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COMPARISON OF EXPERIMENTALLY OBTAINED AND THEORETICALLY DETERMINED IN THE DLUBAL RFEM 5 SOFTWARE PHYSICAL AND MECHANICAL PROPERTIES OF MASSIVE, GLUED LAMINATED AND CROSS-LAMINATED TIMBER BEAMS

S.I. Bilyk,
Doctor of Technical Science, Professor

D.O. Bitiukov,
Postgraduate student

Kyiv National University of Construction and Architecture

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Abstract. The article examines the peculiarities of the work of timber beams made of massive, glued laminated and cross-laminated timber under the action of concentrated loading. The purpose of the study is to determine the influence of the type of timber on the deformation characteristics of beam elements and to assess the accuracy of theoretical calculation models. The results of experimental studies are presented and the criterion for comparing theoretical and practical results is chosen by comparing the values of the maximum deflections. Theoretical calculations were performed in the Dlubal RFEM 5 software. To increase the reliability of the results, three modeling options were implemented: 1D "Member" finite elements, 3D "Solid" finite elements and 3D "Solid" finite elements but with consideration of the direction of the lamella fibers. A comparative analysis of the results showed the correspondence between the theoretically calculated and experimentally determined deflection values, which confirms the adequacy of the applied calculation models. In addition, it was established that the input data of characteristics of the material models in the software correctly reflect the physical and mechanical properties of the studied wood types. In the case of cross-laminated timber, some deviations between theoretical and experimental data were found, which is associated with the complex anisotropic structure of this composite material. In this regard, it is recommended to conduct additional research in order to clarify the elasticity parameters for CLT, which will reduce the error in modeling and provide more accurate prediction of the behavior of structures in real operating conditions.

Keywords: massive timber, glued laminated timber (glulam), cross-laminated timber (CLT), composite material, deformation modulus, shear modulus, deflection, building materials, mechanical resistance, finite element (FE), Poisson's ratio, Dlubal RFEM 5.

Introduction. In recent years, timber construction technologies have undergone significant changes and gained new momentum for development. It is due to both the increased interest in sustainable construction, as well as the emergence of new high-tech materials capable of providing the required level of strength, reliability and durability. Timber, as a traditional building material, combined with innovative methods of its manufacturing and composite technologies, is increasingly being considered as a real alternative to concrete and steel in modern construction.

Among the promising areas of development of wooden structures, special attention is drawn to glued laminated timber (glulam) and cross-laminated timber (CLT), which are already widely used in the construction of residential, public, industrial and even high-rise buildings [13, 15, 17]. Glulam consists of lamellas glued in the fiber longitudinal direction, which allows achieving high strength, resistance to loading and increased operational reliability. Cross-laminated timber, in turn, due to the alternation of the fiber directions of the layers, has improved rigidity in the transverse direction and better stability of the geometric shape [19, 20]. The operation of elements made of cross-glued wood under the action of seismic and dynamic loading is studied [16, 18, 21]. Due to the relatively low volumetric weight and high load-bearing capacity of wooden beams, they can be effectively used as load-bearing elements of coverings for rather large spans and can be considered as an alternative to steel trusses [23, 25]. The manufacturing technology of glued timber elements allows to produce curved shape elements and to successfully use wooden arches in construction [24].

However, despite numerous advantages, the behavior of such composite timber materials under complex types of loading has not yet been sufficiently studied, especially considering the anisotropy and complex internal structure of wood. In particular, this concerns the accuracy of theoretical prediction of deformations and stresses in beam elements under loading [9]. Standard calculation methods, based on simplified isotropic models, do not always allow to adequately reflect the real behavior of the material, which creates potential risks for the safety of structures [12].

The relevance of this research is determined by the need to improve the methods of analysis of wooden structures taking into account the specifics of their structure, which includes both the physical and mechanical properties of individual layers, as well as the interaction between them. This issue is of particular importance in the development of design standards for glulam timber and CLT, where not only experimental verification is required, but also high-precision numerical modeling, which provides the ability to take into account the influence of the orientation of the layers, adhesive joints and other constructive features [15, 20, 21].

One of the promising areas in the study of glued-laminated timber is its reinforcement with composite materials, in particular carbon or fiberglass tapes, which allows significantly increasing its bearing capacity and durability [6-8, 10, 11]. This makes it possible to effectively reduce the susceptibility to deformations, increase resistance to fatigue failure and ensure the stability of structures in difficult operating conditions.

The main advantages of glulam and cross-laminated timber over traditional materials (concrete and steel) include:

- High strength-to-weight ratio, which reduces the load on the foundations and increases installation speed of structures;
- Environmental friendliness, since wood is a renewable natural resource and contributes to the reduction of carbon dioxide emissions during the entire life cycle of the building;
- Thermal insulation properties that significantly exceed the corresponding indicators of steel and concrete;
- Resistance to deformations: warping, cracking - due to the unified structure and pre-treatment of wood;
- The possibility of prefabrication, i.e. the manufacture of large-sized elements with high precision at the factory, which reduces time and costs at the construction site.

Despite the high potential, the issue of accuracy of calculations remains critical, in particular for CLT structures, where due to the complex geometry of the layers and the lack of homogeneity, there is a need for the use of refined deformation models. It is important to consider the direction of the fibers, the modulus of elasticity in different directions, and other physical and mechanical characteristics of timber while creating calculating models in finite element method software complexes. Without taking these parameters into account, significant errors may occur in estimations of the bearing capacity of structures.

Thus, a comprehensive study of the relationship between the timber type, the orientation of the fibers of layers-lamellas, the influence of reinforcement, and the accuracy of numerical modeling is extremely relevant for ensuring the reliability and efficiency of timber buildings. This research aims not only to compare experimental and theoretical results, but also to analyze the accuracy of different modeling approaches and to recommend their practical application.

The purpose. Verification and confirmation of experimentally obtained physical and mechanical characteristics of beams made of massive, glued-laminated and cross-laminated timber, by comparing experimentally obtained and theoretically evaluated deflections calculated with the finite element analysis (FEA) software Dlubal RFEM 5.

The main content. Previously, experimental studies were conducted for the massive, glulam and CLT beams, made of pine wood of local origin. According to the results of the experiments, the mean values of the modified deformation moduli E^{*}_{mean} (deformation moduli taking into account the shear moduli and presented in Table 1) were obtained [22].

In order to verify and confirm the experimentally obtained research results, it was decided to perform verification by comparing theoretical and practical deflections of beams determined in the middle of the span.

Comparative calculations were carried out in three stages:

1. modeling of beams with 1D “Member”;
2. modeling of beams with spatial 3D “Solid” elements (3D);
3. modeling of a beam made of cross-laminated timber with material characteristics obtained for the massive timber, but with observance of the directions of the fibers of the corresponding lamellas (Fig. 1).

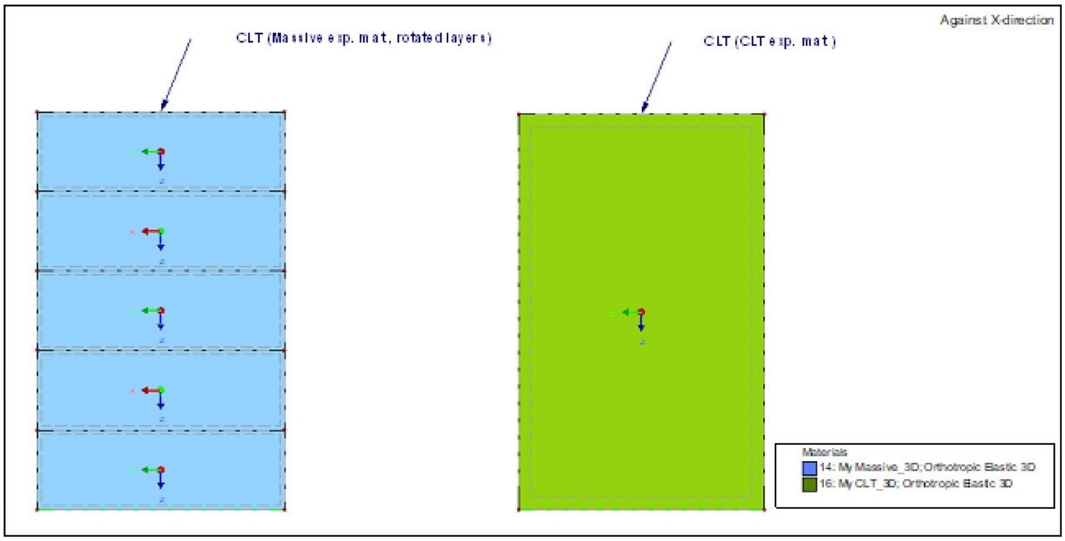

Fig. 1. CLT beam models 3D "Solid" elements, stage 3 (Dlubal RFEM 5)

The above-mentioned stages are adopted for the possibility of comparing the results depending on the modeling features: types of finite elements (FE), material models, modeling with consideration of the lamellae fiber directions.

An isotropic linear elastic model of the material was used to model the wood material for 1D finite elements [14]. For the simulation of wood materials, the mean values of the deformation modulus (E_{mean}) and the mean values of the shear modulus (G_{mean}) were calculated.

According to DBN V.2.6.-161:2017 [1]:

- increasing coefficient at shear k_G for deflection from bending in the middle of the span with a concentrated load in the middle of the span for a simply supported beam:

$$k_G = 1 + 1.2\frac{E_0}{G_0}\left(\frac{h}{l_{ef}}\right)^2, \quad (1)$$

where l_{ef} – design span (mm); h - cross-section height (mm); E_0 - modulus of deformation along the fibers (kN/mm^2); G_0 – shear modulus (kN/mm^2).

- at the previous research, a modified deformation modulus E^* was adopted, which takes into account the shear effects [22]:

$$E^* = \frac{E_0}{k_G}. \quad (2)$$

- the relationship between the mean deformation modulus and the shear modulus for timber elements:

$$G_{mean} = \frac{E_{mean}}{16}. \quad (3)$$

The calculated values of the mean modulus of deformation and the mean shear modulus are given in Table 1.

Table 1

Mean values of modified deformation modulus, deformation modulus and shear modulus

Timber type	E^*_{mean}, GPa	E_{mean}, GPa	G_{mean}, GPa
Massive	6.930	7.658	0.479
Glulam	6.599	7.292	0.456
CLT	5.527	6.108	0.382

Based on the results of beam modeling with 1D "Member" finite elements, comparisons were made between the calculated theoretical deflections and those determined experimentally. The determined theoretical deflections for beams specified by rod elements are performed in Figure 2.

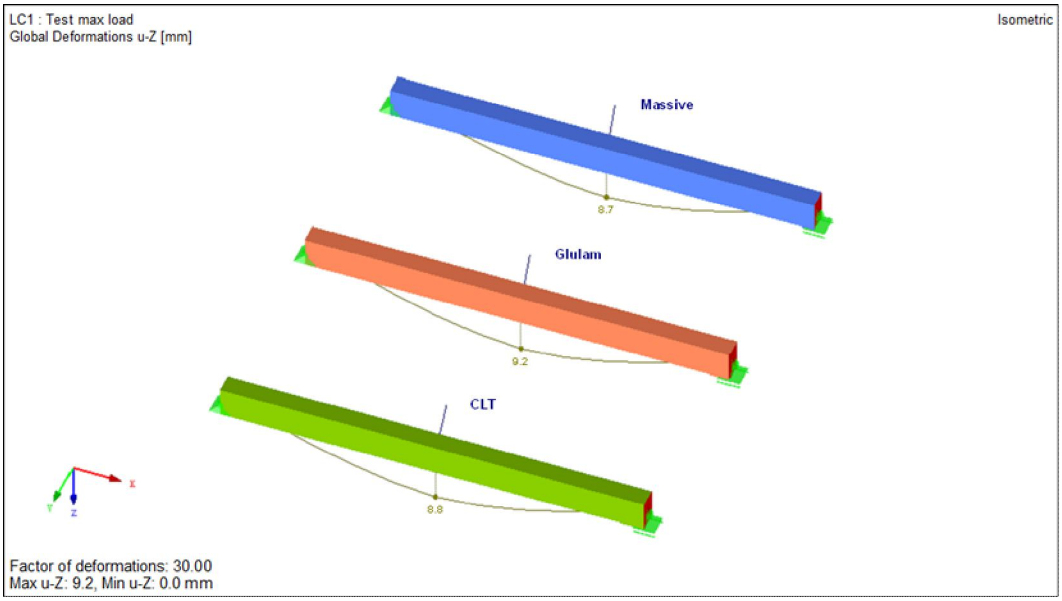

Fig. 2. Deflections of beams modeled with 1D "Member" elements (Dlubal RFEM 5)

Comparing the real and evaluated with the Dlubal RFEM 5 deflections of beams modeled with 1D finite elements, it can be noted that the results for the models of beams made of massive and glued laminated timber correspond to the practically obtained ones, the results for the model of cross-laminated timber material are underestimated, the error compared to the experimental results is in a range of 4%.

The comparison results of the theoretical deflections for the rod elements with the experimentally determined ones are given in Table 2.

Table 2

Theoretical (1D) and experimentally determined beam deflections

Timber type	Load, kN	Deflection, mm	
		Dlubal RFEM 5 / 1D FE	Experiment
Massive	8.81	8.7	8.74
Glulam	8.81	9.2	9.23
CLT	7.11	8.8	9.14

An orthotropic linear-elastic 3D model was used to specify the wood material for "Solid" elements [14].

The properties of wood depend on the direction of load application. For timber material, twelve elasticity parameters are required to solve three-dimensional problems [2]. This is true if we assume that the wood has three principal mutually perpendicular axes about which symmetry exists. Therefore, three main axes are defined for wood (Fig. 3) [4]. The x, y, z indices correspond to the directions of the main axes:

- longitudinal (x): axis parallel to the direction of the fibers;
- tangential (y): axis perpendicular to the direction of the fibers and tangent to the growth rings;
- radial (z): axis normal to the growth rings (perpendicular to the fibers in the radial direction).

Accordingly, the notation used in the orthotropic linear-elastic 3D model for the twelve elastic parameters of wood is:

E_x – deformation modulus in the longitudinal direction *x*;

E_y – deformation modulus in the tangential direction *y*;

E_z – deformation modulus in the radial direction *z*;

G_{yz}, G_{xz}, G_{xy} – shear modulus in the *yz*, *xz*, *xy* plane;

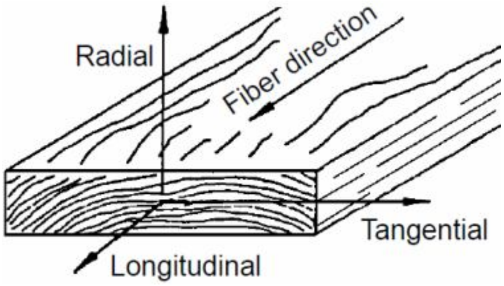

Fig. 3. The principal axes of wood according to the direction of the fibers and growth rings

$\nu_{yz}, \nu_{xz}, \nu_{xy}, \nu_{zy}, \nu_{zx}, \nu_{yx}$ – Poisson's ratio in the *yz*, *xz*, *xy*, *zy*, *zx*, *yx* plane.

The deformation modulus in the longitudinal direction assumed equal to the average deformation modulus E_{mean} defined in Table 1. Table 3 presents the predicted values of the deformation modulus and shear modulus depending on the deformation modulus in the longitudinal direction E_x for softwood species [5].

Table 3

Predicted deformation modulus and shear modulus depending on E_x, GPa

E_x	E_z	E_y	G_{xz}	G_{xy}	G_{yz}
6.0	0.6990	0.3667	0.6564	0.6185	0.0518
7.0	0.7710	0.4069	0.6763	0.6366	0.0566
8.0	0.7856	0.4453	0.6962	0.6546	0.0612

The interpolation method was used to determine intermediate values for the studied types of timber (Table 4).

Table 4

Predicted deformation modulus and shear modulus for the studied types of timber, GPa

Timber type	E_x	E_z	E_y	G_{xz}	G_{xy}	G_{yz}
Massive	7.658	0.781	0.432	0.689	0.648	0.060
Glulam	7.292	0.775	0.418	0.682	0.642	0.058
CLT	6.108	0.707	0.371	0.659	0.620	0.052

For the material models, the mean basic Poisson's ratios for softwood species determined and proposed in [3] were applied (Table 5).

Table 5

Mean Poisson's ratios for softwood species

ν_{yz}	0.35
ν_{xz}	0.37
ν_{xy}	0.42

The secondary Poisson's ratios $\nu_{zy}, \nu_{zx}, \nu_{yx}$ were calculated automatically by the RFEM Dlubal 5 based on the theory of elasticity, taking into account the symmetry of the strain energy, not all twelve elasticity parameters are independent. If the correct nine parameters are known, the other three can be calculated. These correlations are defined as:

$$\frac{\nu_{zy}}{E_z} = \frac{\nu_{yz}}{E_y}, \; \frac{\nu_{zx}}{E_z} = \frac{\nu_{xz}}{E_x}, \; \frac{\nu_{yx}}{E_y} = \frac{\nu_{xy}}{E_x}. \qquad (4)$$

Based on the simulation results, comparisons were made between the theoretically estimated deflections calculated with the RFEM Dlubal 5 software with those determined experimentally. Figure 5 shows the deflections of beams modeled by 3D elements.

Figure 4 shows the deflections of beams modeled by "Solid".

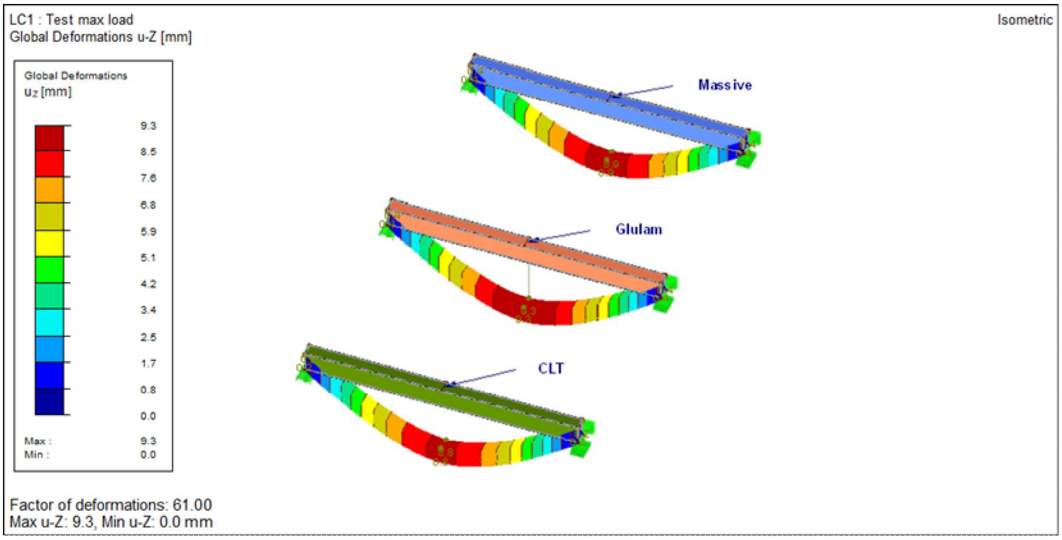

Fig. 4. Deflections of beams modeled with 3D "Solid" elements (Dlubal RFEM 5)

Also, the results of modeling of the cross-laminated beam with the separate lamellas with the observance of the orientation of the principal axes and the application of a material model with characteristics for massive timber were separately compared with a homogeneous section but with a material model with characteristics for cross-laminated timber.

Comparison of deflections of CLT beams modeled by the options described above are shown in Figure 5.

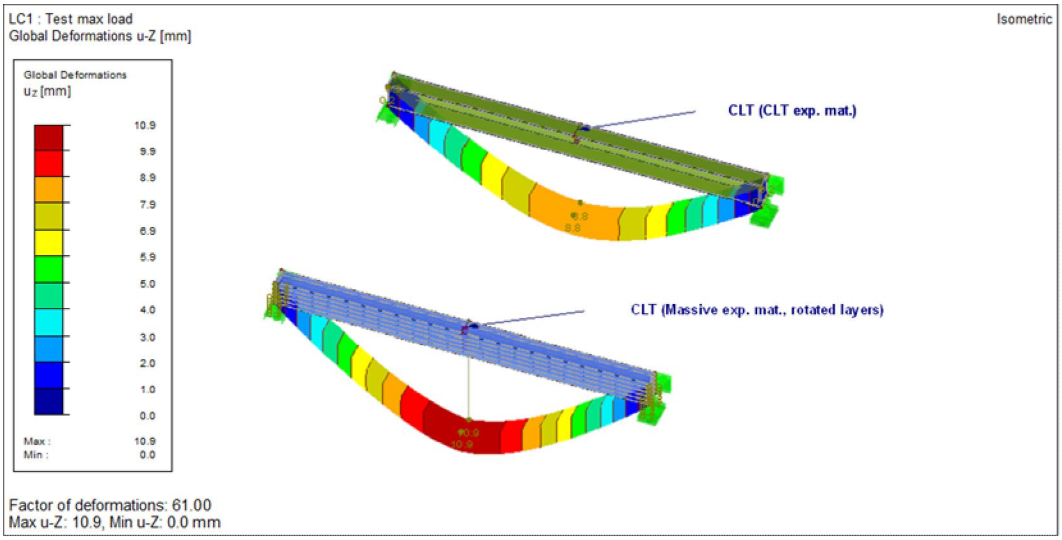

Fig. 5. Deflections of CLT beams modeled with 3D "Solid" elements (Dlubal RFEM 5)

Based on the results of comparing the deflections determined during the experiments and the deflections of beams modeled by 3D finite elements calculated in Dlubal RFEM 5, the following can be noted:

- the results of the models of beams made of massive and glulam timber correspond to the experimentally obtained;

- the results of the comparison of the models of beams made of massive and glued laminated timber correspond to the calculated results for the 1D elements;
- the results of the comparison of the model of the cross-laminated timber beam modeled with a solid section and the material determined for the CLT showed the correspondence of the results with the calculation of the cross-laminated beam modeled with 1D elements, compared to the experimental data, the result is underestimated, the error is in a range of 4%;
- the results of the comparison of the cross-laminated beam modeled with the 3D finite elements and consideration of the direction of the lamella fibers and the massive beam material applied showed the consistency of the results with the calculation of the cross-laminated beam modeled with 1D finite elements, compared to experimental data, the obtained result is on the safe side and overestimation is in a range of 19%.

The results of a comparison of theoretical deflections for "Solid" elements with experimentally determined are performed in Table 6.

Table 6

Theoretical (3D) and experimentally determined beam deflections

Timber type	Load, kN	Deflection, mm	
		Dlubal RFEM 5 / 3D FE	Experiment
Massive	8.81	8.9	8.74
Glulam	8.81	9.3	9.23
CLT	7.11	8.8 / 10.9*	9.14

* Deflection of the CLT beam modeled with consideration of the directions of the lamella fibers and the characteristics of the material as for massive wood

Conclusion. According to the results of the study of experimentally determined and theoretically calculated in the Dlubal RFEM 5 software package deflections of beams made of three types of timber (massive, glued laminated and cross-laminated), the correspondence and confirmation of the results are clearly traced.

For massive and glulam timber, the results of theoretical calculations for models using 1D "Member" and 3D "Solid" finite elements showed full correspondence between the results for theoretical models and the determined experimental values. The reason for the error within the range of 2% for three-dimensional models may be the use of generalized mean values of the elasticity parameters for softwoods for material models.

For cross-laminated timber, the results of theoretical calculations for 1D finite element models and 3D finite elements and cross-laminated material characteristics showed an underestimation of the results of theoretical models compared to those obtained experimentally. In order to reduce the error (within a range of 4%), more detailed research and determination of the relationship between the deformation modulus and the shear modulus for the material of CLT material is proposed.

For a beam made of cross-laminated timber modeled with the appropriate number and orientation of lamellas (3D FE) with the material characteristics of the lamellas as for massive wood, a capacity reserve was shown in relation to the results of the theoretical model in comparison with those obtained experimentally. The reason for the discrepancies between the theoretical deflection and the experimental result may be the use of generalized mean values of the elasticity parameters for softwood species for the timber material models.

Thus, the results of the study confirm the effectiveness and potential of using both simplified and more complex calculation models for the analysis of deflections of timber structures. At the same time, to achieve higher accuracy of calculations in the future, it is advisable to further improve the material models, in particular, taking into account the anisotropy of timber material, the orientation and number of layers in CLT, as well as conducting additional studies of the physical and mechanical properties of wood under complex stress-strain state.

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Білик С.І., Бітюков Д.О.

ПОРІВНЯННЯ ЕКСПЕРИМЕНТАЛЬНО ОТРИМАНИХ ФІЗИКО-МЕХАНІЧНИХ ХАРАКТЕРИСТИК БАЛОК З МАСИВНОЇ, КЛЕЄНОЇ ТА ПЕРЕХРЕСНО-КЛЕЄНОЇ ДЕРЕВИНИ ТА ТЕОРЕТИЧНО РОЗРАХОВАНИХ У ПРОГРАМНОМУ КОМПЛЕКСІ DLUBAL RFEM 5

У статті представлено результати дослідження та верифікації експериментально отриманих фізико-механічних характеристик дерев'яних балок, виготовлених з масивної, клеєної та перехресно-клеєної деревини. Метою дослідження є порівняння реальних та теоретичних прогинів балок, визначених у програмному комплексі кінцево-елементного аналізу Dlubal RFEM 5. Попередньо були проведені експериментальні дослідження з визначення модифікованих модулів деформації для кожного типу деревини із врахуванням впливу модуля деформації зсуву.

Моделювання виконувалось у три етапи: із застосуванням стрижневих 1D кінцевих елементів, просторових тривимірних 3D кінцевих елементів та 3D-моделі CLT-балки з урахуванням орієнтації волокон ламелей. Для кожного типу деревини були визначені характеристики для відповідних моделей матеріалу: ізотропної лінійно-пружньої для 1D елементів та ортотропної лінійно-пружньої 3D моделі матеріалу для 3D елементів. Теоретично рознаховані прогини порівнювались із експериментальними значеннями, що дозволило оцінити точність кожної з моделей.

Результати показали високу точність моделювання для балок з масивної та клеєної деревини з похибкою до 2%. Для балок з CLT-деревини відзначено недооцінку теоретичних прогинів для моделей зі стрижневих та просторових кінцевих елементів та запас теоретичних прогинів для моделей із просторових кінцевих елементів з урахуванням орієнтації волокон ламелей.

Дослідження підтверджує доцільність використання як спрощених, так і більш детальних моделей при аналізі деформацій дерев'яних конструкцій. Для підвищення точності розрахунків рекомендовано подальше уточнення характеристик досліджуваних матеріалів, зокрема залежності між модулем деформації та модулем зсуву, а також врахування складних умов навантаження, типів опор та довготривалих впливів у майбутніх дослідженнях. Також доцільним є проведення додаткових експериментів для уточнення параметрів міцності й жорсткості, характерних для різних конфігурацій перехресно-клеєних балок.

Ключові слова: масивна деревина, клеєна деревина, перехресно-клеєна деревина, композитний матеріал, модуль деформації, модуль зсуву, прогин, будівельні матеріали, механічна стійкість, скінченний елемент, коефіцієнт Пуассона, Dlubal RFEM 5.

Bilyk S.I., Bitiukov. D.O.

COMPARISON OF EXPERIMENTALLY OBTAINED AND THEORETICALLY DETERMINED IN THE DLUBAL RFEM 5 SOFTWARE PHYSICAL AND MECHANICAL PROPERTIES OF MASSIVE, GLUED LAMINATED AND CROSS-LAMINATED TIMBER BEAMS

The article presents the results of research and verification of experimentally obtained physical and mechanical characteristics of beams made of massive, glued laminated (glulam) and cross-laminated timber (CLT). The purpose of the study is to compare the real and theoretical deflections of the beams, determined with the Dlubal RFEM 5 finite element analysis software. Previously, experimental studies were conducted to determine the modified deformation modulus (deformation modulus with consideration of influence of shear modulus) for each type of timber beams.

The modeling was performed in three stages: using 1D member finite elements, 3D Solid finite elements and a 3D Solid model of the CLT beam considering the orientation of the lamellae fibers in each layer. For each type of timber beam, characteristics were determined for the corresponding material models: isotropic linear-elastic material model for 1D finite elements and orthotropic linear-elastic 3D material model for 3D finite elements. Theoretically calculated deflections were compared with experimentally obtained values, which made it possible to evaluate the accuracy of each model.

The results showed high accuracy of modeling for massive and glulam timber beams with an error of up to 2%. For CLT beams, an underestimation of the theoretical deflections for models from 1D and 3D finite elements and an overestimation of theoretical deflections for models from 3D finite elements, taking into account the orientation of the fibers of the lamellae, was noted.

The research confirms the expediency of using both simplified and detailed models in the analysis of deformations of timber structures. To increase the accuracy of the calculations, it is recommended to further refine the characteristics of the studied materials, in particular, the dependence between the deformation modulus and the shear modulus, as well as considering complex loading conditions, types of supports, and long-term effects in future studies. It is also advisable to carry out additional experiments to clarify the parameters of strength and stiffness characteristic of various configurations of cross-glued beams.

Keywords: massive timber, glued laminated timber, cross-laminated timber, composite material, deformation modulus, shear modulus, deflection, building materials, mechanical resistance, finite element, Poisson's ratio, Dlubal RFEM 5.

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У статті представлено результати порівняння експериментально отриманих та теоретично визначених методом скінчених елементів у програмному комплексі Dlubal RFEM 5 прогинів рознахованих на основі попередньо визначених експерементально фізико-механічних характеристик дерев'яних балок, виготовлених з масивної, клеєної та перехресно-клеєної деревини.
Іл. 5. Табл. 6. Бібліогр. 25 назв.

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Bilyk S.I., Bitiukov D.O. **Comparison of experimentally obtained and theoretically determined in the Dlubal RFEM 5 software physical and mechanical properties of massive, glued laminated and cross-laminated timber beams //** Strength of Materials and Theory of Structures. Scientific-and-technical collected articles. – K.: KNUBA, 2025. – Issue 114. – P. 101-110.
The article presents the results of a comparison of experimentally obtained and theoretically determined by the finite element method in the Dlubal RFEM 5 software deflections of beams based on previously determined experimentally physical and mechanical characteristics of massive, glued laminated (glulam) and cross-laminated timber (CLT) beams..
Figs. 5. Tabl 6. Refs. 25.

Автор (науковий ступінь, вчене звання, посада): доктор технічних наук, професор БІЛИК Сергій Іванович
Адреса: 03037, Україна, м. Київ, Проспект Повітряних Сил, 31, Київський національний університет будівництва і архітектури
Робочий тел.: +38 (044) 241-54-89
E-mail: vartist@ukr.net
ORCID: https://orcid.org/0000-0001-8783-5892

Автор (науковий ступінь, вчене звання, посада): аспірант БІТЮКОВ Дмитро Олегович
Адреса: 03037, Україна, м. Київ, Проспект Повітряних Сил, 31, Київський національний університет будівництва і архітектури
Робочий тел.: +38 (044) 241-54-89
Мобільний тел.: +38(097) 76-77-286
E-mail: bitiukov.do@gmail.com
ORCID: https://orcid.org/0009-0002-1438-7595