating on the top of cross-rod frame. It is also possible to install other coatings that are similar in strength characteristics.
The plate consists of mutually perpendicular glued rods forming 560x560mm cells. These rods are bars with a 40x30 mm cross section, which are glued together on the face with two-component Chartek 7 fire-proofing glue. This variant is better, then designed from CLT plates [5-8].

The pitch of ribs is assumed to be 600 mm, based on the calculations and design features of the used materials, which is no more than 880 mm. The walls; cross section of the resulting cells is 210x40 mm, the material is second-class wood (pine). The plate is 4.5 m long and 3.3 m wide.

![Figure 1. Layout of the load-bearing elements of the covering plate.](image)

According to the summary statistics [4] the damage from fires is not only difficult to compensate, but at the same time it still requires large expenses for the restoration of buildings, structures or individual structural elements which damaged by fire.

The Chartek 7 fire-proofing adhesive, used in the production of cross-core covering plates for buildings and structures, ensures the resistance of adhesive joints to various temperature and humidity influences, and provides the strength of adhesive joints. The glue contains components that contribute to the formation of an increased volume of the coke layer, exposed to flames on the engineering wood structure to ensure the normalized limit of wooden building structures’ fire resistance.

### 2. Materials and Methods

The collection of loads according to the impacts. An updated version of BNP 2.01.07-85, to Table 8.3, per 1 m² of horizontal surface, is shown in Table 1.

| Load name     | Standard load, kN/m² | The reliability coefficient for the load | Design load, kN / m² |
|---------------|----------------------|----------------------------------------|----------------------|
| Full load     | 3.16                 | 1.3                                    | 3.93                 |

Software package is used for numerical analysis, the SCAD Office 21.1. The plate edges are set by volumetric elements to account for the anisotropic properties of the wooden frame (Figure 2). The plate is assumed to be supported pivotally on the four sides.

The values of total displacements relative to the Z axis for the design scheme specified as volumetric bodies are shown in Figure 3.

The maximum value of displacement, setting the design scheme in the form of volumetric bodies, is 12.67 mm; it is 13.02 mm in the form of core elements. Thus, the error is 2.68%, which is less than 5% and is within the norms.
Figure 2. Calculation scheme of the covering plate, specified by volumetric bodies.

Figure 3. Total movement of the covering plate along the Z axis.

Figure 4. The value of calculated bending moments.

The maximum moment of the weakened section is taken according to Figure 4 to be equal to 3.46 kNm. The condition for strength is fulfilled with a margin 15.2% strength, which is less than 20%, respectively, the design decisions are correct. The permissible deflection for a span of 4.2 m is 24.7 mm.

Numerical dynamic calculation is performed in a modal analysis form of the cross-rod covering structure in order to establish the natural vibrations values of the system under study. The calculation is correct; the static loads of each system element's own weight are converted to mass.
The natural oscillation frequencies values of the cross-rod structure of the covering plate under study for the design scheme, specified by the rod elements, are presented in Table 2. The natural frequencies values of the structure vibrations, specified by volumetric bodies, are presented in Table 3.

Table 2. The values of natural vibrations in the rod design scheme.

| Loading | Form | Own value | Frequency 1/sec | Frequency Hz | Periods (sec) |
|---------|------|-----------|----------------|--------------|---------------|
| 3       | 1    | 0.005     | 369.412        | 55.712       | 0.017         |
| 3       | 2    | 0.002     | 412.486        | 65.683       | 0.015         |
| 3       | 3    | 0.001     | 704.852        | 112.238      | 0.009         |
| 3       | 4    | 0.001     | 797.349        | 126.966      | 0.008         |
| 3       | 5    | 0.001     | 856.451        | 136.378      | 0.007         |

Table 3. The values of natural oscillations in the volumetric calculation scheme.

| Loading | Form | Own value | Frequency 1/sec | Frequency Hz | Periods (sec) |
|---------|------|-----------|----------------|--------------|---------------|
| 11      | 1    | 0.006     | 330.447        | 52.619       | 0.019         |
| 11      | 2    | 0.004     | 403.540        | 64.258       | 0.016         |
| 11      | 3    | 0.002     | 650.150        | 103.527      | 0.010         |
| 11      | 4    | 0.002     | 748.796        | 119.235      | 0.008         |
| 11      | 5    | 0.001     | 844.735        | 134.512      | 0.007         |

Within the framework of the study, we take into account the first form values of oscillation. The deformation scheme 1 of the oscillation form is shown in Figure 5.

Figure 5. The 1st form of oscillation of the system under study.

The difference between the considered methods for setting the design scheme is 5.5 %

The data obtained are used for comparison with the data obtained from dynamic tests performed on a full-size covering plate model.

For the test, a frame was made to secure the covering plate, as shown in Figure 6.
Figure 6. A frame for testing the model.

The panel is loaded with concrete blocks weighing 58 kg, with dimensions of 600x400x100mm. The layout of the first and second concrete blocks layers is shown in Figure 7. The layout of the third concrete blocks layer is shown in Figure 8.

Figure 7. The diagram of the first and second layers of concrete blocks.

Figure 8. The layout of the third layer of concrete blocks.

The mechanical tests’ results of a full-size covering plate are shown in Table 4.

| No | Layer-by-layer loading | The weight of the layer, kg | Z-axis movement, mm | Total movement along the Z axis, mm |
|----|------------------------|-----------------------------|--------------------|-----------------------------------|
| 1  | 1 layer of concrete blocks | 2436                        | 6.39               | 6.39                              |
| 2  | 2 layer of concrete blocks | 2436                        | 4.55               | 10.94                             |
| 3  | 3 layer of concrete blocks | 232                         | 0.56               | 11.5                              |

A comparison of the data, obtained as a result of static tests with the numerical calculations values in SCAD software package, is presented in Table 5.

| Loading                        | Displacement, mm |
|--------------------------------|-------------------|
| Structure own weight           | 0.4               |
| Design load                    | 12.61             |
| The main combination of loading| 13.02             |

| Loading                              | SCAD rod system | SCAD Volumetric elements | Static tests |
|--------------------------------------|-----------------|--------------------------|--------------|
| Structure own weight                 | 0.37            | 0.35                     |              |
| Design load                          | 12.28           | 12.67                    | 12.57        |
| The main combination of loading      | 12.67           | 12.57                    |              |
The difference between the results, obtained during static tests on a full-size model of a cross-rod plate from the values of numerical calculation result in SCAD software complex, specifying the design scheme with volumetric elements is 0.79%.

The difference between the results, obtained during static tests on a full-size model of a cross-rod plate from the values of numerical calculation result in SCAD software complex, specifying the design scheme with rod elements is 3.5%.

It could be argued that the purity of static tests was ensured, since the obtained values of vertical displacements during numerical calculation and static tests differed by less than 5%.

Dynamic tests are performed in order to obtain the natural frequencies values of the system’s vibrations under study. The IV-99 vibrator was used as the exciter of forced vibrations. The engine itself was installed on a platform, which was rigidly attached to the central cell of the covering plate.

![Figure 5. The IV-99 vibrator.](image)

This type of engine has the ability to adjust the static torque. The MG 4.01 vibration test was used to fix the test work, which was attached to a previously prepared steel support in the immediate vicinity of the vibration exciter (vibrator).

Figures and tables, as originals of good quality and well contrasted, are to be in their final form, ready for reproduction, pasted in the appropriate place in the text. Try to ensure that the size of the text in your figures is approximately the same size as the main text (10 point). Try to ensure that lines are no thinner than 0.25 point.

3. Results

Analysis of the data measuring device is based on the methods of mathematical statistics by calculating the average of obtained results of dynamic tests as part of the determination of natural frequencies of cross-rod design of the plate. The final value of the natural frequencies of vibrations is obtained using the three sigma method, with the exception of values that differ significantly from the arithmetic average, taking into account the Wright criterion.

The final results of dynamic tests of the full-size covering plate are presented in Table 6.

| Parameter                      | Frequency F, Hz |
|--------------------------------|-----------------|
| 1                              | 2               |
| The arithmetic average         | 54.52           |
| σ                              | 0.036           |
| 3σ                             | 0.108           |
| Δ                              | 0.072           |
| δ                              | 0.0013          |
| Confidence probability of 0.95 |                 |
| Total                          | 54.59           |

The value of the natural oscillation frequencies of the studied structure as a result of dynamic tests is 54.59 Hz.
Summary data of the values of natural oscillation frequencies of the design under study are presented in Table 7.

Table 7. Summary table of natural frequency values.

| Natural oscillation frequencies of the cross-rod covering structure | SCAD rod system | SCAD volumetric elements | Tests |
|---------------------------------------------------------------|-----------------|--------------------------|-------|
| Tests                                                         | 55.71           | 52.62                    | 54.59 |

In comparison with the numerical calculation’s results of the cross-rod covering structure, a difference is found:
- compared with the rod design scheme.

\[ \Delta_{part1} = \frac{f_{max1} - f_{min1}}{f_{max1}} \times 100% = \frac{55.71 - 54.59}{55.71} \times 100% = 2.01\% \]  
(1)

- compared with a volumetric calculation scheme

\[ \Delta_{part2} = \frac{f_{max2} - f_{min2}}{f_{max2}} \times 100% = \frac{54.59 - 52.62}{54.59} \times 100% = 3.61\% \]  
(2)

The obtained values of differences between the results of the dynamic tests performed and the numerical dynamic calculation with various options for setting the design scheme are less than 5%, and it can be argued that the purity of the scientific experiment was ensured.

V. I. Korobko derived a regularity that proves the connection between the maximum deflection and the frequency of own transverse vibrations of elastic isotropic plates [1-4]:

\[ W_0 \omega^2 = K \frac{q}{m} \]  
(3)

From the equation above, the authors conclude that for all plates with unchangeable boundary conditions, the product \( W_0 \omega^2 \) will be represented by a single curved line (Figure 10).

It is worth noting that the product \( W_0 \omega^2 \) considered in this regularity does not depend on the bending stiffness and dimensions of structures. Shapes can be diverse - from round to infinitely elongated.

![Figure 10. Dependency \( W_0 \omega^2 - 1/K_f \).](image)

Let us perform an analytical comparison of the obtained values of the similarity coefficient K:

\[ \Delta_1 = \frac{K_{theory} - K_{number1}}{K_{theory}} \times 100% = \frac{1.614 - 1.6}{1.614} \times 100% = 0.87\% \]  
(4)
Thus, it can be noted that the most approximate theoretical data is the method for setting the design scheme using rod elements. We will perform an analytical comparison of the similarity coefficient $K$, obtained theoretically with the values as a result of static and dynamic full-size model tests of the cross-bar covering plate:

$$
\Delta_1^P = \frac{K_{\text{number}} - K_{\text{fact}}}{K_{\text{number}}} \cdot 100\% = \frac{1.614 - 1.394}{1.614} \cdot 100\% = 13.88\% 
$$

(5)

Based on the data obtained, it can be noted that the difference between the values of the similarity coefficient $K$ between theoretical and practical values is from 6.33% to 8.05%. The difference is essentially small, which allows suggesting the possibility of using the functional dependence of the square product of the natural frequencies’ vibration in the unloaded state and the maximum deflections at the calculated load for the cross-rod structures of floor slabs, derived by V. I. Korobko.

4. Discussion
As part of the research, a cross-rod covering plate of engineered wood was constructed for use in buildings and structures reconstruction, as well as possible use in individual construction. Various design solutions were proposed that allow different types of floor coverings to be arranged for this design, taking into account modern requirements for fire safety in the construction sector. The proposed covering plate solutions assume full compliance with fire safety requirements for buildings of the II and III fire resistance degree – the fire resistance limit of the proposed solutions REI45.

A scientific study was also conducted the possibility of using the functional dependence of the square product of the natural frequencies’ vibration in the unloaded state and the maximum deflections at the calculated load for the cross-rod structures of floor slabs, derived by V. I. Korobko.

A numerical simulation of the structure under study was performed using SCAD Office 21.1 software package in two variants of the design scheme: using rod elements and volumetric bodies that allow taking into account wood anisotropic properties. Later, numerical calculations were performed for the impact of static and dynamic loads. The results of numerical calculations under study showed that there was a slight error in different methods of setting the design schemes. Data from static tests differed by 2.68%, and dynamic tests by 5.5%.

Displacement values were calculated from exposure to combinations of loading, which differed from numerical simulations by 0.79% and 3.5%, and natural frequencies values of the investigated structure in an unloaded state, by 2.01% and 3.61 per cent, conducting full-scale static and dynamic tests on full-sized model of cross-rod plate from engineered wood. Such differences allow us to assert that the purity of conducting field tests was ensured.

The similarity coefficient $K$ was taken as the parameter under study, taking into account the method of supporting the plate and its geometric shape, investigating the possibility of using the functional dependence, derived by V. I. Korobko. The comparison was made with reference materials containing values of similarity coefficients for different situations. Numerical simulations showed differences of 0.87% and 13.88% from the theoretical data. At the same time, full-scale tests showed differences in the similarity coefficient from the theoretical values by 8.05%.

Experimental data showed that the obtained values largely coincide with the theoretical values, as well as with the values of numerical calculation result.

5. Conclusion
The main reason for the discrepancy between practical and theoretical values is that static and dynamic tests themselves have differences in relation to the options, used for numerical calculations of
the design under study[13]. These differences indicate that it is impossible to give the stress-strain state results of structures, made of solid and engineered wood with maximum accuracy, since wood has anisotropic properties as a material, the lumber, used in the work, has uneven shrinkage and various defects, while the nodal joints of the structure are not absolutely rigid, but on the contrary malleable, which leads to errors. It is necessary that timber and wood-based components and structural elements should not be unnecessarily exposed to climatic conditions more severe than those expected in the finished structure[14].

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