UDC 624.011

MODELING AND CALCULATION OF PANEL BUILDINGS MADE OF CROSS-LAMINATED TIMBER

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DOI: 10.32347/2410-2547.2023.110.164-177

Abstract. Buildings made using cross-laminated timber have become widespread over the last decade. The experience of designing and operating such buildings of various functional purposes confirms the expediency of their construction and use. This article provides a solution to the problem of modeling and calculating panel houses made of cross-laminated timber using the finite element method using the given mechanical characteristics of the material. The possibility of modeling and calculating panel buildings made of cross-laminated timber using the finite element method with the use of flat finite elements, taking into account the orthotropic properties of the material, under the condition of using the reduced modulus of elasticity according to the previously proposed method and adjusting Poisson's coefficients, in such a way as to maintain the condition of existence of elastic potential. The algorithm for modeling panel buildings made of cross-laminated timber using the finite element method as a system "soil base-foundation-above-ground structure system" is given.
Keywords: cross-laminated timber, panel building, calculation scheme, finite element method, stress-strain state, soil base-foundation-above-ground structure system.

Introduction. The world experience of the wide use of timber structures for various purposes [1-3] confirms the expediency of their use. Over the past decades, the construction of panel buildings from cross-laminated timber (CLT) has become widespread, including in the construction of multi-story buildings [4-6]. This is facilitated by the fact that cross-laminated timber effectively accumulates in itself the positive properties of timber as a construction material, primarily relatively high strength, and allows you to largely eliminate the disadvantages of solid timber. Cross-laminated timber (CLT) is produced by laminating an odd number of layers of boards with mutually perpendicular arrangement of timber fibers. Panels made of cross-laminated timber, as a rule, consist of three, five or seven layers, the number of which depends on the stress-strain state (SST) of the panels in the house. Usually, the outer layers of CLT panels are made of stronger timber strength classes and are located in the direction along the element in slab panels and in height - in wall panels - to absorb the maximum normal bending stresses. If necessary, CLT panels are made with holes in the places where windows, doors and other technological openings are installed. The thicknesses of the boards of the longitudinal and transverse layers can be the same or different. CLT panels are used as load-bearing walls and slabs and coverings in low- and multi-story buildings of various purposes [7-9].

An important and urgent issue is the calculation of multi-story panel buildings made of CLT. Over the last decade, such houses have become increasingly widespread not only in Europe, but also in Canada, the USA, Australia, Japan, etc. Due to the rapid development of panel construction made of CLT, there is a need for constant development and improvement of calculation methods and development of an algorithm for creating calculation models and calculating houses made of CLT in modern software complexes using the finite element method.

Literature review

Domestic experience of using CLT panels in residential construction is practically absent, including due to the lack of a domestic regulatory framework and methodical literature regarding the calculation and design of both individual panels and buildings made of them as a whole.

Famous European scientists made a significant contribution to the methodology of designing and calculating CLT panels: Blass H.J. [10], Hofstetter K. [11], Schickhofer G. [12], Reinhard B. [13].

In articles [14, 15], a review of the regulatory bases of different countries of the world regarding the calculation and design of CLT is carried out, and in article [16] the method of calculation of CLT panels by the finite element method using flat finite elements, taking into account the orthotropic properties of the material, under the condition of using the given modules, is given elasticity and adjusting Poisson's coefficients in such a way that the condition for the existence of elastic potential in timber is maintained. From all of the above, we can conclude that there is an urgent need to develop an algorithm for the design of panel buildings made of CLT using the finite element method as a system "soil base - foundation - above-ground structure".

The purpose and tasks of the research

The purpose of the research is to present the modeling and calculation algorithm of panel houses made of cross-laminated timber.

To achieve the goal, the following tasks were set:

1. Development of an algorithm for creating a calculation model of panel buildings made of cross-laminated timber.
2. Numerical modeling and calculation of multi-story panel buildings made of cross-laminated timber using the finite element method.
3. Development of recommendations for the calculation of multi-story panel buildings made of cross-laminated timber using the finite element method as a "soil base - foundation - above-ground structure" system.

Algorithm for high-rise buildings made of cross-laminated timber panels modeling and calculation

When creating calculation schemes as a "soil base - foundation - above-ground structure" system of high-rise buildings, it is faster and easier to model with rod and plate finite elements. Detailed recommendations for creating models of buildings and structures of various purposes for calculation by the finite element method are given in [16, 17].

The research carried out in the article [18] confirmed the possibility of using of orthotropic FE No. 41 for modeling panel houses made of cross-laminated timber using the reduced modulus of elasticity according to the proposed method and adjusting Poisson's coefficients in such a way that the condition of existence of elastic potential in timber is preserved. You can pre-set two types of FE that will simulate slabs and vertical wall elements (Fig. 1).

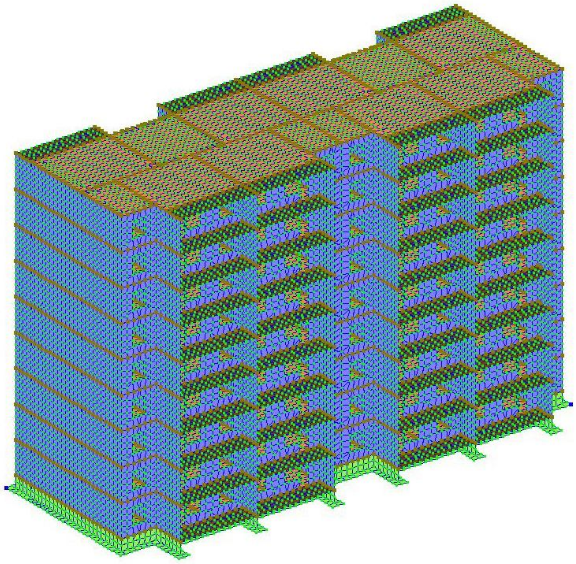

Fig. 1. Calculation diagram of a 9-story building made of cross-laminated timber panels

Characteristic values of temporary loads, load reliability coefficients, calculated coupling coefficients should be taken in accordance with DBN B.1.2-2 [19]. Reliability coefficients by class of responsibility should be taken according to DBN B.1.2-14 [20] depending on the class of the building responsibility.

The characteristics of the base are determined according to the results of engineering and geological investigations in two ways: either by the soil massif formed by volumetric finite elements with the corresponding stiffness characteristics, or by the coefficients of the elastic base (bed), which are determined in accordance with the characteristics of the soils obtained from the investigations.

Foundations are modeled from the materials which they are designed from in accordance with the calculation.

Slabs and wall elements can be specified from any type of cross-laminated timber panel (three-, five-, seven-layer) with a predetermined thickness of individual boards and, accordingly, timber strength classes.

After calculating the building model, the stress-strain state of individual elements should be analyzed for deformability, stability and strength, with their verification using the method of calculating cross-laminated timber elements described in [18], with the replacement of the cross-section geometric characteristics with the reduced ones. The analysis of slabs with permanent layouts can be performed for one typical slab of a house, it is more rational to analyze wall panels for each floor separately.

If necessary (violation of the conditions of the first or second limit states or large safety margins), we replace the necessary elements by changing the type of panel (number of layers), the thickness of the board layers or the strength class of the timber. We change the FE building calculation scheme to the required ones using the reduced modulus of elasticity according to the method proposed in this work and (Application B of the dissertation). We recalculate the calculation model and re-analyze the stress-strain state of individual elements in terms of deformability and strength, checking them according to the standard method of calculating cross-laminated timber elements.

The number of iterations should be sufficient to select rational cross-sections of cross-laminated timber panels. In the final model, both the building itself and its individual components (slab panels, wall panels) must satisfy the conditions of the first (strength, stability) and second (serviceability) limit states.

An example of a 9-story residential building made of cross-laminated timber panels modeling and calculation

For the first iteration of the calculation of the house from flat FE No. 41, we accept the characteristics for the CLT slab panels, giving them the reduced stiffness characteristics of the slab. The orientation of the local axes of the plates was modeled in such a way that the x-axis coincided with the direction of the fibers of the boards of the outer layers.

As slab panels, we accept 5-layer timber boards of strength class C24, with the following material characteristics: modulus of elasticity along the fibers $E_{0,mean}$ = 11000 MPa, modulus of elasticity across the fibers $E_{90,mean}$ = 370 MPa, shear modulus G_{mean} = 690 MPa. The panel is made of boards of the same thickness t_1 = 4 cm. Thus, the total thickness of the panel is 200 mm. Flat FE No. 41 were modeled by giving them the physical and mechanical characteristics of timber: the modulus of elasticity is determined according to the formulas given in the previous paragraph, along the E_1 fibers and across the E_2 fibers, the shear modulus G = G_{mean} = 690 MPa. The accepted size of the finite element is 0.2x0.2x0.2 m. Reduced modules of elasticity for the adopted CLT panel are given: along the fibers of the outer layers E_1 = 8789 MPa, across the fibers of the outer layers E_2 = 2581 MPa.

As wall panels, we accept 5-layer timber boards of strength class C30, with the following material characteristics: modulus of elasticity along the fibers $E_{0,mean}$ = 12000 MPa, modulus of elasticity across the fibers $E_{90,mean}$ = 400 MPa, shear modulus G_{mean} = 750 MPa. The panel is made of boards of the same thickness t_1 = 5 cm. Thus, the total thickness of the panel is 250 mm. Flat FE No. 41 were modeled by giving them the physical and mechanical characteristics of timber: the modulus of elasticity is determined according to the formulas given in the previous paragraph, along the E1 fibers and across the E2 fibers, the shear modulus $G = G_{mean}$ = 750 MPa. The accepted size of the finite element is 0.2x0.2x0.2 m. Reduced modules of elasticity for the accepted CLT panel are given: along the fibers of the outer layers E_1 = 9587 MPa, across the fibers of the outer layers E_2 = 2813 MPa.

Table 1

The physical and mechanical properties of the base soils
which are specified in the calculation model

№	Name	Marking	Units of measurement	Dusty sand of medium density	Sand of medium density	Loam
1	Natural density	ρ	kg/m^3	1,94	2,03	1,79
2	Particle density	ρ_s	kg/m^3	2,66	2,65	2,68
3	Natural humidity	ω		0,22	0,21	0,15
4	Humidity on the verge of rolling	ω_P				0,12
5	Humidity at the yield point	ω_L				0,22
6	Modulus of deformation	E	MPa	18	30	17
7	Angle of internal friction	φ	Deg.	25	33	18
8	Specific clutch	C	MPa	0,003	0,001	0,022

Based on the characteristics of the soil massif (coordinates and characteristics of the soil layers (Table 1) in each well), a spatial model of the soil was created in the "Soil" subprogram, and the real topography of the surface was constructed based on the wellhead markings. The average pressure under the sole of the foundations for the first iteration is defined as the vertical constant load from the entire building divided by the area of the foundations and is P_z = 22708.3 / 766.8 = 0.29 MPa. The refinement of the bed coefficients is carried out in such a way that the stresses Rz differ from the load on the soil Pz by less than 5%.

The foundations of the building are adopted strip from monolithic reinforced concrete. Flat FE No. 41 with the characteristics of reinforced concrete, sole 1.0 m wide and 400 mm thick, foundation walls 400 mm thick were used for the calculation. modulus of elasticity along the fibers E = 30,000 MPa, Poisson's ratio 0.2.

Characteristic values of temporary loads are adopted in accordance with DBN B.1.2-2 [19]. The characteristic value of the snow load is taken for the 5th snow district, and the characteristic value of the wind load is for the 1st wind district. Reliability coefficients for loads are also adopted in accordance with DBN B.1.2-2 [19] for a normative period of operation of 50 years. Reliability coefficients by class of responsibility were taken according to DBN B.1.2-14 [20]. According to DBN B.1.2-2 [19] calculated combinations of loads are accepted, taking into account the coefficients of combination.

Based on the results of the calculation, a stress-deformation diagram of the building was obtained. General deformations are presented in Fig. 2, 3.

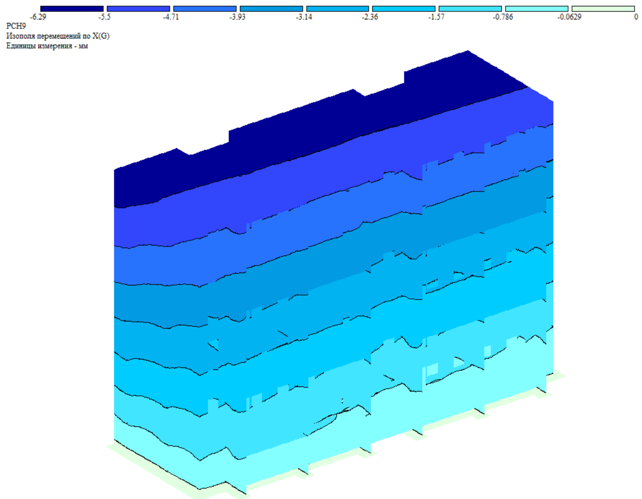

Fig. 2. General deformed scheme of a 9-story building with isopolies of vertical movements along the *x* axis

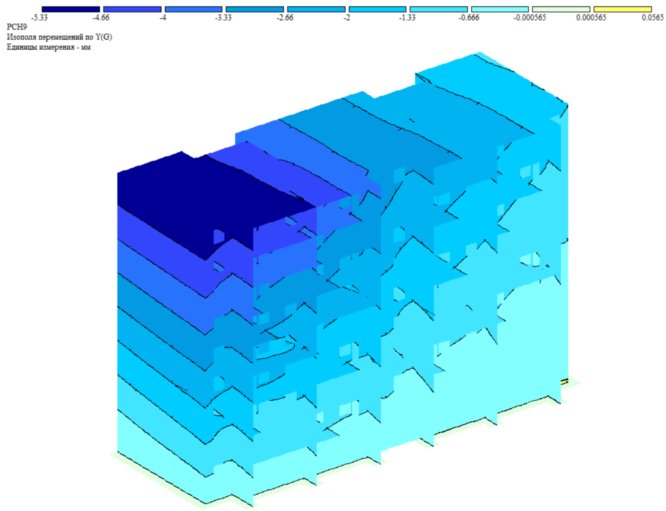

Fig. 3. General deformed diagram of a 9-story building with isopolies of vertical movements along the y axis

As we can see from the results of the house calculation, the overall stiffness is within the permissible limits of the current design norms.

The stress-strain diagram of a typical slab according to the calculation results is shown in Fig. 4, 5, 6.

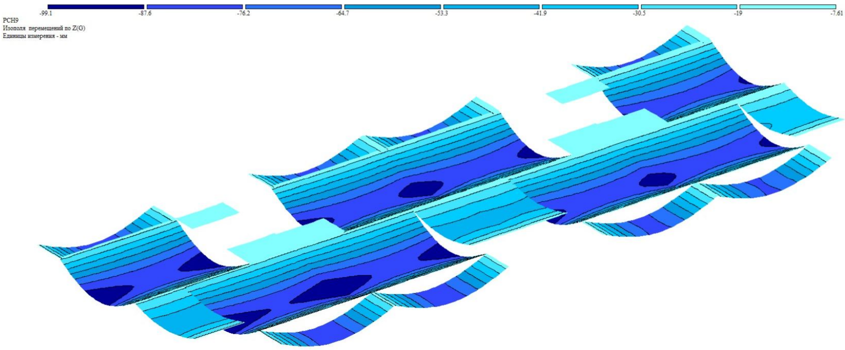

Fig. 4. Deformed slab plan of a typical floor of a 9-story building with isopolies of vertical movements along the z axis

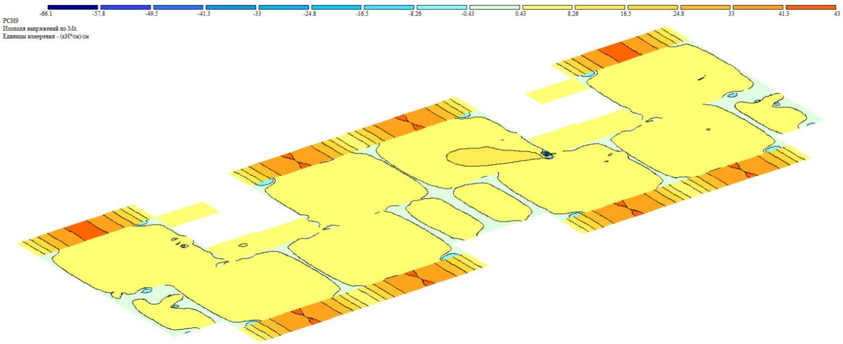

Fig. 5. Stress isopolies Mx in the slab of a typical floor of a 9-story building

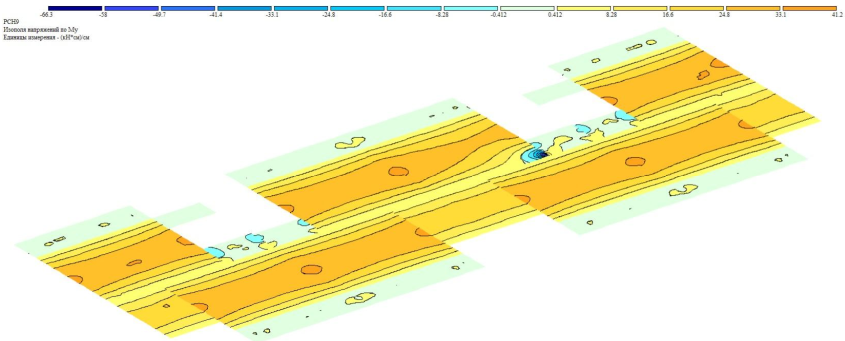

Fig. 6. Stress isopolies My in the slab of a typical floor of a 9-story building

Taking into account significant deformations, we accept 7-layer slabs of timber of strength class C24 for the slab panels, with the following material characteristics: $E_{0,mean}$ = 11000 MPa, $E_{90,mean}$ = 370 MPa, G_{mean} = 690 MPa. The panel is made of boards of the same thickness t_1 = 4 cm. Thus, the total thickness of the panel is 280 mm. Flat FE No. 41 were modeled by giving them the physical and mechanical characteristics of timber: the modulus of elasticity is determined according to the formulas given in the previous paragraph, along the E_1 fibers and across the E_2 fibers, the shear modulus $G = G_{mean}$ = 690 MPa. The accepted size of the finite element is 0.2x0.2x0.2 m. Reduced modules of elasticity for the adopted CLT panel are given: along the fibers of the outer layers E_1 = 7932 MPa, across the fibers of the outer layers E_2 = 3438 MPa.

The stress-strain scheme of the house walls according to the calculation results is shown in Fig. 7, 8, 9.

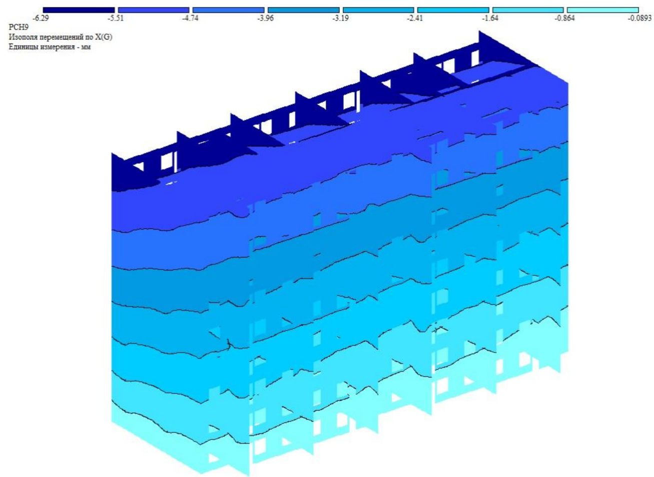

Fig. 7. The general deformed scheme of the walls of a 9-story building with isopolies of movements along the x axis

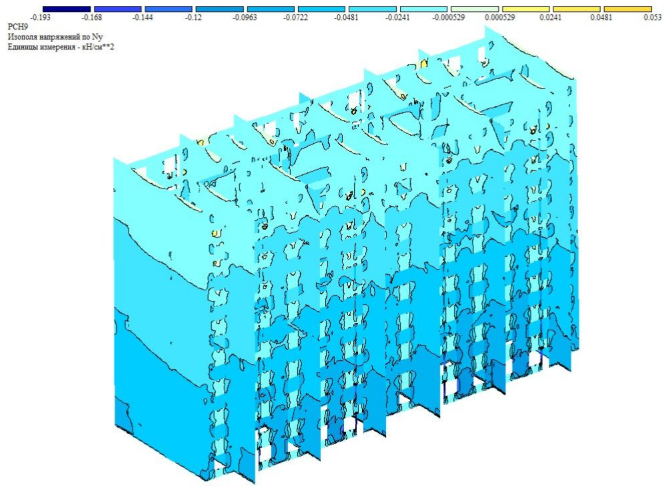

Fig. 8. Stress isopolies in wall panels along the fibers of the outer layers

We increase the rigidity of the wall panels of the first three floors by using 7-layer boards made of timber of strength class C30, with the following material characteristics: modulus of elasticity along the fibers $E_{0,mean}$ = 12000 MPa, modulus of elasticity across the fibers $E_{90,mean}$ = 400 MPa, shear modulus G_{mean} = 750 MPa. The panel is made of boards of the same thickness t_1 = 5 cm. Thus, the total thickness of the panel is 350 mm. Flat FE No. 41 were modeled by giving them the physical and mechanical characteristics of timber: the modulus of elasticity is determined according to the formulas given in the previous paragraph, along the E_1 fibers and across the E_2 fibers, the shear modulus G = G_{mean} = 750 MPa. The accepted size of the finite element is 0.2x0.2x0.2 m. Reduced modules of elasticity for the adopted CLT panel are given: along the fibers of the outer layers E_1 = 8652 MPa, across the fibers of the outer layers E_2 = 3748 MPa.

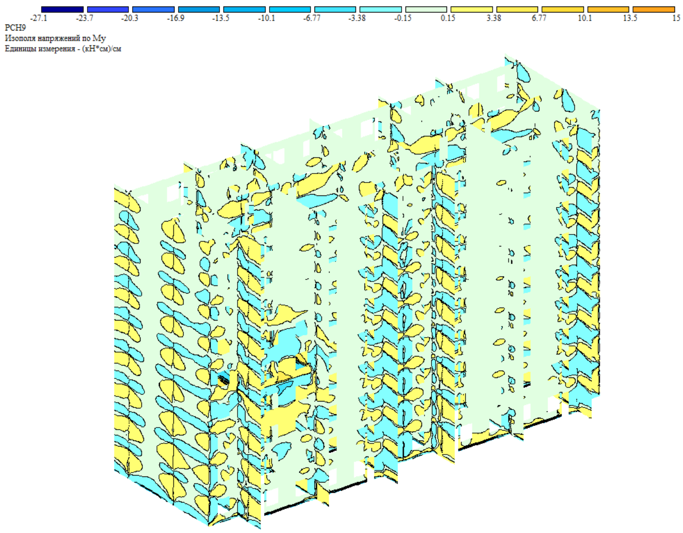

Fig. 9. Isopolies of bending moments in wall panels along the fibers of the outer layers

According to the results of the calculation with 7-layer panels, a stress-deformation diagram of the building was obtained. General deformations are presented in Fig. 10.

The stress-strain diagram of a typical slab according to the calculation results is shown in Fig. 11, 12, 13. As can be seen from the given results, the deformations of the floor slabs are within the permissible limits, and after calculating the stresses from the given internal forces according to the methodology given in Application B, it is possible to make sure that the conditions of the first limit state are also fulfilled.

The stress-strain scheme of the walls of the house according to the calculation results is shown in fig. 14, 15, 16.

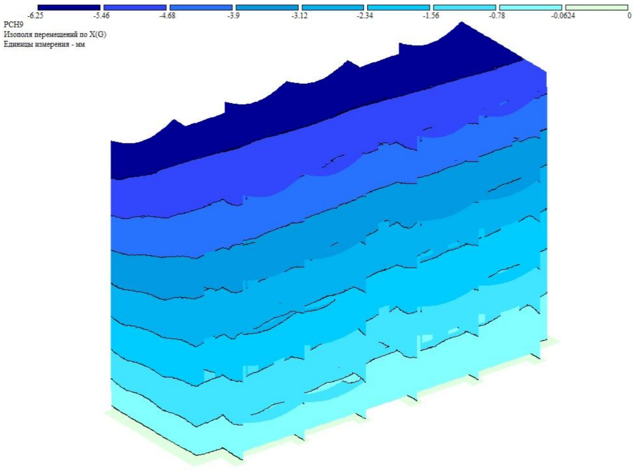

Fig. 10. General deformed diagram of a 9-story building with isopolies of vertical movements along the x axis

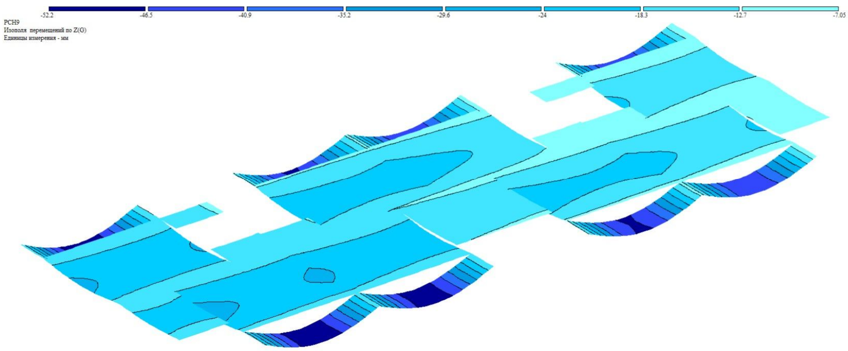

Fig. 11. Deformed slab plan of a typical floor of a 9-story building with isopolies of vertical movements along the z axis

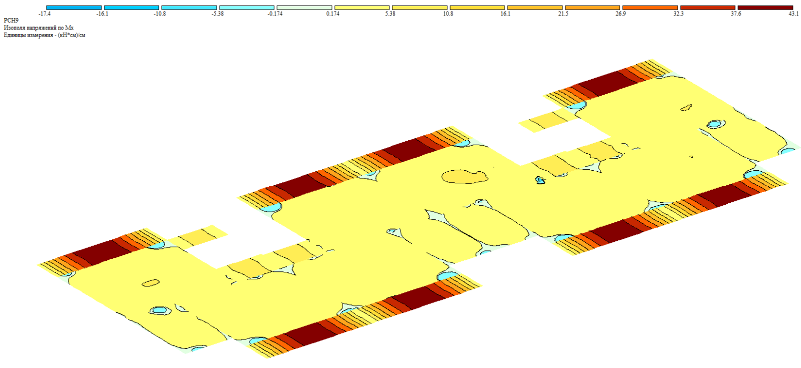

Fig. 12 Stress isopolies M_x in the slab of a typical floor of a 9-story building

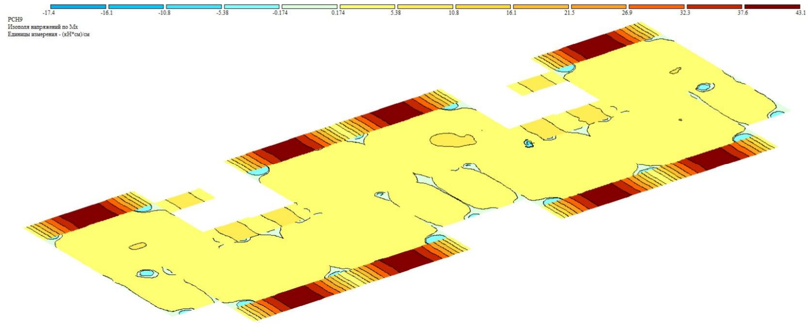

Fig. 13. Stress isopolies M_y in the slab of a typical floor of a 9-story building

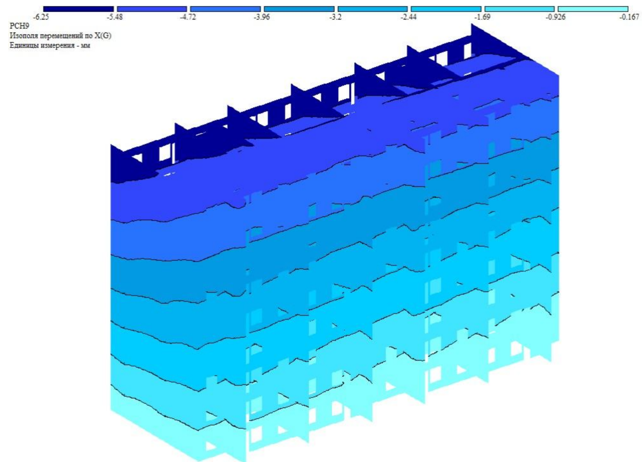

Fig. 14. General deformed scheme of the walls of a 9-story building with isopolies of movements along the x axis

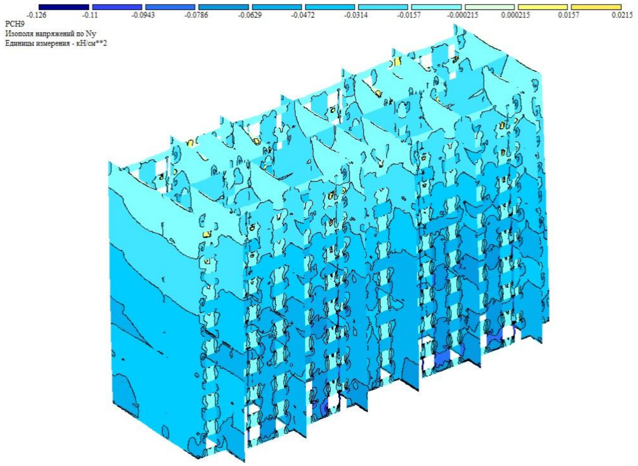

Fig. 15. Stress isopolies in wall panels along the fibers of the outer layers

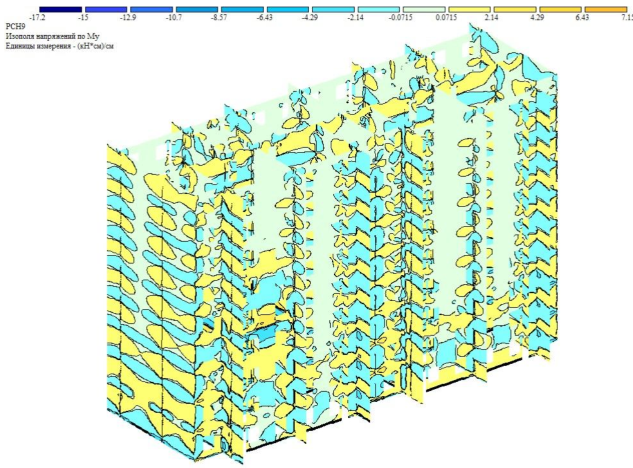

Fig. 16. Isopolies of bending moments in wall panels along the fibers of the outer layers

As you can see, increasing the thickness of the walls with the use of seven-layer panels made of transversely glued timber does not affect the overall rigidity of the house, although the stresses in the panels themselves are reduced quite significantly.

It can be seen from the conducted research that the proposed method of using flat FE No. 41 with giving them the reduced modulus of elasticity in the modeling of multi-story buildings is quite acceptable and significantly simplifies the creation of calculation models "soil base - foundation - above-ground structure", analysis of calculation results and selection of cross-sections of panels made of cross-laminated timber.

Conclusions

1. When creating calculation schemes as a "soil base - foundation - above-ground structure" system of high-rise buildings using CLT panels, it is possible to use rod and plate finite element modeling using the reduced modulus of elasticity according to the methodology given in [18].

2. The algorithm of modeling and calculation by the method of finite elements of high-rise buildings made of CLT panels with the use of flat FE No. 41 with the use of reduced modulus of elasticity according to the proposed method as a "soil base - foundation - above-ground structure" system due to the possibility of taking into account the deformed scheme of the building as a whole is given.

3. The method proposed in the article for the application of flat FE No. 41 with the provision of reduced modulus of elasticity for the modeling and calculation of multi-story buildings is quite acceptable and significantly simplifies the creation of calculation models "soil base - foundation - above-ground structure", analysis of calculation results and selection of cross-sections of panels made of cross-laminated timber.

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Стаття надійшла 25.01.2023

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МОДЕЛЮВАННЯ ТА РОЗРАХУНОК ПАНЕЛЬНИХ БУДІВЕЛЬ З ПОПЕРЕЧНО-КЛЕЄНОЇ ДЕРЕВИНИ

Будівлі з застосуванням поперечно-клеєної деревини набули широкого розповсюдження за останнє десятиріччя. Досвід проектування та експлуатації таких будівель різноманітного функціонального призначення підтверджує доцільність їх зведення і використання. В цій статті приведено вирішення задачі моделювання та розрахунку панельних будинків з поперечно-клеєної деревини за допомогою методу скінчених елементів із застосуванням приведених механічних характеристик матеріалу. Обґрунтовано можливість моделювання і розрахунку панельних будівель з поперечно-клеєної деревини методом скінчених елементів з застосування плоских скінчених елементів з врахуванням ортотропних властивостей матеріалу за умови використання приведених модулів пружності за запропонованою раніше методикою та коригуванням коефіцієнтів Пуассона, таким чином, щоб зберігалась умова існування в деревини пружного потенціалу. Наведено алгоритм моделювання панельних будівель з поперечно-клеєної деревини за допомогою методу скінчених елементів як системи «ґрунтова основа – фундамент – надземна конструкція».

Ключові слова: поперечно-клеєна деревина, панельний будинок, розрахункова схема, метод скінчених елементів, напружено-деформований стан, система ґрунтова основа-фундамент-надземна конструкція.

УДК 624.011
Михайловський Д.В. **Моделювання та розрахунок панельних будівель з поперечно-клеєної деревини** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2023. – Вип. 110. – С. 164-177.
Табл. 1. Іл. 16. Бібліогр. 20 назв.

UDC 624.011
Mykhailovskyi D.V. **Modeling and calculation of panel buildings made of cross-laminated timber** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUBA, 2023. – Issue 110. – P. 164-177.
Tabl. 1. Fig. 16. Ref. 20.

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