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EXPERIMENTAL AND THEORETICAL STUDIES OF DYNAMIC CHARACTERISTICS OF WOODEN FRAME BUILDINGS

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Abstract: The research carried out in this paper is reduced to studying the design features of wooden frame structures and analyzing the nature and degree of influence of individual structural elements on the work of the frame as a whole based on a comparison of experimental and theoretical data. The results of the studies with the evaluation of natural oscillations are the basis for the correct modeling of structural systems when performing static and dynamic calculations.

Keywords: wooden frame buildings, dynamic characteristics, natural oscillation frequencies

ЭКСПЕРИМЕНТАЛЬНО-ТЕОРЕТИЧЕСКИЕ ИССЛЕДОВАНИЯ ДИНАМИЧЕСКИХ ХАРАКТЕРИСТИК ДЕРЕВЯННЫХ КАРКАСНЫХ ЗДАНИЙ

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Аннотация: Проводимые в данной работе исследования сводятся к изучению особенностей конструирования деревянных каркасных сооружений и анализу характера и степени влияния отдельных конструктивных элементов на работу каркаса в целом на основе сопоставления экспериментальных и теоретических данных. Результаты исследований с оценкой показателей собственных колебаний лежат в основе корректного моделирования конструктивных систем при выполнении статических и динамических расчетов.

Ключевые слова: деревянные каркасные здания, динамические характеристики, частоты собственных колебаний

INTRODUCTION

The construction of buildings and structures with a wooden load-bearing frame is currently being increasingly used, both in the world and in domestic practice. There is a tendency to increase the number of floors of wooden frame housing construction. A serious advantage of frame structures is the fact that, having a low weight, high spatial strength and stability, they allow you to build buildings on lightweight foundations.

The article is devoted to the study of the dynamic characteristics of wooden frame buildings. The relevance of the presented topic is due to the need to further reduce the cost of frame construction in compliance with the standards of structural reliability, safety and energy efficiency by improving the design schemes performed on the basis of an in-depth study of the nature and degree of influence of the elements of the frame and cladding on the spatial strength and rigidity of the structure. Such studies are of absolute practical importance for objects being built in seismically active zones.

The basis of the load-bearing skeleton of the buildings in question is a wooden frame formed by racks, bindings and floor beams, which are combined into a single spatial scheme using various rigidity elements in the form of struts, sheathing, diaphragms, etc. The spatial strength and immutability of the system can be realized in different design variants: due to the joint work of the main elements of the frame with diagonal bracing elements in the plane of walls and ceilings, or due to the joint work of the frame and sheathing, in the absence of bracing connections. Combined variants are also possible, combining the joint work of all elements – braces, paneling in the form of plates or composite boards made of boards, profiled sheet, etc.

The calculation of wooden frame structures is a complex task that requires taking into account many factors. It should be noted that one of the main problems in the design of such structures is associated with their modeling in computational complexes, namely, the difficulty of analyzing and taking into account factors affecting their stress-strain state, since wood as a structural material, due to natural anisotropy, has a significantly greater spread of mechanical characteristics compared to such materials, like steel and concrete. Additional and very important parameters for modeling and calculation in software and computing complexes are the deformation characteristics of joints. Most often, nodal joints are assembled on nagel-type joints that have a certain malleability.

These problems contributed to the development of new methods and approaches to the calculation of wooden frame structures [1-17]. So, Saule Tulebekova and co-authors in their work investigated the effect of operational load on the rigidity of frame high-rise buildings made of glued beams [18]. P.V. Maksimov, A.I. Volkov in their work consider the features of numerical calculation of VAT of frame wooden structures using the finite element method and give recommendations for taking into account the complex physical and mechanical properties of wood, implementation of numerical counting in the ANSYS package [19].

In this article, the analysis of the influence of individual structural elements on the work of the frame as a whole is carried out by comparing experimental and theoretical data. For this purpose, the following tasks were set:

1. Production of an experimental fragment of a frame structure in different structural variants – a frame, a frame with plywood sheathing, a frame with diagonal braces, a frame with diagonal braces and an outer plywood sheathing.
2. Conducting experimental studies of the dynamic characteristics of fragments using the RSV-150 vibration measuring system.
3. Modeling of the computational schemes of the test fragments in the SCAD Office and Lira soft package.
4. Analysis of experimental and theoretical data to assess the comparability of the results of experimental and theoretical studies.
5. Drawing up recommendations based on the data obtained on improving the calculation methods of wooden frame structures in software and computing complexes.
6. Preparation of recommendations for the program of further studies of the dynamic characteristics of wooden frame systems, assemblies and parts.

1. EXPERIMENTAL STUDY OF NATURAL VIBRATIONS OF STRUCTURES OF WOODEN FRAME BUILDINGS

To identify the dynamic characteristics of natural vibrations of structures, the RSV-150 Polytec vibration meter was used, which is a universal device used to measure vibrations of structures located at short and long distances (from 5 to 300 m).

The sensor head contains an optical detector module with an infrared laser beam. It also contains a green “binding” laser and a video camera used to indicate the object of study. The controller includes a decoder of the speed of the measured signal, as well as electronic control modules for the sensor head and its power supply. To perform vibration measurement, a beam of a helium-neon laser is directed at an oscillating object and reflected from it. Due to the occurrence of the Doppler effect, the speed and movement of the oscillating object form a frequency or phase modulation, which is restored in the signal processing module using appropriate demodulators (or decoders). The speed information is recovered from the frequency modulation of the Doppler signal, the displacement signal is recovered from the simultaneously available phase modulation. The values of the velocities or movements of an object are recorded at equal very small intervals (from thousandths to millionths of a second), forming discretized functions of time, and digitized on electronic media, stored in the PC memory.

Polytec Vibrometer Software (VibSoft) is used to display and analyze measurement results using a PC. Next, a high-precision spectral display of measurement results is carried out using Fourier transforms. Spectral functions are also stored in the PC memory in separate files. With the help of this device, the frequency of natural vibrations of the object in the longitudinal and transverse directions was determined.

The object under study is a fragment of a frame structure. The fragment is a rectangular structure with dimensions of 2.08x1.56 m. The height of the walls is 2.08 m. The frame is made of a grade 1 board with a cross section of 120x40mm. The cladding on the outside is made of plywood with a thickness of 9 mm.

Dynamic characteristics were tested for four different combinations of the frame in order to study the effect of each element on the spatial rigidity of the structure as a whole:

Frame 1 – Frame without braces. The frame consists of vertical racks, upper and lower strapping, horizontal jumpers.

Frame 2 is a frame with inclined braces.

Frame 3 is a frame with plywood covering on the outside of the fragment.

Frame 4 – Frame with braces and plywood sheathing (so-called full frame).

Figure 1. Frame 1

Figure 2. Frame 2

Figure 3. Frame 3

Figure 4. *Frame 4*

To exclude noise processes, noise vibrations were measured, followed by spectral mapping of frequency peaks characteristic of noise processes (Fig. 5).

The displacement values were measured horizontally along the transverse and longitudinal axes of the structure.

The fixation of oscillatory processes was loaded in digitized form into the memory of the PC hard disk. Further, the oscillations were subjected to spectral mapping to detect the frequency peak characteristic of the impact.

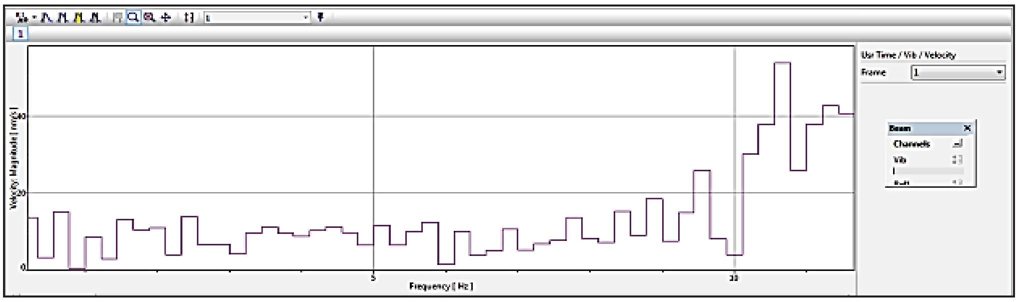

Figure 5. *Spectral display of noise vibrations*

The distances from the measuring equipment to the building had values from 7 to 10 m, which satisfies the conditions of effective measurements of the RSV-150 device.

The results of spectral mapping are presented in Figures 6-13.

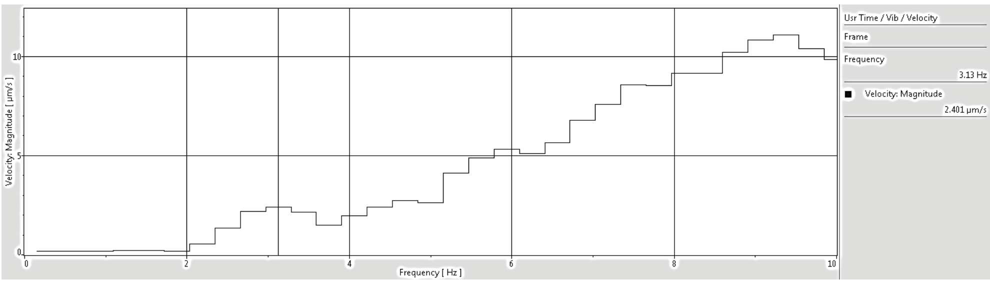

Figure 6. Frame 1. Time interval and spectral mapping of oscillatory processes in the longitudinal direction

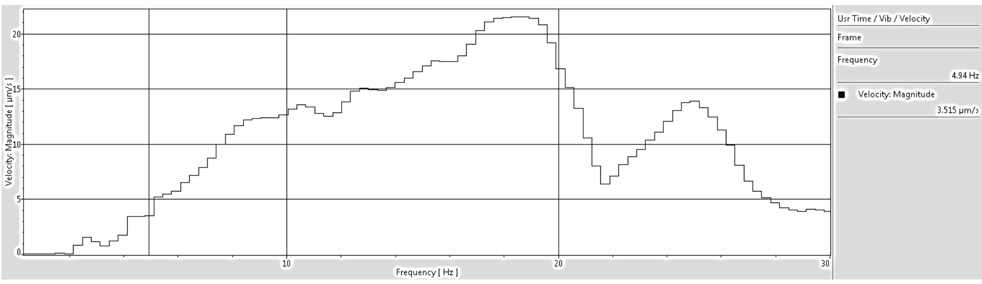

Figure 7. Frame 1. Spectral mapping of oscillatory processes in the transverse direction

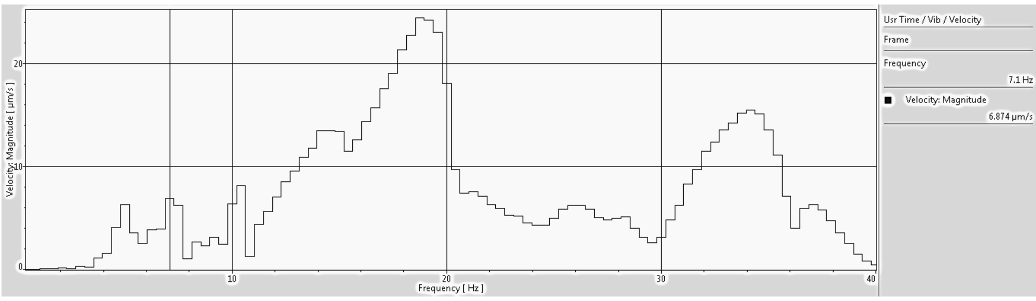

Figure 8. Frame 2. Spectral mapping of oscillatory processes in the longitudinal direction

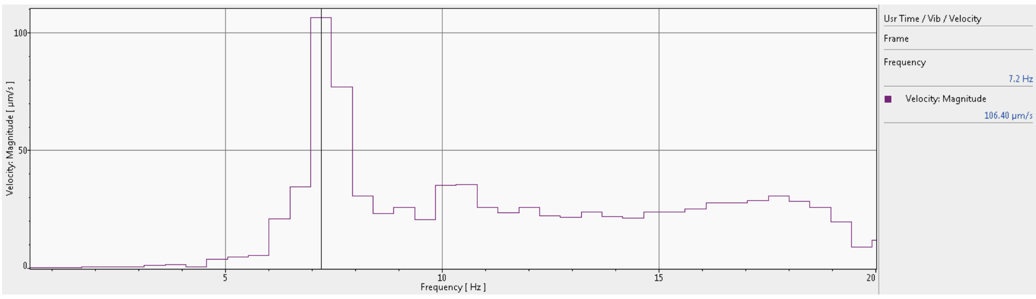

Figure 9. Frame 2. Spectral mapping of oscillatory processes in the transverse direction

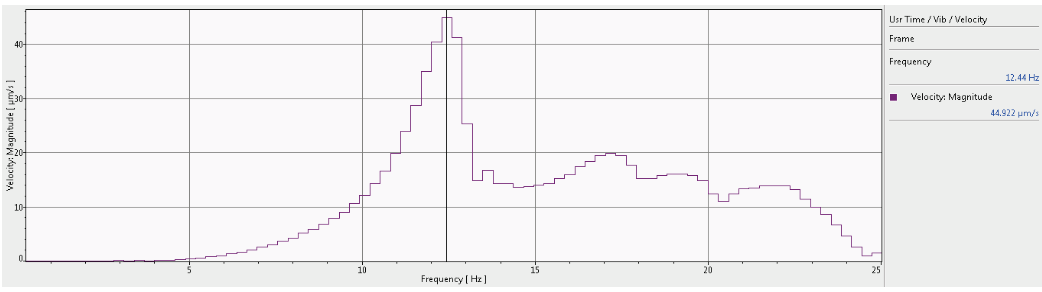

Figure 10. Frame 3. Spectral mapping of oscillatory processes in the longitudinal direction

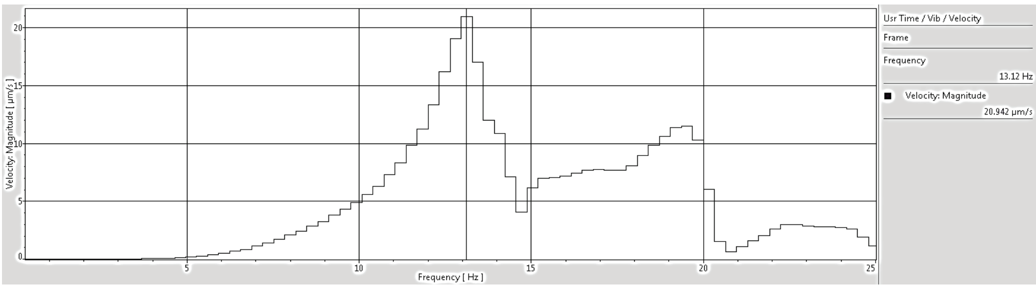

Figure 11. Frame 3. Spectral mapping of oscillatory processes in the transverse direction

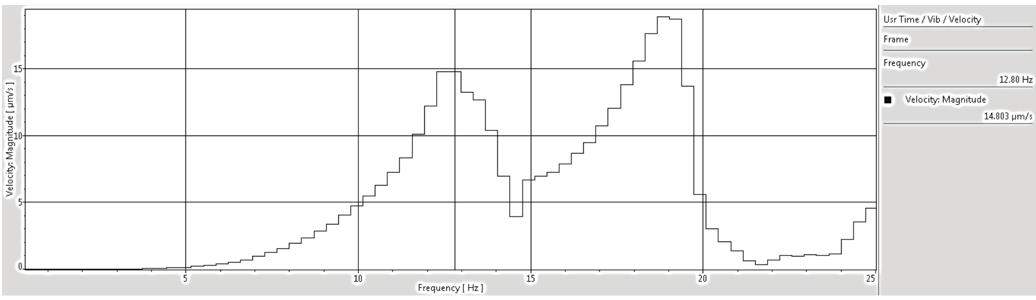

Figure 12. Frame 4. Spectral mapping of oscillatory processes in the longitudinal direction

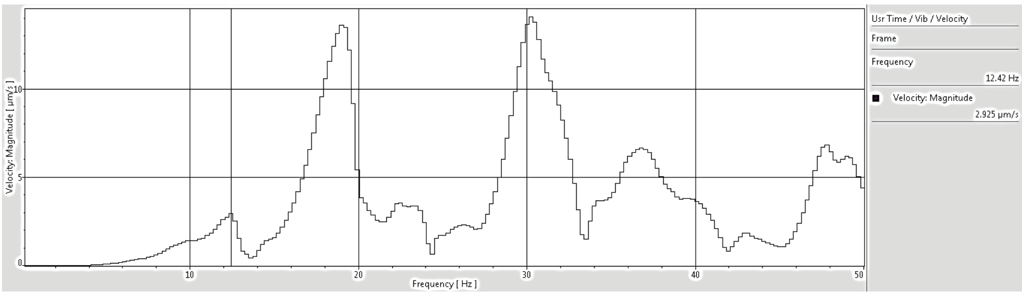

Figure 13. Frame 4. Spectral mapping of oscillatory processes in the transverse direction

2. MODELING AND CALCULATION OF THE STUDIED OBJECTS IN SCAD OFFICE AND LIRA SOFT PCS

The frame struts, lintels and lower strapping were modeled in the form of core elements. The connections of the racks with the horizontal surface of the concrete floor of the laboratory are set in the form of a hinge-fixed support, limiting movement along the X, Y, Z axes and the average Z racks for some variants of the design schemes. To obtain the dynamic characteristics of natural oscillations, a modal analysis was carried out based on the transformation of the static load of its own weight from the considered variant of the structural scheme of the fragment into masses.

To model wooden frame structures, it is necessary to take into account the nodal connections of elements: racks with strapping, braces and horizontal spacers with a frame, a frame with a skin, which in this case are attached to screws. These compounds are malleable, which causes difficulty in modeling in computational complexes.

In the SCAD Office PC, when modeling rod elements, there is no possibility of taking into account the orthotropic properties of wood and the elements are set to be isotropic. The lamellar elements of plywood sheaths are set to be otrotropic.

In the Lira Soft PC, on the contrary, when modeling rod elements, it is possible to take into account the orthotropic properties of wood, but at the same time the plate elements of plywood sheaths are set to be isotropic.

In the study of dynamic characteristics in computational complexes, many variants of computational schemes were created, and this paper presents the most successful of all with a description of the modeling tools used.

2.1 Frame 1

The frame has a hinged coupling of racks with strapping and jumpers. The corner and paired pillars of the frame fragment are connected by combining displacements, thereby modeling a malleable (conditionally hinged) joint.

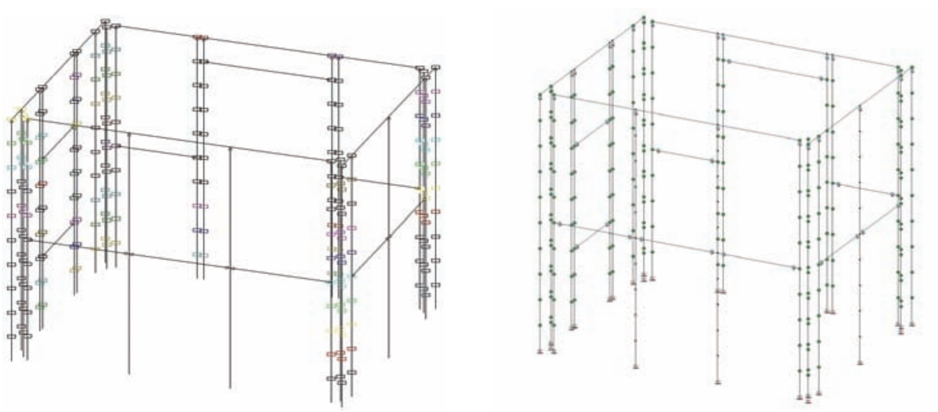

Figure 14. Frame 1. Model in PVC SCAD Office and Lira Soft

Table 1. The results of natural oscillations of the fragment of the frame 1 in SCAD Office and Lira Soft

SCAD Office	Lira Soft
X - 2,92 Гц	X - 2,7 Гц
Y - 6,03 Гц	Y - 5,54 Гц

2.2 Frame 2

Additionally, we model diagonal braces in the form of rod elements in the frame. The connection of the braces with the pillars of the main frame is made pivotally.

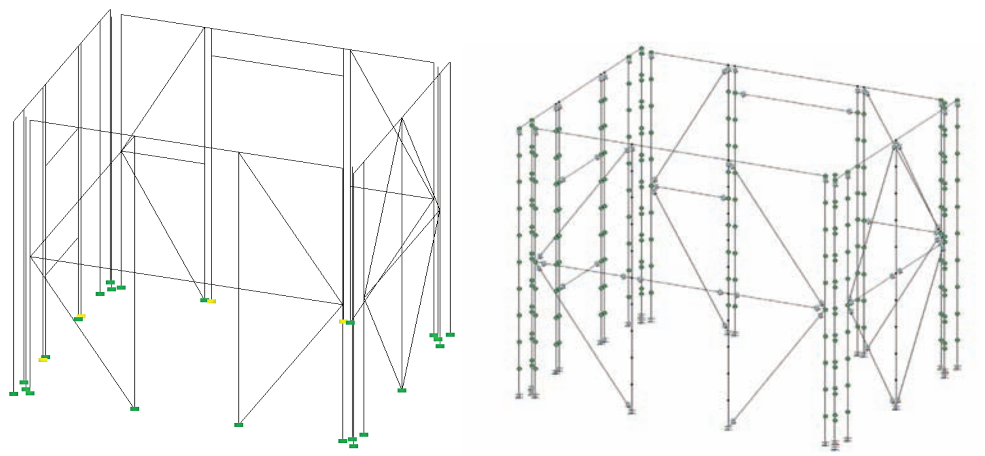

Figure 15. Frame 2. Model in PVC SCAD Office and Lira Soft

Table 2. The results of the natural oscillations of the fragment of the frame 2 in SCAD Office and Lira Soft

SCAD Office	Lira Soft
X - 6,49 Гц	X – 6,64 Гц
Y - 7,17 Гц	Y – 8,52 Гц

2.3 Frame 3

Plywood panels in the form of plate elements with a thickness of 9 mm were added to the design scheme and diagonal braces were removed. Characteristics of the cladding material: elastic modulus X = 400000 kN/m2, elastic modulus Y = 10000000 kN/m2. Poisson's ratio V_{XY} = 0.45, V_{YX}=0.02. The shear modulus G_{XY}=500000 kN/m2.

The frame with the skin is connected pivotally by introducing a connection in the form of a combination of movements.

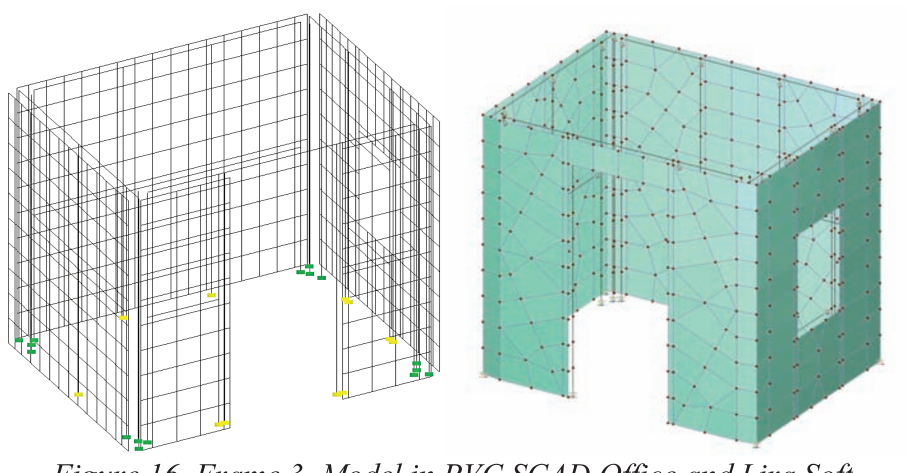

Figure 16. Frame 3. Model in PVC SCAD Office and Lira Soft

Table 3. Results of natural oscillations of a fragment of the frame 3 in SCAD Office and Lira Soft

SCAD Office	Lira Soft
X - 15,74 Гц	X - 15,88 Гц
Y - 8,80 Гц	Y - 10,20 Гц

2.4 Frame 4

Diagonal braces are reintroduced into the design scheme of the frame with plywood sheathing. The core elements are connected to each other pivotally. The plywood skin is attached with the help of the "movement unification" tool.

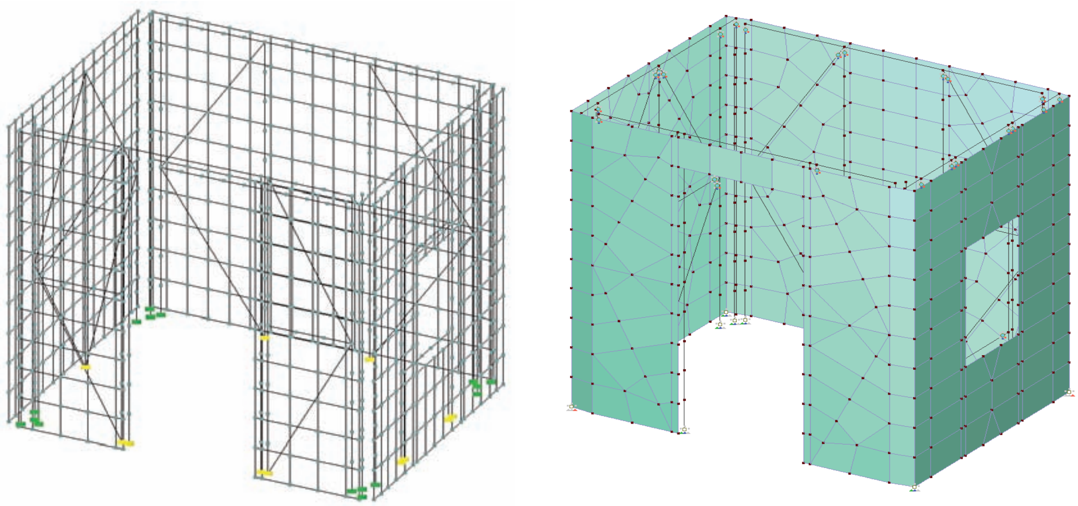

Figure 17. Frame 4. Model in PVC SCAD Office and Lira Soft

Table 4. Results of natural oscillations of a fragment of the frame 4 in SCAD Office and Lira Soft

SCAD Office	Лира Софт
X - 16,82 Гц	X - 16,26 Гц
Y - 13,43 Гц	Y - 10,87 Гц

3. COMPARATIVE ANALYSIS OF THE VALUES OF DYNAMIC CHARACTERISTICS OBTAINED BY THEORETICAL NUMERICAL CALCULATION AND EXPERIMENTAL METHODS

A comparative analysis of the values obtained by measuring the dynamic characteristics of a fragment of a wooden frame with the values obtained as a result of modeling the frame in the computing complexes SCAD Office and Lira Soft.

The purpose of the analysis was to identify errors in experimental data and theoretical numerical calculations, which are manifested due to incomplete consideration of the natural origin of wood and inaccuracy of modeling nodal joints of structural elements in calculation complexes.

Another, no less important, task is a comparative analysis of the dynamic characteristics of 4 combinations of a fragment of a wooden frame and a conclusion about the need to install diagonal braces to increase the strength of the building.

Based on the results obtained, we will form a general summary table 5.

Table 5. Summary table of natural oscillation frequency

№	Name of the measurement	Direction of measurement	Values from SCAD Office, Hz	Value from Lira Soft, Hz	Values from the VibSoft, Hz	The coefficient of reduction to the indicators of the VibSoft	
						SCAD Office	Lira Soft
1	2	3	4	5	6	7	8
1	Frame 1	Longitudinal direction	2,92	2,7	3,13	1,07	1,16
		Transverse direction	6,03	5,54	4,94	0,82	0,89
2	Frame 2	Longitudinal direction	6,49	6,64	7,1	1,09	1,07
		Transverse direction	7,17	8,52	7,2	1,00	0,85
3	Frame 3	Longitudinal direction	15,74	15,88	12,44	0,79	0,78
		Transverse direction	8,8	10,2	13,12	1,49	1,29
4	Frame 4	Longitudinal direction	16,82	16,26	12,8	0,76	0,79
		Transverse direction	13,43	10,87	12,42	0,92	1,14

The natural oscillation frequencies of the system are determined by the formula:

$$w_0 = \sqrt{\frac{EJ}{m}} \tag{1}$$

where EJ is the rigidity of the system; m is the mass of the system.
Then the rigidity of the system is determined by the formula:

$$EJ = w_0^2 m \tag{2}$$

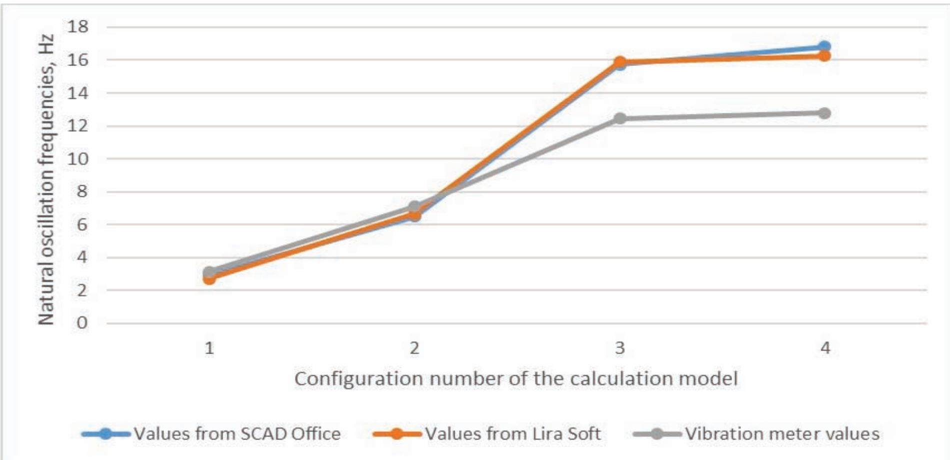

Figure 18. Indicators of natural oscillation frequencies in the longitudinal direction of the frame fragment

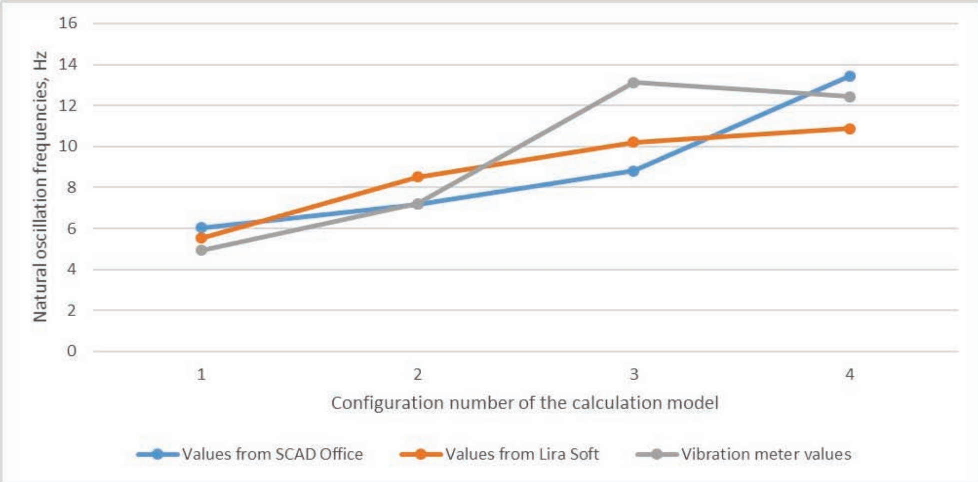

Figure 19. Indicators of natural oscillation frequencies in the transverse direction of the frame fragment

Table 6. Summary table of the rigidity of the frame system

№	Name of the measurement	Direction of measurement	System weight, kN	Rigidity of the SCAD Office system (EJ), kN m^2	Rigidity of the system (EJ) Lira Soft, kN m^2	Stiffness (EJ) of the experimental fragment, kN m^2	The coefficient of reduction to the indicators of the VibSoft	
							SCAD Office	Lira Soft
1	2	3	4	5	6	7	8	9
1	Frame 1	Longitudinal direction	2,18	18,55	15,86	21,31	1,15	1,34
		Transverse direction	2,18	79,11	66,77	53,09	0,67	0,80
2	Frame 2	Longitudinal direction	2,55	107,43	112,45	128,58	1,20	1,14
		Transverse direction	2,55	131,12	185,15	132,22	1,01	0,71
3	Frame 3	Longitudinal direction	2,83	701,67	714,21	438,29	0,62	0,61
		Transverse direction	2,83	219,33	294,66	487,52	2,22	1,65
4	Frame 4	Longitudinal direction	3,20	906,62	847,26	525,04	0,58	0,62
		Transverse direction	3,20	578,00	378,65	494,33	0,86	1,31

Comparing the data obtained as a result of theoretical numerical calculations and experimental studies given in Tables 5 and 6, it can be concluded that the greatest increase in the rigidity of the frame is achieved when using a structural variant with plywood cladding. In addition, correction coefficients were calculated that allow us to bring the characteristics of the natural oscillation frequencies (Table 5, columns 7, 8) and the rigidity of structures (Table 6, columns 8, 9) obtained in the SCAD

Office and Lira Soft software complexes to the indicators of the VibSoft.

It should also be noted that the nodes connecting the elements to each other are elastic, since they are made using nagel-type connections. Modeling of such nodes with the help of hinges or rigid fastening does not correspond to their actual work in the structure. To account for and evaluate these features, several different types of calculation schemes with different combinations of frame elements were considered and analyzed. The obvious disadvantage of the calculation systems used is the lack of the possibility of taking into account the orthotropic properties of wood when modeling elements using rod and plate elements. The results of the simulation indicate the absolute need for further improvement of the SCAD Office and Lira Soft software complexes in terms of taking into account the features of the anisotropic structure of wood and the nonlinear operation of nodes and parts in wooden frame systems.

CONCLUSION

Based on a comparative analysis of numerical calculations and experimental dynamic characteristics of fragments of wooden frame structures, the following conclusions are made:

1. It is proved that there is no need to use braces in the frames of buildings with sheathing at the standard step of the racks. The use of braces in combination with the skin does not significantly increase the performance compared to the option without braces: in the longitudinal direction by about 20% and 1.4% in the transverse direction.

2. Comparison of the results of numerical calculations and experimental data of natural vibration frequencies of wooden frame buildings revealed the need to introduce correction coefficients to the stiffness indicators or natural vibration frequencies obtained in the calculation complexes.

3. The numerical calculation revealed significant difficulties in modeling wooden frame structures. The SCAD Office and Lira Soft software systems used do not allow modeling a design scheme that would reflect the actual operation of nodes, such as the coupling of racks with cladding, diagonal braces with racks, horizontal jumpers with racks.

Further studies to assess the dynamic characteristics of wooden frame buildings should include static and dynamic tests of individual components and parts with an in-depth study of their strength and deformability indicators. Of course, it is necessary to increase the number of studied objects, which will reduce the error of the data obtained.

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