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COMPARATIVE ANALYSIS OF CALCULATION METHODS OF CLT STRUCTURES

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One of the important tasks of modern construction is the search for new constructive solutions and the introduction of new construction technologies. Cross-Laminated Timber (CLT) technology is a new material for Ukraine that has proven itself in Europe and America as effective and environmentally friendly with many advantages. Since CLT panels are not widely distributed, studied and do not contain references in the normative literature in Ukraine, the study of these structures is extremely relevant. This paper presents a comparative analysis of the CLT calculation methods of panels: using the RFEM 6 and LIRA-FEM software and analytical calculation. The research concerns three types of panels: three-layer, five-layer, and seven-layer under the action of a load of 1.5 and 5.0 kN/m^2. The main parameter under consideration is the vertical deflection of the panels. The results of all calculations are collected in one table, where you can analyze the discrepancy between different methods of calculating the CLT structures.

Key words: cross-laminated timber; CLT; calculation method; RFEM; LIRA-FEM; finite element method.

Introduction

Cross-Laminated Timber (CLT) is a relatively new technology for the production of wooden panels, which gives opportunities for the construction of residential and public facilities of not only medium, but even high-rise buildings. Traditional methods of construction from wooden structures do not provide an opportunity to create ecological and at the same time high-rise building due to the limited bearing capacity of usual wooden structures. Instead, in 1996, Austrian industry developed an idea that originated in Switzerland: to produce a multi-layered wooden panel, which will consist of several layers perpendicular to each other, which are glued together under high pressure. This idea has spread so much around the world that in a very short time, using CLT technology, they began to build environmentally friendly and impressive houses in Europe, Canada and Japan. CLT panels have proven themselves so well in modern construction that they are called “an alternative to reinforced concrete”.

CLT structures have a number of advantages:

- significantly lower volumetric weight, compared to metal and concrete, which reduces the load on foundations and, accordingly, their cost;
- CLT panels are an excellent solution for ensuring the characteristics of the internal microclimate of buildings and structures due to their natural qualities;
- the strength characteristics of the panels boldly compete with structures made of reinforced concrete;

- it is an environmentally friendly and safe material;
- high limit of fire resistance, which is confirmed by relevant test certificates provided by the manufacturer;
- it has been experimentally proven that the seismic resistance of buildings made of CLT panels allows building in areas with probable earthquakes of magnitude nine;
- cost-effective, as ready-made panels are assembled with minimal time expenditure and do not require a large crew of workers, panels are quickly manufactured at the factory and there is a minimal amount of waste during their production;
- CLT panels are quite versatile structural elements that can be used to achieve bold and unique architectural solutions.

Despite the advantages of cross-laminated timber, there are many factors that restrain or limit the development of the design of buildings and structures using CLT technology:

- this is a new technology for Ukraine and many developers are not ready to take risks, so they willingly choose traditional materials for construction;
- high price due to the small number of manufacturers and lack of competition in this direction;
- lack of qualified structure engineers familiar with CLT and able to calculate and design them;
- lack of a regulatory rules containing items with recommendations, restrictions and guidelines for CLT design.

For today the scientific and regulatory rules for research and design of CLT structures is not sufficiently developed in Ukraine. In the normative literature (DBN V.2.6-161-2017) there are no instructions regarding the calculation of these structures. In monograph (Mykhailovskyi, 2022), in chapter 3, considered the existing methods of calculating CLT panels according to the first and second limit states. The author also produced a comparative table in which he numerically outlined the existing methods of calculating cross-laminated timber panels loaded with a uniformly distributed load, including Timoshenko’s beam theory, γ-method, composite method, and Kreisinger’s theory.

A team of authors (Bidakov et al., 2021) was engaged in a comparative analysis of Tymoshenko's methods and γ-methods, investigating the calculation of the bending strength of CLT panels. The advantages and disadvantages of this method are outlined (Bidakov et al., 2019), among the disadvantages were found that the γ-method can be used only with 3- and 5-layer panels. The strength of these panels in shear and torsion and in tension and compression along the fibers were studied in (Bidakov et al., 2020). Another possible method of calculating CLT panels is the sliding analogy method (Mykhailovskyi & Komar, 2018).

Europe and East countries, America are more actively developing methods and tools for calculating and designing CLT structures and have more scientific and methodological publications, design guides (Wieruszewski et al., 2017; De Araujo et al., 2023; Llana Daniel et al., 2023; Kurzinski et al., 2022; Sandoli et al., 2021; Mohammad, 2018; Li et al., 2023; Demirci et al., 2017; Loss et al., 2018). Also, companies producing CLT panels actively participate in the development of products specifically for designers (FPInnovations and Binational Softwood Lumberg Council, 2013). In Ukraine there is a large-scale factory for the production of CLT panels, which has a corresponding quality certificate.

In addition to the above-described analytical methods for calculating CLT panels, the structural data can be calculated using the finite element method. In particular, such a calculation can be performed using LIRA-FEM and Dlubal RFEM software complexes.

In (Mykhailovskyi, 2022), the possibility of using the LIRA-FEM software complex for the calculation and analysis of the stress-strain state of CLT panels was investigated and substantiated, and the author proposed an analytical method for calculating the reduced geometric characteristics of the cross-section of multilayer panels, according to which the reduced modulus of elasticity along (E1) and across the fibers is calculated (E2) (formulas (1)–(2)).

Materials and Methods

According to the proposed methodology (Mykhailovskyi, 2022), we used formulas to calculate the reduced modulus of elasticity in the LIRA-FEM software complex for modeling the operation of CLT panels. The general form of the formulas for the reduced modulus of elasticity for a 3-layer panel:

$$E_1 = \frac{12E_x}{(h_1+h_2+h_3)^3}\left(\frac{1}{12}\left(h_1^3 + h_2^3 + h_3^3\frac{E_y}{E_x}\right) + \left(\frac{h_1}{2}+\frac{h_2}{2}\right)^2 h_1 + \left(\frac{h_3}{2}+\frac{h_2}{2}\right)^2 h_3\right) \quad (1)$$

$$E_2 = \frac{12E_y}{(h_1+h_2+h_3)^3}\left(\frac{h_1^3+h_3^3}{12} + \left(\frac{h_1}{2}+\frac{h_2}{2}\right)^2 h_1 + \left(\frac{h_3}{2}+\frac{h_2}{2}\right)^2 h_3 + \frac{h_2^3}{12}\frac{E_y}{E_x}\right) \quad (2)$$

where E_x, E_y – modulus of elasticity of the panel layers along and across the fibers, respectively; h_1… h_2…h_3…h_n – panel layer thicknesses.

To implement the study of comparative calculation based on the finite element method (FEM), the given plates characteristics are calculated for the use of flat finite elements (FE) No. 44, which simulate the properties of work in two directions – along and across the wood fibers.

Three types of CLT panels were calculated in this work: three-layer, five-layer and seven-layer, with spans of 3, 6, and 9 meters (Fig. 1).

The load is evenly distributed, equal to q = 1.5 kN/m^2 and q = 5 kN/m^2.

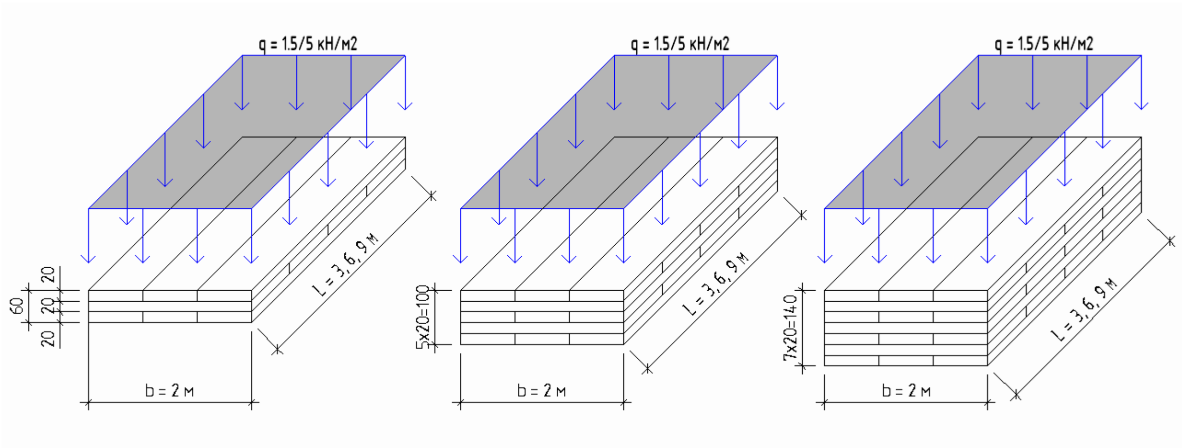


Fig. 1. Schemes of the investigated CLT panels

The wood class is C24.

Shear modulus $G = G_{mean}$ = 690 MPa.

Layer thickness: t = 20 mm.

Dimensions of FE plate No. 44: 0.2×0.2 m

After carrying out calculations, the following values of the reduced modulus of elasticity were determined and accepted:

Three-layer panel: E_1=10606 MPa, E_2=764 MPa.

Five-layer panel: E_1=8789 MPa, E_2=2581 MPa.

Seven-layer panel: E_1=7932 MPa, E_2=3438 MPa.

Poisson's ratios

– along the fibers ν_0 = 0.49;

– across the fibers ν_{90} = 0.0161.

The calculated parameters were entered into the program (Fig. 2).

In the Dlubal RFEM complex, the calculation of multilayer structures is implemented using the additional module RF-LAMINATE. Layers of constructions can be created and configured based on materials from the base of the software complex itself or changed as needed. The program also allows you to combine material models - it is possible to specify orthotropic and isotropic materials in one design.

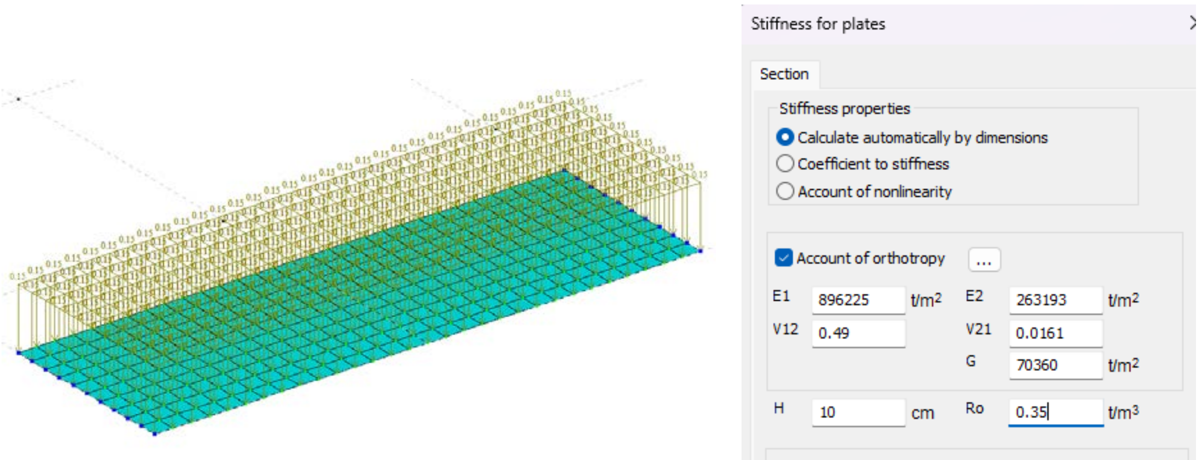
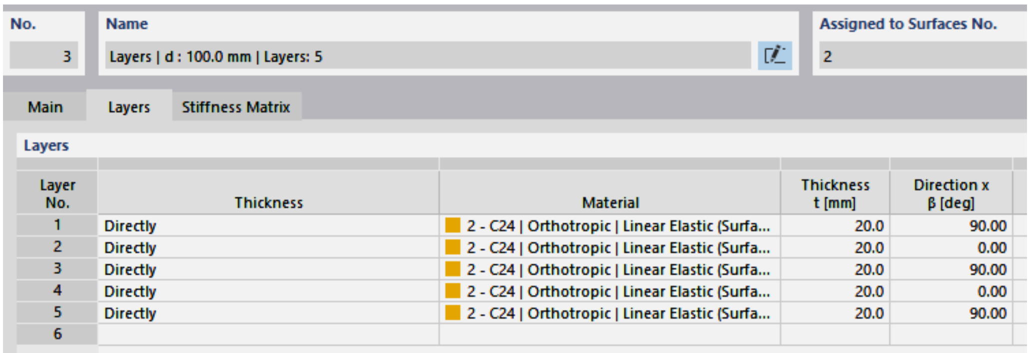


Fig. 2. The general view of the calculation scheme in LIRA-CAD and setting of rigidity for CE



No.	Name	Assigned to Surfaces No.
3	Layers | d : 100.0 mm | Layers: 5	2

Main | Layers | Stiffness Matrix

Layers

Layer No.	Thickness	Material	Thickness t [mm]	Direction x β [deg]
1	Directly	2 - C24 | Orthotropic | Linear Elastic (Surfa...	20.0	90.00
2	Directly	2 - C24 | Orthotropic | Linear Elastic (Surfa...	20.0	0.00
3	Directly	2 - C24 | Orthotropic | Linear Elastic (Surfa...	20.0	90.00
4	Directly	2 - C24 | Orthotropic | Linear Elastic (Surfa...	20.0	0.00
5	Directly	2 - C24 | Orthotropic | Linear Elastic (Surfa...	20.0	90.00
6				

Fig. 3. Specifying the layers of the CLT panel in RFEM

In this work, orthotropic material models were used with editing of C24 material characteristics from the database in order to bring the values to those used during calculation in LIRA-FEM. The thicknesses of the panel layers are adjusted taking into account the thickness and direction of rotation of each layer (Fig. 3). On the basis of the specified layers of the structure, the general stiffness matrix of the panel is automatically formed (Fig. 4).

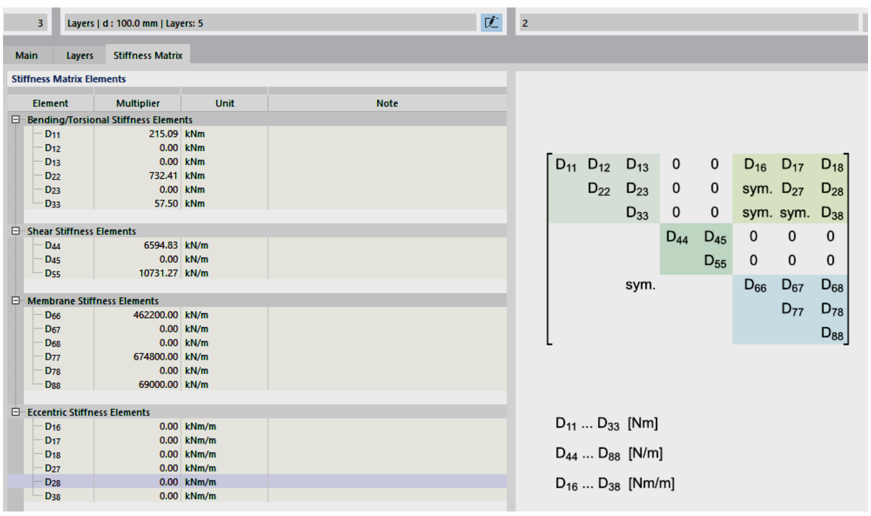


Fig. 4. Stiffness matrix of the CLT panel in RFEM

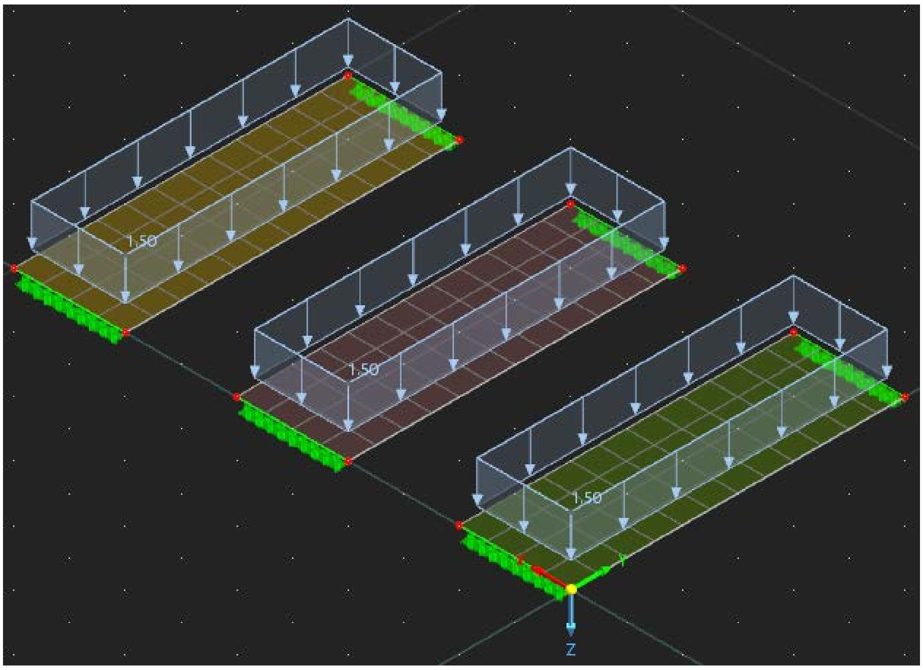


Fig. 5. General view of the calculation scheme in Dlubal RFEM

To study and compare the results of the calculation of CLT panels, calculation schemes of panels of similar sizes and with the same load as for the PC LIRA-FEM were created in PC RFEM (Fig. 5).

Results and discussion

The results of vertical deformations of CLT panels are presented in Table 1.

Table 1

Values of deflections for CLT panels under a uniformly distributed load of 1.5 kN/m² and 5.0 kN/m²

Number of layers	Load	Calculation method	Flight, m		
			3	6	9
			w, mm	*w*, mm	*w*, mm
3-layer	1.5 kN/m²	γ-method	9.52	152.38	766.73
		FE No. 44 in LIRA-FEM	21.1	371.6	1987.5
		Dlubal RFEM	13.0	198.1	996.7
	5.0 kN/m²	γ-method	29.005	461.86	2336.05
		FE No. 44 in LIRA-FEM	59.8	1053.91	5637.1
		Dlubal RFEM	30.0	463.2	2335.9
5-layer	1.5 kN/m²	γ-method	2.706	43.07	217.86
		FE No. 44 in LIRA-FEM	3.5	52.57	260.7
		Dlubal RFEM	3.8	56.2	282.1
	5.0 kN/m²	γ-method	7.82	124.565	636.018
		FE No. 44 in LIRA-FEM	9.85	149.1	739.4
		Dlubal RFEM	8.3	124.9	627.6
7-layer	1.5 kN/m²	γ-method	1.18	18.796	95.076
		FE No. 44 in LIRA-FEM	1.3	19.9	99.14
		Dlubal RFEM	1.8	24.7	123.3
	5.0 kN/m²	γ-method	3.256	51.856	262.3
		FE No. 44 in LIRA-FEM	3.7	56.5	281.2
		Dlubal RFEM	3.6	52.4	261.6

Table 2 analyzes the discrepancy in the calculation results of the deflections of three types of CLT panels: three-layer, five-layer and seven-layer, with spans 3, 6, 9 meters under a uniformly distributed load of 1.5 kN/m^2 and 5.0 kN/m^2. Also, the discrepancy in results with different calculation methods is graphically demonstrated in the form of diagrams on the example of panels with 3 and 6 meter spans under the action of a load of 1.5 kN/m^2.

Fig. 6 and Fig. 7 show comparative diagrams with the results of calculation in LIRA-FEM and Dlubal RFEM software complexes in the form of isofields of vertical deformations (deflections) on the example of panels with a span of 6 m at a load of 1.5 kN/m^2.

Table 2

Comparison of the results of calculation of panel deflection of three methods of calculation of CLT panels, discrepancy between methods, %

Flight	Comparison type	Three-layer		Five-layered		Seven-layered	
		1.5 kN/m^2	5.0 kN/m^2	1.5 kN/m^2	5.0 kN/m^2	1.5 kN/m^2	5.0 kN/m^2
3 m	γ-method – LIRA-FEM	121.6	106.2	29.3	26.0	10.2	13.6
	γ-method – RFEM	36.6	3.4	40.4	6.1	52.5	10.6
	RFEM – LIRA-FEM	62.3	99.3	7.9	18.7	27.8	2.8
6 m	γ-method – LIRA-FEM	143.9	128.2	22.1	19.7	5.9	9.0
	γ-method – RFEM	30.0	0.3	30.5	0.3	31.4	1.0
	RFEM – LIRA-FEM	87.6	127.5	6.5	19.4	19.4	7.8
9 m	γ-method – LIRA-FEM	159.2	141.3	19.7	16.3	4.3	7.2
	γ-method – RFEM	30.0	0.0	29.5	1.3	29.7	0.3
	RFEM – LIRA-FEM	99.4	141.3	7.6	17.8	19.6	7.5

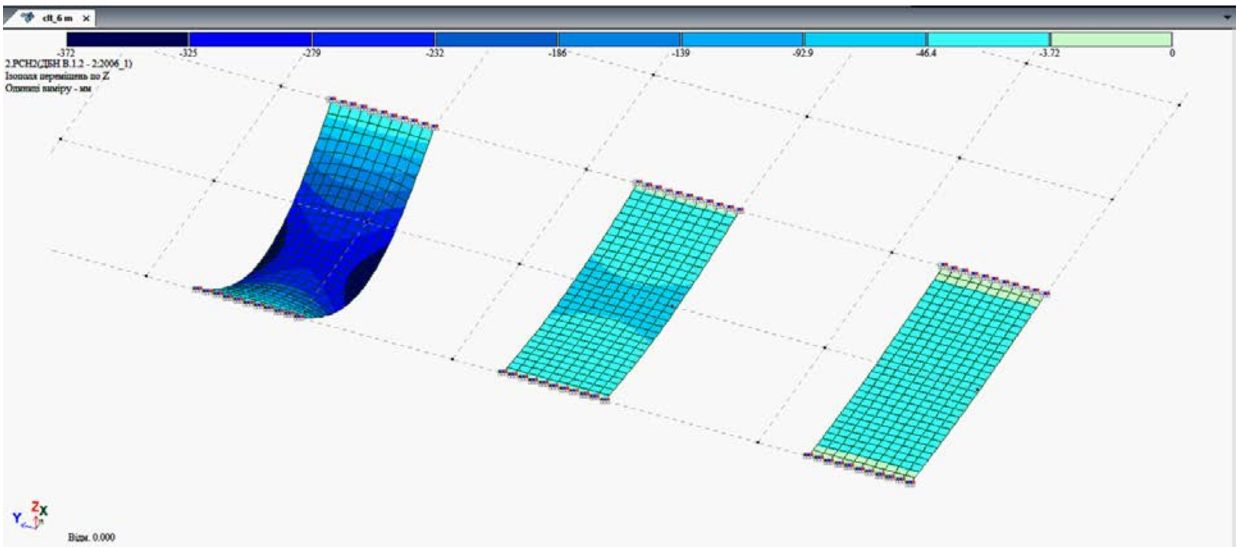


Fig. 6. Isofield of vertical deformations of CLT panels with a span of 6 meters under the action of a load of 1.5 kN/m^2 in LIRA-FEM

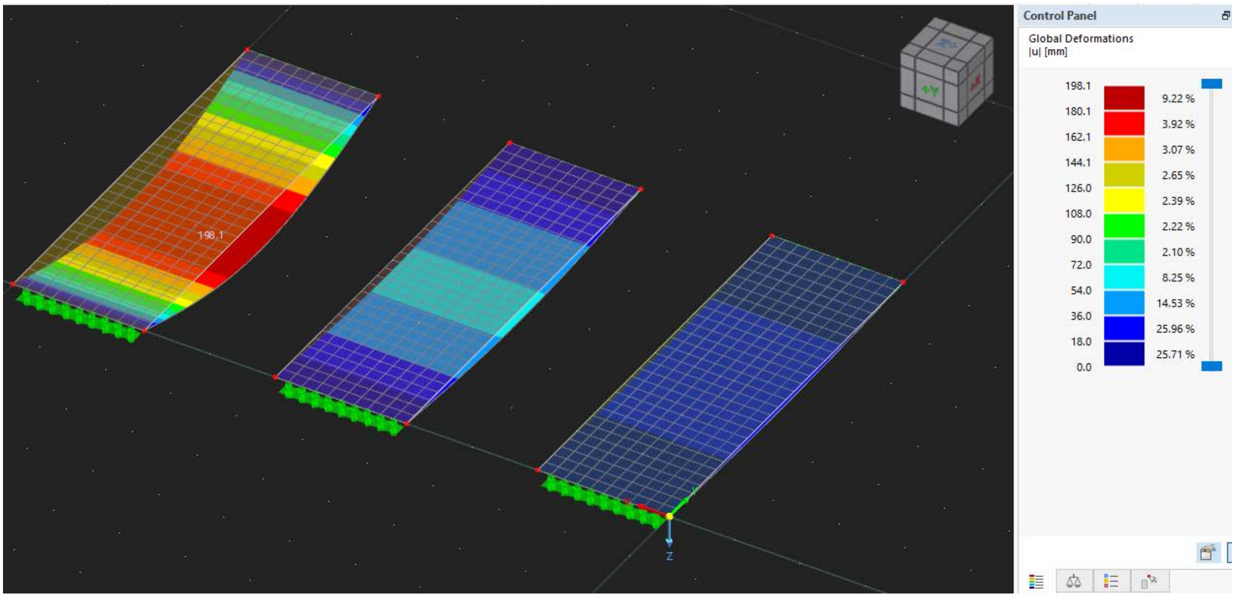


Fig. 7. Isofield of vertical deformations of CLT panels with a span of 6 meters under a load of 1.5 kN/m^2 in RFEM

There are significant discrepancies in the results of different research methods, especially for the three-lower panels. That is why the research of CLT structures requires further study and improvement of calculation methods.

Conclusions

1. CLT (cross-laminated timber) is a new construction technology for Ukraine, providing strength, stability, fire resistance, environmental friendliness and impressive indicators of building construction speed.

2. Three methods of calculating CLT panels are considered: analytical method, using the domestic LIRA-FEM software complex and the RFEM 6 program of the Dlubal Company.

3. The accepted methods of calculating CLT panels showed a significant and disproportionate discrepancy. In particular:

• Comparison of analytical γ-method and PC LIRA-FEM results showed the largest discrepancy for three-layer panels, ranging from 106 % to 159 %. When calculating five-layer panels, this discrepancy is much smaller and amounts to 16–29 %, and for seven-layer panels – 4.3–13.6 %, which is a satisfactory result.

• The comparison of the analytical γ-method and the results in RFEM is different from the comparison with LIRA-FEM. Under a load of 1.5 kN/m^2 for panels with spans of 6 m and 9 m, the discrepancy ranges from 29.7 to 31.4 %, and for a span of 3 m – from 36.6 to 52.5 %. However, at a load of 5 kN/m^2 for panels with a span of 6 m and 9 m, the discrepancy with the analytical method did not exceed 1.3 %, and for a span of 3 m – no more than 10.6 %.

• Comparing the deflections calculated in two software complexes, the discrepancy between them for three-layer panels exceeds 62 %, for five-layer panels it reaches 19.4 %, for seven-layer panels the discrepancy ranges from 2.8 % to 27.8 %.

4. The conducted research clearly indicates the need to improvement the methods of calculating CLT structures using software complexes and further research on this issue.

5. For the implementation CLT technology in Ukraine, a scientific and experimental base is needed, as well as practical guides for designers, which are currently partially or even completely missing.

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ПОРІВНЯЛЬНИЙ АНАЛІЗ МЕТОДІВ РОЗРАХУНКУ CLT КОНСТРУКЦІЙ

CLT (*cross-laminated timber*) або поперечно-клеєна деревина (ПКД) – новий для України матеріал, що зарекомендував себе у Європі та Америці як ефективний та екологічний з великою кількістю переваг. У роботі подано порівняльний аналіз розрахунку ПКД панелей: за допомогою програмних комплексів RFEM 6, ЛІРА-САПР та аналітичного методу. Дослідження виконано для трьох типів панелей: тришарових, п’ятишарових та семишарових, прольотами 3 м, 6 м, 9 м, під дією навантаження 1,5 кН/м^2 та 5,0 кН/м^2. Основним досліджуваним параметром є вертикальні переміщення. Результати розрахунків зведено в таблиці. Порівняння аналітичного γ-методу та результатів у ПК ЛІРА-САПР виявило найвищу розбіжність для тришарових панелей, що коливається від 106 % до 159 %. Розрахунок п’ятишарових панелей показав значно меншу розбіжність, яка становить 16–29 %, а для семишарових – 4,3–13,6 %, що є задовільним результатом. Порівняння аналітичного γ-методу та результатів у ПК RFEM відрізняється від порівняння з ЛІРА-САПР. Під навантаженням 1,5 кН/м^2 для панелей прольотами 6 м та 9 м розбіжність коливається у межах 29,7–31,4 %, а для прольоту 3 м – 36,6–52,5 %. Однак у разі навантаження 5 кН/м^2 для панелей прольотом 6 м та 9 м розбіжність з аналітичним методом не перевищила 1,3 %, а для прольоту 3 м – не більше ніж 10,6 %. Порівняно прогини, розраховані в двох програмних комплексах: розбіжність між ними для тришарових панелей перевищує 62 %, для п’ятишарових – досягає 19,4 %, для семишарових – коливається від 2,8 % до 27,8 %. Виконане дослідження засвідчило потребу удосконалення методів розрахунку CLT конструкцій та подальших досліджень цього питання. Для упровадження будівництва за технологією CLT в Україні необхідні наукова та експериментальна база, практичні посібники для проєктувальників.

Ключові слова: cross-laminated timber; CLT; ПКД; RFEM; ЛІРА-САПР; метод скінченних елементів.