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PROBABILISTIC RELIABILITY ANALYSIS OF A BENDING CLT ROOF SLAB BASED ON DEFLECTION CRITERION

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Abstract
Introduction: Cross-laminated timber structural elements are being actively introduced into the construction practice of residential and public buildings. A special factor in the design of CLT structures is the principles of ensuring their reliability, since a large amount of statistical data on the safety level of such structures has not yet been accumulated due to their relative novelty. **Objective of the study** is to develop an algorithm for probabilistic analysis of a bending CLT roof slab over a given service life based on the deflection criterion (linear displacements). **Methods**: The reliability indicator of a CLT roof slab is taken as the probability of failure-free operation, which is estimated by frequency based on random variable generation using the Monte Carlo method, employing an adopted mathematical model of the limit state. The numerical approach to reliability assessment, based on an analytical expression of the limit state, is the most effective approach due to the simplicity of algorithm implementation and reliable results when using various types of random variables. **Results**: An algorithm has been developed to evaluate the probability of failure-free operation of a CLT roof slab based on the deflection criterion when designing the panel for a design service life. Probabilistic analysis allows selecting the most efficient structural solution for a CLT roof slab for a given reliability index β. The influence of lamella thickness tolerance factors of the CLT roof slab on reliability (probability of failure-free operation) has been established.

Keywords: cross-laminated timber; deflection; probability of failure; bending; slab; reliability index.

Introduction

Cross-laminated timber (CLT) is actively used for load-bearing and enclosing structures of residential and public buildings and structures. From a structural point of view, a CLT roof slab is a factory-manufactured solid timber slab consisting of at least three orthogonally glued layers of solid or finger-jointed boards. This structural solution allows its effective use under various types of stress-strain states, including bending, in the form of beams and roof / floor slabs.

The global cross-laminated timber production market volume in 2023 amounted to USD 1,024.4 million and, according to forecasts (Fortune Business Insights, 2025), will grow from USD 1,174.1 million in 2024 to USD 3,537.9 million by 2032. It is also noted there that CLT structural elements have advantages in terms of construction assembly speed — building assembly reaches up to 14,000 square feet (1,300 m²) per day with 6 technical workers, while construction work of a similar scale using classical building materials can take several weeks and require significantly more labor. According to data (Zhang and Lan, 2022), the demand for CLT structural elements in the Pacific Northwest region will reach 0.190 million m³/year by 2035, compared to approximately 0.008 million m³/year in 2016–2018 (less than 1 % of the annual timber harvest volume in the Pacific Northwest region). In 2020, the global volume of cross-laminated timber production was estimated at 3.4 million cubic meters per year (De Araujo and Christoforo, 2023). The development prospects for constructing buildings and structures from CLT panels are also widely discussed in research (Younis and Dodoo, 2022; D’Amico et al., 2021; Anwar et al., 2024).

In a recent study (Kurzinski et al., 2022), it is noted that the technology of using cross-laminated timber in construction has only been introduced over the last three decades, as a result of which production and design standards for CLT structural elements are still under development. One of the key factors in regulating the calculation and design of CLT structures is the principles of ensuring their reliability and forming a system of design parameters and limit states.

The reliability of building structures within the current normative design method is ensured by using safety factors (partial factors) for design parameters in mathematical models of limit states. This method of justifying the reliability of building structures is called the limit state design method. Limit state design, developed by a team of Soviet scientists in the 1940s and first adopted into the USSR regulatory document system in 1955, has gained wide recognition worldwide and was subsequently

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used as the basis for ISO-2394 and the Eurocode system, where it is called the “partial factor method”. As noted in a study (Mkrtychev, 2022), “the limit state design method allows ensuring the required level of reliability of buildings and structures, which is confirmed by design, construction, and operation experience. However, this method has a number of disadvantages, for example, it is impossible to determine what level of reliability in quantitative terms is formed as a result of applying design codes, and whether this reliability level is the same for buildings and structures of different structural schemes and made from different materials”.

The next stage in the evolution of design codes is the use of full probabilistic calculations for building structures. This approach allows quantifying the reliability of a building structure or its individual element in the form of the probability of failure-free operation or the reliability index β. One of the key studies in this direction is the article (Köhler et al., 2016), which provides statistical information on random variables in CLT panel design and the main principles of probabilistic calculation.

Currently, there are already a number of studies containing algorithms for probabilistic reliability assessment of CLT slabs. Bending tests of a CLT slab were conducted (Solovev et al., 2024), and a methodology for probabilistic reliability analysis based on the strength criterion of normal sections of the panel was developed. The probability of failure of CLT panel building walls is assessed (Aloisio and Fragiacomo, 2021), depending on the peak ground acceleration (PGA) during an earthquake. Probabilistic reliability analysis of CLT panels under seismic loads is also considered in (Sun et al., 2018; Sun et al., 2020). The influence of load duration on the rolling shear strength of cross-laminated timber panels with different cross-sectional arrangements (five-layer and three-layer) was evaluated using probabilistic reliability analysis (Li and Lam, 2016).

Algorithms for probabilistic reliability analysis of CLT slabs under bending should also be supplemented with criteria of the second group of limit states, including deflection. Bending tests of CLT slabs, for example, (He et al., 2018; Song and Hong, 2018; O’Ceallaigh et al., 2018; Ma et al., 2021; Dong et al., 2021), show that the maximum permissible deflection according to aesthetic-psychological requirements in slabs occurs earlier than the maximum permissible normal or shear stresses, as noted in Fig. 1.

Thus, in a number of tasks, the factor of the second group of limit states (states exceeding which disrupts the normal operation of building structures, exhausts their durability resource, or violates comfort conditions) may become decisive when assigning cross-sectional dimensions of elements.

Subject, Tasks and Methods

The subject of this study is the reliability of a CLT slab under bending based on the stiffness (deflection) criterion. To develop an algorithm for probabilistic reliability analysis of a bending cross-laminated timber slab, it is necessary to solve the following tasks: formulation of a mathematical model of the limit state in analytical form; substantiation of the randomness / determinism of parameters in the limit state model with selection of the most reliable distribution functions of random variables and their parameters; development and automation of a calculation algorithm with analysis of factors affecting the reliability of the CLT slab. The Monte Carlo data generation method, which is most

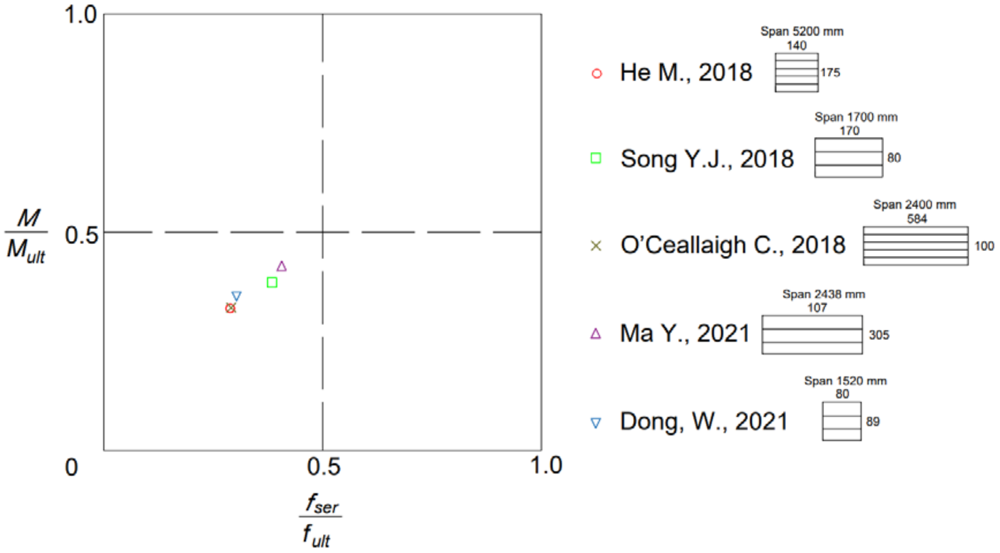

Fig. 1. Graphs of reaching maximum relative deflections during testing of CLT slabs depending on the relative ultimate bending moment based on strength

effective for simple analytical mathematical models of limit states and a set of different types of random variable distributions, is adopted as the reliability assessment method.

According to CSA O86-14 and the Canadian CLT Handbook (2019), the maximum deflection of a bending CLT slab can be determined by the formula:

$$\Delta = \Delta_{ST} + \Delta_{LT} \cdot \quad {}_{creep}, \tag{1}$$

where Δ_{ST} is the elastic deflection caused by short-term and / or standard loads, without combination with permanent loads; Δ_{LT} is the elastic deflection caused by the action of long-term and permanent loads; K_{creep} is the creep factor, taken as K_{creep} = 2.0 for dry service conditions (DeSantis, 2023).

Loads can be classified by duration of application based on Eurocode 5 “Design of timber structures” (Table 1).

The deflection under a given uniformly distributed load q, acting perpendicular to the surface of a single-span slab (beam), can be calculated as the sum of deflections caused by the bending moment and transverse shear, using the effective bending stiffness $(E \cdot I)_{eff}$ and the effective shear stiffness $(G \cdot A)_{eff}$:

$$\Delta = \frac{5}{384}\frac{q \cdot l^4}{(E \cdot I)_{eff}} + \frac{1}{8}\frac{q \cdot l^2 \cdot k}{(G \cdot A)_{eff}}, \tag{2}$$

where l is the span of the CLT slab; k is the shear correction factor, taken as 1.0 for rectangular cross-sections according to CSA O86-14.

For the case of a concentrated force *P* at mid-span, formula (2) becomes:

$$\Delta = \frac{1}{48}\frac{P \cdot l^3}{(E \cdot I)_{eff}} + \frac{1}{4}\frac{P \cdot l \cdot k}{(G \cdot A)_{eff}}. \tag{3}$$

Table 1. **Classification of load duration according to Eurocode 5**

Load Duration Class	Cumulative Load Duration
Permanent	> 10 years
Long-term	6 months – 10 years
Medium-term	1 week – 6 months
Short-term	< 1 week
Instantaneous	not specified

The effective bending stiffness is calculated by the formula:

$$(E \cdot I)_{eff} = \sum_{i=1}^{n} E_i \cdot b_y \cdot \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i \cdot b_y \cdot t_i \cdot z_i, \tag{4}$$

where E_i is the modulus of elasticity of the *i*-th layer of wood in the CLT slab; designations of geometric parameters are shown in Fig. 2.

The effective shear stiffness $(G \cdot A)_{eff}$ can be calculated by the following formula:

$$(G \cdot A)_{eff} = \\ = \frac{\left(h - \frac{t_1}{2} - \frac{t_n}{2}\right)^2}{\left[\left(\frac{t_1}{2G_1 \cdot b_y}\right) + \left(\sum_{i=2}^{n-1} \frac{t_i}{G_i \cdot b_y}\right) + \left(\frac{t_n}{2G_n \cdot b_y}\right)\right]}, \tag{5}$$

where G_i is the shear modulus of the *i*-th layer of wood in the CLT slab; designations of geometric parameters are shown in Fig. 2.

In (Volynsky, 2006), statistical indicators of the properties of softwood timber in the USSR at 12 % moisture content are established. The average density of softwood timber is 485 kg/m³ (4.76 kN/m³) with a coefficient of variation of 18 %. The JCSS Probabilistic Model Code, Part 2 — Load models: 2.1 — Self-Weight states that for the self-weight of structural elements, a normal (Gaussian) distribution hypothesis can be used. The cross-sectional dimensions of the CLT slab and individual lamellas have certain tolerances established by the manufacturer’s standard and industry standards (e.g., GOST R 56706–2015 “Glued slabs made of cross-laminated timber. Technical specifications” and GOST 24454–80 “Softwood lumber. Dimensions”). In the absence of sufficient data for fitting a probability distribution, but having the variability bounds of dimensions as random variables, a uniform probability distribution for the geometric parameters of the cross-section is adopted at the first stage of reliability analysis.

The modulus of elasticity and shear modulus of wood have shown good convergence with a normal probability distribution in many practical studies (Solovev and Soloveva, 2025).

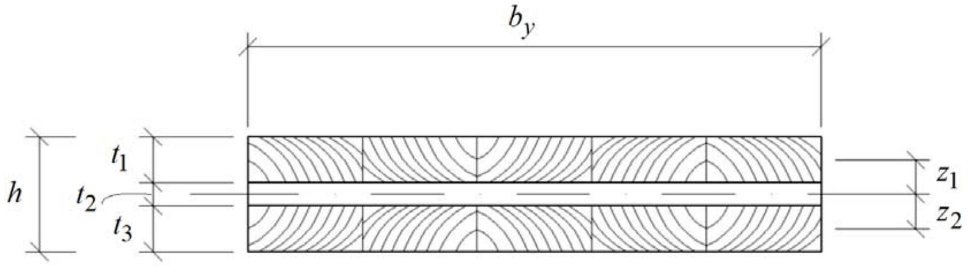

Fig 2. Geometric parameters of CLT panel cross-section using the example of a three-layer panel

Research Results and Discussion

Suppose the following statistical information for random parameters in the mathematical model of the limit state is known (Table 2).

Parameter values are given in N/m due to the adopted panel width b_y = 1 m.

The roof slab is represented by a design model of a single-span simply supported beam with a uniformly distributed load.

The maximum snow load values s over n years of operation of a CLT slab can be described by the Gumbel distribution law:

$$F(s) = \exp\left[-\exp\left(\frac{\alpha - s + \beta \ln n}{\beta}\right)\right], \qquad (6)$$

where α is the location parameter of the Gumbel distribution; β is the scale parameter of the Gumbel distribution.

For example, for a weather station near the city of Vologda, the following values were obtained over >50 years of observations: $\alpha = 86{,}9$ kg/m² (0,852 kPa), $\beta = 28{,}5$ kg/m² (0,280 kPa).

To generate random variable values using the Monte Carlo method, it is necessary to perform an inverse transformation of function (6) using the N.V. Smirnov method. Hence:

$$S_i = F^{-1}(s) = \alpha - \ln\left(-\ln(U\left[0;\ 1\right])\right) + \beta \ln n, \qquad (7)$$

where $U\left[0;\ 1\right]$ are generated values from a uniform distribution in the interval [0; 1].

The limit state function $g(X)$ can be written as:

$$g\left(\mathbf{X}\right) = \Delta_{ult} - \Delta\left(\mathbf{X}\right), \qquad (8)$$

where $\mathbf{X}$ is the vector of random variables (Table 2); Δ_{ult} is the maximum permissible deflection; $\Delta\left(\mathbf{X}\right)$ is the random deflection calculated from $\mathbf{X}$ values based on the mathematical model (1).

The probability of failure P_f can be calculated using Monte Carlo data generation as:

$$P_f \approx \frac{1}{N} \sum_{j=1}^{N} I\left[g\left(\mathbf{X}\right) < 0\right], \qquad (9)$$

where $I\left[g\left(\mathbf{X}\right) < 0\right]$ is the indicator function, which takes the value 1 if condition $I\left[g\left(\mathbf{X}\right) < 0\right]$ is true and 0 if condition $I\left[g\left(\mathbf{X}\right) < 0\right]$ is false; N is the number of initial data generations.

Based on the mathematical model of the limit state (8) and the statistical data in Table 2,

Table 2. **Statistical information for random parameters**

Random Variable	Probability Distribution		
	Distribution Function	**Parameters**	**Note**
Self-weight of CLT slab, γ	Normal distribution	$m_\gamma = 4850$ N/m³, $S_\gamma = 873$ N/m³	–
Weight of structures on CLT slab (insulation, membrane), q_1	Normal distribution	$m_{q1} = 250$ N/m, $S_{q1} = 25$ N/m*	–
Snow load, q_2	Gumbel distribution	$\alpha_{q1} = 869$ N/m, $\beta_{q1} = 285$ N/m*	Based on processing data from weather station No. 27026
Span, l	Deterministic value	$l = 4.0$ m	–
Thickness of slab layer elements (i=1, 3), $t_1 = t_3$	Uniform	$\underline{t}_1 = \underline{t}_3 = 39.0$ mm, $\overline{t}_1 = \overline{t}_3 = 41.0$ mm	According to GOST 24454–80
Thickness of slab layer elements (i=2), t_2	Uniform	$\underline{t}_2 = 19.0$ mm, $\overline{t}_2 = 21.0$ mm	According to GOST 24454–80
Slab width, b_y	Uniform	$\underline{b}_y = 996.0$ mm, $\overline{b}_y = 1004.0$ mm	According to GOST 56706–2015
Modulus of elasticity parallel to grain (layers 1, 3)	Normal	$m_E = 12.0$ GPa, $S_E = 1.8$ GPa	According to SP 64.13330.2017
Modulus of elasticity perpendicular to grain (layer 2)	Normal	$m_{E\perp} = 400$ MPa, $S_E \perp = 60$ MPa	According to SP 64.13330.2017
Shear modulus parallel to grain (layers 1, 3)	Normal	$m_G = 500$ MPa, $S_G = 50$ MPa	
Shear modulus perpendicular to grain (layer 2)	Normal	$m_{G\perp} = 500$ MPa, $S_{G\perp} = 50$ MPa	

100,000 values of each parameter were generated for a CLT slab over a 50-year service life, as shown in the histogram (Fig. 3).

If the obtained data array of maximum deflections is approximated by a normal distribution with distribution parameters fitted using the Distribution Fitter App of the MATLAB software package, the following parameters can be obtained: m_Δ = 0.0125 m, S_Δ = 0.0020 m.

It is proposed to approximate the obtained empirical distribution functions with a GEV (Generalized Extreme Value) distribution with the analytical form:

$$F(s(x),k)=\begin{cases}\exp(-e^{-s(x)}) \text{ if } k=0;\\ \exp(-(1+k\cdot s(x))^{-1/k})\\ \text{if } k\neq 0 \text{ and } k\cdot s(x)>-1;\\ 0 \text{ if } k>0 \text{ and } s(x)\leq -\dfrac{1}{k};\\ 1 \text{ if } k<0 \text{ and } s(x)\geq \dfrac{1}{|k|},\end{cases} \qquad (10)$$

where $s(x)=\dfrac{x-\mu}{\sigma}$ is the standardized random variable, where μ is the location parameter, σ is the scale parameter; *k* is the shape parameter.

Using parameters k = –0,0775; σ = 0,0017 m and μ = 0,0117 m, obtained by fitting the distribution function through the Distribution Fitter App of the MATLAB software package for 100,000 generated deflection values $\Delta(\mathbf{X})$, a closer density distribution can be obtained (Fig. 3).

Let the maximum deflection be 20 mm. Calculate using (10):

$$\exp\left(-\left(1+k\cdot s(x)\right)^{-1/k}\right)=$$

$$=\exp\left(-\left(1-0,0775\frac{0,0200-0,0117}{0,0017}\right)^{-1/(-0,0775)}\right)=$$

$$=0,99779.$$

From 100,000 generations, in 99,723 cases the design deflection over 50 years of operation was less than 20 mm. Consequently, the reliability (probability of failure-free operation) of the CLT slab over 50 years of operation based on the deflection criterion is 99.723 %. The relative error in calculating the probability of failure-free operation using the approximation (10) and by frequency is 0.56 %. Therefore, the GEV distribution approximation can be used when there are computational difficulties with generating a large number of random parameters.

Thus, the presented algorithm for calculating the probability of failure-free operation can be reduced to the following steps:

1. Statistical parameters of distribution functions of random variables (according to Table 2) of the mathematical model of the limit state are established;
2. 100,000 values of each random variable are generated;
3. 100,000 values of the design deflection are calculated based on the mathematical model (1);

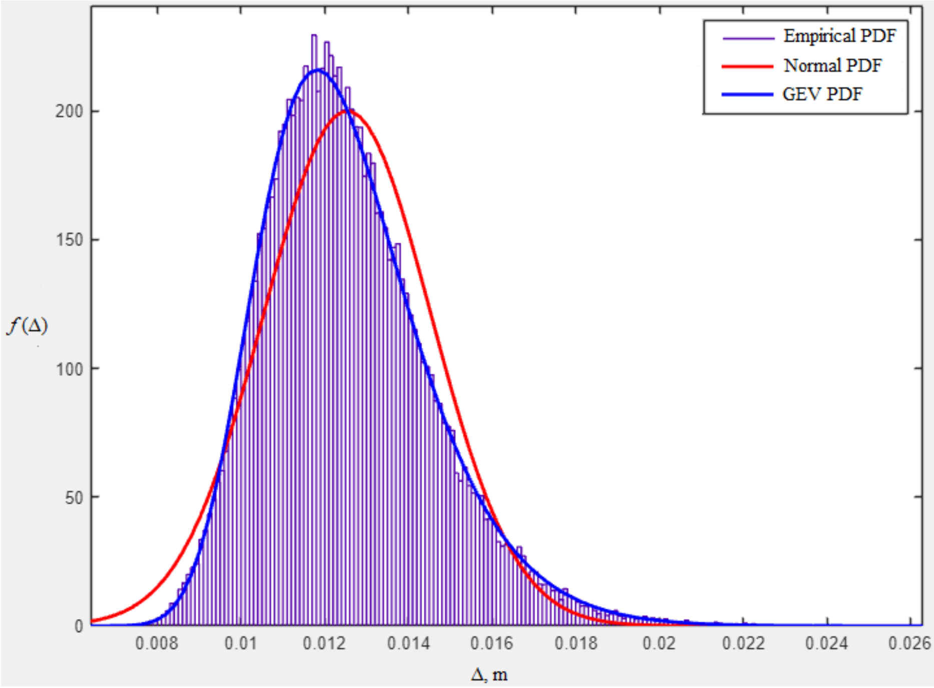

Fig. 3. Geometric parameters of CLT slab cross-section using the example of a three-layer panel: vertical axis: $f(\Delta)$ is probability density function of deflection Δ; horizontal axis: Δ is deflection value in meters

4. The empirical probability distribution function of the calculated values $\Delta(\mathbf{X})$ is approximated using the GEV probability distribution;

5. In the obtained analytical form of function (10), the variable x is replaced by the value of the maximum deflection Δ_{ult} and the probability of failure-free operation of the CLT roof slab is calculated;

6. Using the inverse Laplace function, the reliability index β is calculated from the obtained probability of failure-free operation.

According to the relationship equation between the probability of failure-free operation and the reliability index according to Eurocode 0 “Basis of structural design,” the probability value obtained above corresponds to a reliability index $\beta = 2,77$.

There are various proposals for standardizing the reliability index and probability of failure (or failure-free operation). For example, (Marek, 2003) proposes the following values (Table 3).

If the data in Table 3 are taken as design values, then the reliability of the investigated CLT roof slab structure over a 50-year service life based on the deflection criterion can be considered assured under the given operating conditions. In the Table, the target reliability index β for structural elements of class RC2 over a 50-year service life is taken as β = 1.500 — the calculated reliability index for the CLT roof slab (β = 2.77) is also above this value.

However, the most effective solution for assigning the target reliability index of a building structural element or its probability of failure-free operation is an individual calculation based on the acceptable level of risk, expressed in financial equivalent of the damage cost from the occurrence of a “failure” event. More detailed information can be found in Solovev’s study (Solovev and Soloveva, 2025).

An additional advantage of the developed methodology is also that the CLT roof slab can be designed for any service life, while the normative approach provides discrete division depending on the structural consequence class. Fig. 4 shows a graph of the decrease in panel reliability over time. This is mainly due to an increased probability of peak snow load occurrence over a longer service period.

Under known operating conditions of the CLT roof slab, it may be necessary to form a catalog for structures, which indicates, for example, permissible span values for the slab based on the required reliability level. The change in reliability level depending on the span for the investigated CLT roof slab under given operating conditions (Table 2) is shown in Fig. 5.

From Fig. 5, it can be seen that increasing the span of the CLT roof slab significantly affects its reliability based on the deflection criterion. Using the same slab for a span 1 meter longer leads to an almost 100 % probability of exceeding the maximum permissible deflection Δ_{ult}. In the case of unacceptably low probability of failure-free operation, a repeat reliability analysis can be performed for a shorter design service life of the slab (Fig. 4).

Table 3. **Standardized probability of failure values (Marek, 2003)**

Structural Consequence Class	First Group of Limit States	Second Group of Limit States
Low	0.000500 (β=3.291)	0.160 (β=0.995)
Medium	0.000070 (β=3.808)	0.070 (β=1.476)
High	0.000008 (β=4.314)	0.023 (β=1.995)

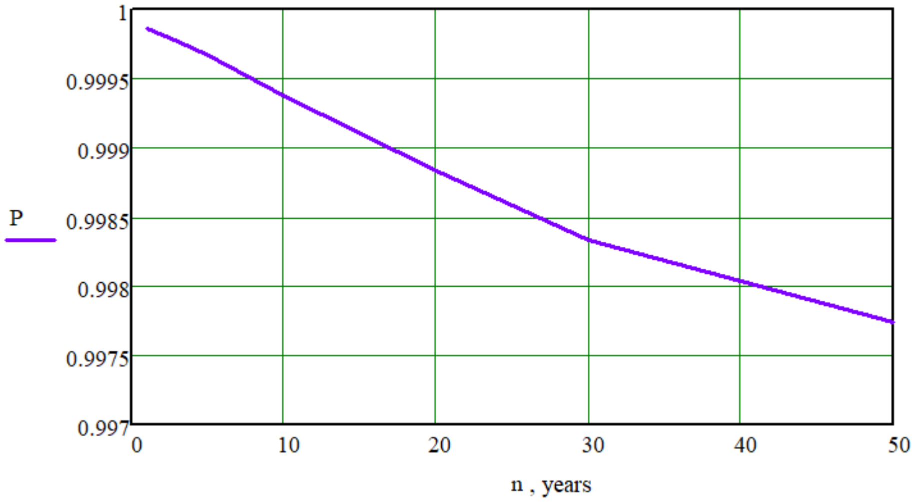

Fig. 4. Graph of reliability dependence of the designed CLT roof slab on the design service life

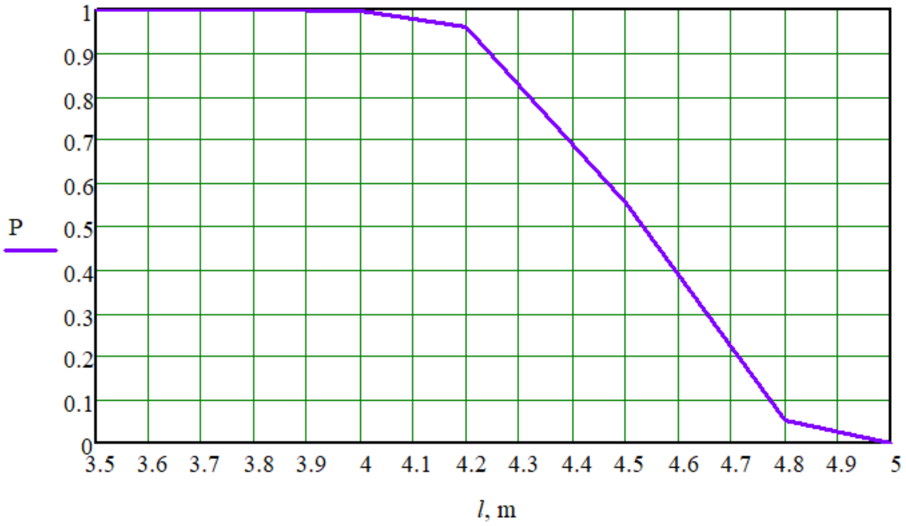

Fig. 5. Graph of reliability dependence of the designed CLT roof slab on span (based on deflection criterion)

Given statistical data from the manufacturer, such tables can be constructed for various structural panel options under different operating conditions (climatic regions, types of loads, etc.).

It is also possible to analyze the thickness tolerances of the panel lamellas t_i and their influence on reliability.

From Table 4, it can be seen that an increase in tolerance of 0.5 mm leads to a proportional increase in the probability of failure of approximately 0.06 %.

Probabilistic analysis allows identifying the factors whose variability most significantly affects reliability indicators, which will enable the formulation of control measures and, accordingly, ensure the required level of load-bearing capacity and serviceability of building structural elements.

Conclusions

1. Structural elements made of cross-laminated timber (CLT) began to be used in the 1990s, and the dynamics of their production and the construction of buildings and structures based on them have grown exponentially in recent years. Due to the fact that CLT structural elements are relatively new and do not have a sufficiently large volume of data on their durability, dynamics of load-bearing capacity and serviceability, an important scientific and technical task is the design justification of the required level of safety during the design and operation of buildings and structures made of CLT. One of the most effective tools for design reliability justification at present is full probabilistic calculations.

2. The paper proposed an algorithm for probabilistic reliability analysis of a cross-laminated timber panel based on the stiffness (deflection) criterion over a given service life. Using the developed algorithm for reliability analysis will allow selecting the most rational cross-section options for CLT roof slabs, taking into account the design service life of the building structure. Every 10 years, the expected reliability in terms of probability of failure-free operation decreases by approximately 0.5 %, which is associated with an increased probability of occurrence of a large snow load over a longer service period. Technical tolerances also affect reliability — an increase in tolerance of 0.5 mm leads to a proportional increase in the expected probability of failure by approximately 0.06 %.

3. Under known operating conditions of a CLT roof slab, it may be necessary to form a catalog for structures, which indicates, for example, permissible span values for the panel based on the required reliability level (according to load-bearing capacity and serviceability criteria). Given statistical data from the manufacturer, such diagrams can be constructed for various structural panel options under different operating conditions (climatic regions, types of loads, etc.) based on the probabilistic algorithm proposed in this study.

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Table 4. **Influence of lamella thickness tolerances of CLT roof slab on reliability**

Tolerance t_i	±0.5 mm	±1.0 mm	±1.5 mm	±2.0 mm	±2.5 mm
Reliability *P*	0.99818	0.99723	0.99713	0.99646	0.99603

References

Aloisio, A. and Fragiacomo, M. (2021). Reliability-based overstrength factors of cross-laminated timber shear walls for seismic design. *Engineering Structures*, 228, pp. 111–547. DOI: 10.1016/j.engstruct.2020.111547.

Anwar, U. M. K., Lee, S. H., CB, O., and Asniza, M. (2024). The properties of cross laminated timber (clt): A review. *International Journal of Adhesion and Adhesives*, pp. 103–924.

D'Amico, B., Pomponi, F., and Hart, J. (2021). Global potential for material substitution in building construction: The case of cross laminated timber. *Journal of Cleaner Production*, 279, pp. 123–487. DOI: 10.1016/j.jclepro.2020.123487.

De Araujo, V. and Christoforo, A. (2023). The global cross-laminated timber (CLT) industry: A systematic review and a sectoral survey of its main developers. *Sustainability*, 15 (10), pp. 78–27. DOI: 10.3390/su15107827.

DeSantis, A. G. (2023). *Experimental Investigation of the Long-Term Bending Deflection and Creep Performance of Cross-Laminated Timber (CLT).* Available at: https://open.clemson.edu/cgi/viewcontent.cgi?article=5122&context=all_theses (accessed on: 27.05.2025).

Dong, W., Wang, Z., Zhou, J., and Gong, M. (2021). Experimental study on bending properties of cross-laminated timber-bamboo composites. *Construction and Building Materials*, 300, pp. 124–313. DOI: 10.1016/j.conbuildmat.2021.124313.

(2025). *Fortune Business Insights.* Available at: https://www.fortunebusinessinsights.com/cross-laminated-timber-clt-market-102884 (accessed on: 21.04.2025).

He, M., Sun, X., and Li, Z. (2018). Bending and compressive properties of cross-laminated timber (CLT) panels made from Canadian hemlock. *Construction and Building Materials*, 185, pp. 175–183. DOI: 10.1016/j.conbuildmat.2018.07.072.

Köhler, J., Fink, G., and Brandner, R. (2016). Basis of Design Principles — Application to CLT. *Proceedings of the Joint Conference of COST Actions FP1402 & FP1404 Cross Laminated Timber — A competitive wood product for visionary and fire safe buildings*, 10 (3), pp. 45–61.

Kurzinski, S., Crovella, P., and Kremer, P. (2022). Overview of cross-laminated timber (CLT) and timber structure standards across the world. *Mass Timber Construction Journal*, 5 (1), pp. 1–13.

Li, Y. and Lam, F. (2016). Reliability analysis and duration-of-load strength adjustment factor of the rolling shear strength of cross laminated timber. *Journal of wood science*, 62, pp. 492–502. DOI: 10.1007/s10086-016-1577-0.

Ma, Y., Wang, X., Begel, M., Dai, Q., Dickinson, Y., Xie, X., and Ross, R. J. (2021). Flexural and shear performance of CLT panels made from salvaged beetle-killed white spruce. *Construction and Building Materials*, 302, pp. 124–381. DOI: 10.1016/j.conbuildmat.2021.124381.

Marek, P. (2003). *Probabilistic Assessment of Structures Using Monte Carlo Simulation* Czech Republic, Prague: CAS.

Mkrtychev, O.V., Shchedrin, O., and Lokhova, E.M. (2022). Determination of individual coefficients on the basis of probabilistic analysis. *Vestnik MGSU*, 17 (10), pp. 1331–1346. DOI: 10.22227/1997-0935.2022.10.1331-1346.

O'Ceallaigh, C., Sikora, K., and Harte A. M. (2018). The influence of panel lay-up on the characteristic bending and rolling shear strength of CLT. *Buildings*, 8 (9), p. 114. DOI: 10.3390/buildings8090114.

Song, Y. J. and Hong, S. I. (2018). Performance evaluation of the bending strength of larch cross-laminated timber. *Wood research*, 63 (1), pp. 105–116. Available at: https://www.woodresearch.sk/wr/201801/10.pdf (accessed on: 27.05.2025).

Solovev, S., Puchkov, V., and Soloveva, A. (2024) Probabilistic design of flexural cross-laminated timber structural elements. *International Journal for Computational Civil and Structural Engineering*, 20 (2), pp. 99–108. DOI: 10.22337/2587-9618-2024-20-2-99-108.

Solovev, S. and Soloveva, A. (2025). *Reliability of building structures: history, analysis, forecast*. Moscow: Publishing House ABC.

Sun, X., Li, Z., and He, M. (2020). Seismic reliability assessment of mid-and high-rise post-tensioned CLT shear wall structures. *International Journal of High-Rise Buildings*, 9 (2), pp. 175–185. DOI: 10.22337/2587-9618-2024-20-2-99-108.

Sun, X., He, M., Li, Z., and Shu, Z. (2018). Performance evaluation of multi-storey cross-laminated timber structures under different earthquake hazard levels. *Journal of wood science*, 64, pp. 23–39. DOI: 10.1007/s10086-017-1667-7.

Volynsky, V. (2006). Interrelation and variability of indicators of physical and mechanical properties of wood. Arkhangelsk.

Zhang, Z. and Lan, K. (2020). Understanding the impacts of plant capacities and uncertainties on the techno-economic analysis of cross-laminated timber production in the southern US. *Journal of Renewable Materials*, 10 (1), p. 53.

Younis, A. and Dodoo, A. (2022). Cross-laminated timber for building construction: A life-cycle-assessment overview. *Journal of Building Engineering*, 52, pp. 104–482. DOI: 10.1016/j.jobe.2022.104482.

ВЕРОЯТНОСТНЫЙ АНАЛИЗ НАДЕЖНОСТИ ИЗГИБАЕМОЙ ПЛИТЫ ПОКРЫТИЯ ИЗ CLT ПО КРИТЕРИЮ ПРОГИБА

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Аннотация

Введение. Элементы строительных конструкций из перекрестно-клееной древесины активно внедряются в практику строительства жилых и общественных объектов. Особым фактором при проектировании строительных конструкций из CLT являются принципы обеспечения их надежности, т.к. на текущий момент не накоплено большого количества статистических данных об уровне безопасности таких конструкций в связи с их относительной новизной. **Цель исследования**: разработка алгоритма вероятностного анализа изгибаемой плиты покрытия из CLT в течение заданного периода эксплуатации по критерию прогиба (линейных перемещений). **Методы**: показателем надежности плиты покрытия из CLT принята вероятность безотказной работы, которая оценивается по частоте на основе генераций случайных величин по методу Монте-Карло на базе принятой математической модели предельного состояния. Численный подход к оценке надежности, на базе аналитического выражения предельного состояния, является наиболее эффективным подходом, вследствие простоты реализации алгоритма и достоверного результата при использовании различных видов случайных величин. **Результаты**: разработан алгоритм, позволяющий оценить вероятность безотказной работы плиты покрытия из CLT по критерию прогиба при проектировании панели на расчетный период эксплуатации. Вероятностный анализ позволяет подобрать наиболее эффективное конструкционное решение плиты покрытия из CLT на заданный индекс надежности β. Установлено влияние фактора допусков на толщину ламелей плиты покрытия из CLT на надежность (вероятность безотказной работы).

Ключевые слова: перекрестно-клееная древесина, прогиб, вероятность отказа, изгиб, плита, индекс надежности.