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PROBABILISTIC DESIGN OF FLEXURAL CROSS-LAMINATED TIMBER STRUCTURAL ELEMENTS

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Abstract: The article presents a probabilistic approach to the design of flexural elements made of cross-laminated timber (CLT) as one of the promising materials for sustainable construction. The variability of the elasticity modulus and the ultimate strength of the timber layers effects on the structural safety. Such uncertainty can be modeled by using probabilistic and statistical methods. Information is presented on tests of a three-layer CLT panel during bending, and statistical parameters are given for wooden control samples of the CLT panel layers. The implementation of the presented approach makes it possible to obtain an estimate of the reliability index or the failure probability for the CLT structural element according to the criterion of normal cross-sections strength. With a given target level of reliability or risk value, the reliability level of the design solution of a cross-laminated structure can be quantified.

Keywords: cross-laminated timber, CLT, reliability index, probabilistic design, failure probability, flexural element, risk analysis

ВЕРОЯТНОСТНОЕ ПРОЕКТИРОВАНИЕ ИЗГИБАЕМЫХ ЭЛЕМЕНТОВ ИЗ ПЕРЕКРЕСТНО-КЛЕЕНОЙ ДРЕВЕСИНЫ

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Аннотация: В статье представлен вероятностный подход к проектированию изгибаемых элементов из перекрестно-клееной древесины как одного из перспективных материалов для устойчивого строительства. Изменчивость модуля упругости и предела прочности слоев древесины влияет на безопасность эксплуатации конструкции, что может быть достоверно смоделировано путем использования вероятностно-статистических методов. Приведены данные об испытаниях трехслойной CLT панели при изгибе, а также статистическая информация об испытаниях контрольных образцов древесины слоев панели. Реализация представленного подхода позволяет получить оценку индекса надежности или вероятности безотказной работы для CLT элемента по критерию прочности нормальных сечений. При заданном целевом уровне надежности или значении риска можно количественно выразить уровень надежности проектного решения конструкции из перекрестно-клееной древесины.

Ключевые слова: перекрестно-клееная древесина, CLT, индекс надежности, вероятностное проектирование, вероятность отказа, изгибаемый элемент, анализ риска

INTRODUCTION

Cross-laminated timber (CLT), an engineered wood product that was originally developed in Europe in the 1990s, has been gaining worldwide popularity in helping to define a new class of timber products known as massive or “mass” timber. By GOST 56706-2022, cross-laminated timer is a massive wooden slab, manufactured in a factory manner and consisting of at least three orthogonally glued layers of solid or fused boards along a toothed joint and intended for use as a load-bearing and enclosing structural element. Besides gluing, nails, screws, or wooden dowels can be used to attach the layers. Innovative CLT products such as Interlocking Cross-Laminated Timber (ICLT) are in the process of development. As noted in Canadian CLT Handbook [1], “CLT is one of several mass timber products considered to be the “game changer” in this endeavor and the catalyst to enable other wood products to be used in those applications”. Regarding the ongoing global activities, CLT production volume is expected to significantly increase over the next decade [2].

Since CLT is a relatively new structural material, at the moment there is not a large amount of statistical data on failures of CLT structural elements during construction or maintenance. The design of CLT elements is based on the semi-probabilistic methods (limit state design or partial safety factor method).

Eurocode 0 "Basis of structural design" divides the structural design methods into three levels: Semi-probabilistic methods (Level I), First-Order Reliability Methods (FORM) (Level II) and Full probabilistic methods (Level III). It is noted, that full probabilistic methods (Level III) give in principle correct answers to the reliability problem. Thus, the research and development of probabilistic methods for designing CLT elements is an urgent task aimed at developing the design theory of such structures.

There are some researches of probabilistic problems in cross laminated timer elements behavior. The article [3] presents the stochastic-mechanical multivariate model approach was established describing the load–displacement behavior of self-tapping screws. In the research [4] noted that "the present work should have shown the capability of the employed probabilistic methods to efficiently predict the variability of glued laminated timber. In future, probabilistic simulations will help in accomplishing more efficient timber structures, starting at the grading of wooden boards and development of timber products to engineering design of complex timber structures". A probabilistic approach is used in [5] for analyze the mechanical properties of three types of CLT connections.

The article [6] presents use of probabilistic methods for determination of stiffness and strength parameters of the CLT panels based on test data. Authors of the fundamental research of glued laminated timber beams stochastic behavior [7] notes "Due to the natural growth process of trees, wooden boards show a high amount of random fluctuation in their mechanical properties. Currently, in engineering practice, a homogeneous material behavior is assumed within wooden boards and uncertainties in loading and load-bearing capacity are considered through design procedures based on partial safety factors. These partial safety factors are not directly linked to the individual mechanical behavior of the considered structural system/element. Thus, a stochastic framework opening up the possibility to establish such links, by combining structural analysis tools with probabilistic descriptions of wooden boards, could be an important step in timber design, also to improve the competitiveness of wood against other building materials".

This paper considers the problem of probabilistic design of flexural CLT structural elements by the normal cross-section strength criterion on a target reliability level.

MATERIALS AND METHODS

According to Canadian CLT Handbook (2019) [1], the limit state condition for normal sections of flexural CLT structural elements can be written as:

$$\sigma = \frac{0,5 \cdot M \cdot h \cdot E_{mean}}{(E \cdot I)_{eff}} \leq \sigma_{ult}, \qquad (1)$$

where M is a bending moment in the cross-section; h is a thickness of the CLT panel; E_{mean} is an average elasticity modulus of the cross-section; $(E \cdot I)_{eff}$ is effective bending stiffness of the panel for the major strength axis; σ_{ult} is bending strength or ultimate stress in the cross-section.

The effective bending stiffness can be determined as:

$$(E \cdot I)_{eff} = \sum_{i=1}^{n} E_i \cdot b_y \cdot \frac{t_i^3}{12} + \sum_{i=1}^{n} E_i \cdot b_y \cdot t_i \cdot z_i^2, \qquad (2)$$

where b_y is a width of the panel for the major strength axis; E_i is a modulus of elasticity of laminations in the *i*-th layer; t_i is a thickness of laminations in the *i*-th layer; z_i is a distance between the center point of the *i*-th layer and the neutral axis (Fig. 1).

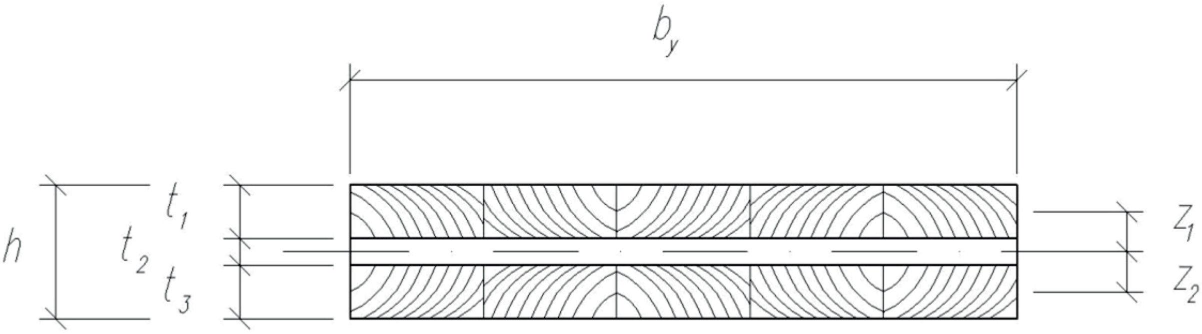

Figure 1. Cross-section parameters for a CLT structural element

The resistance factor of CLT in bending $\phi = 0{,}9$ and the strength modification factor $K_{rb,y} = 0{,}85$ as the partial safety factors are neglected in (2) because probabilistic approach will be used further. Some other safety factors by National Building Codes are also neglected in probabilistic models because it should be taken into account in probability distribution functions and parameters directly.

The dimensions of the geometric parameters are assumed to be deterministic, because the production technology of CLT panels allows controlling woodworking process with high precision.

The limit state function can be written as:

$$g = \frac{0{,}5 \cdot \widetilde{M} \cdot h \cdot E_{mean}}{\widetilde{\sigma}_{ult} \cdot b_y \cdot \left[\sum_{i=1}^{n} \widetilde{E}_i \cdot \frac{t_i^3}{12} + \sum_{i=1}^{n} \widetilde{E}_i \cdot t_i \cdot z_i^2 \right]} \leq 1, \quad (3)$$

where are random variables denoted by the wavy lines.

The Mechanically Jointed Beams Theory can also be used of estimation of normal cross-section's bearing capacity. This method, also named Gamma Method (γ-method), was developed in 1955 by Professor Karl Möhler. According to this method, the stiffness properties of the mechanically jointed beams are defined using the Effective Bending Stiffness $(E{\cdot}I)_{eff}$, which is dependent on the section properties of the beams and the connection efficiency factor γ. The γ factor depends on the slip characteristics of the fasteners (also called s/K ratio), being zero for no mechanical connection between the beams and equaling unity for rigidly connected beams.

$$g = \frac{\widetilde{M} \cdot E_1}{\widetilde{\sigma}_{ult} \cdot (\widetilde{E} \cdot I)_{eff}} \left[\gamma_1 a_1 + \frac{h_1}{2} \right] \leq 1,$$

where a_1 is the distance between the centroid of the first lamina and the centroid of the panel cross-section, and h_1 is the thickness of the first (outermost) lamina. As noted in [1], the γ factor may typically vary from 0.85 to 0.9.

The reliability index for CLT structural element by the normal cross-section strength can be expressed as:

$$\beta = \frac{1 - m_g}{S_g},$$

where m_g is an expected value and S_g is a standard deviation for limit state function *g*.

The failure probability of normal cross-sections is presented as $P_f = \Pr(g > 1)$, or $P_f = \Phi(\beta)$ if all random variables is described by the normal distribution, where Φ(.) is the value from the standard normal table (z-value table).

Two groups of methods for probabilistic reliability analysis can be distinguished:

- Analytical methods: FOSM (First Order Second Moment); FORM (First Order Reliability Method); SORM (Second Order Reliability Method); TANA (Two-point Adaptive Nonlinear Approximation), etc.
- Numerical methods: Monte Carlo methods, data sampling, discretization into Dempster-Shafer structures, etc.

Analytical methods obtain an accurate solution for the probability of non-failure of structural elements, but have a number of limitations: approximation of highly nonlinear limit state functions leads to computational errors; complexity of constructing models for mechanical systems taking into account the dependence of random variables; influence of the type and form of the mathematical model of the limit state (invariance problem); the complexity of the combination of different models of random variables – within the framework of one practical task, fuzzy variables, interval parameters, random sets, etc. may be present simultaneously.

Numerical methods make it possible to effectively model highly nonlinear mathematical models of limit states and analyze the reliability of complex systems, but the accuracy of such approaches may be low in cases of low probabilities of failure [8]. Computational time costs should also be taken into account when probabilistic reliability analysis using numerical methods, which can be quite high in the case of complex systems.

The Monte Carlo method in [9] refers to the methods of the level III (see above). It is also noted that for tasks with a low probability of failure, which is often found in engineering and construction practice, a large number of random variable generations are needed to achieve the required accuracy of the results.

The failure probability P_f based on the Monte Carlo simulations is defined as:

$$P_f \approx \frac{1}{N}\sum_{j=1}^{N} I\left[g\left(\mathrm{X}_j\right) > 1\right], \qquad (4)$$

where $I[.]$ is an indicator function, which takes value 1 if I[.] equal “true” and 0 if I[.] equal “fall”; N is number of simulations.

The simulation of random variables according to the basic probability distributions (normal, uniform, etc.) can be performed, for example, in the MathCAD software. However, often the probability distribution function may differ from well-known distributions or represent a model of a partially nonparametric p-box [10]. In this case, N.V. Smirnov's inverse transformation method can be used: N values of a uniformly distributed random variable u_i are simulated ranging from [0; 1]. The values of a random variable in the form are obtained by the inverse transformation method $x_i = F^{-1}(u_i)$. For more information, see the research [10].

RESULTS AND DISCUSSION

The CLT panel was tested in the laboratory of structural researches in Vologda State University. The design scheme and the general view of tested element are presented at the Fig. 2.

The strain gauges were installed in the middle of the span of the CLT-panel. The deflection gauge (the clock-type indicator) was also installed in the span middle. A test load was created by reinforced concrete beams. The test load was maintained until the strains and deformations were stabilized.

The load-strain curve and the load-deflection are presented at the Fig. 3 and Fig. 4.

a)

b)

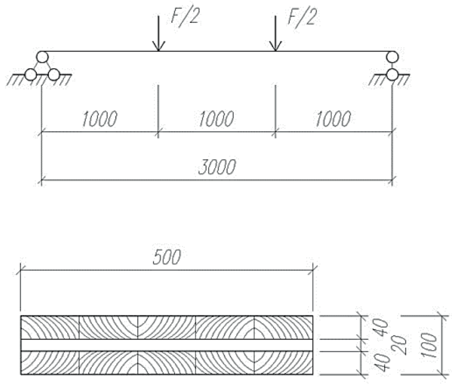

Figure 2. a) general view b) design parameters of the CLT panel

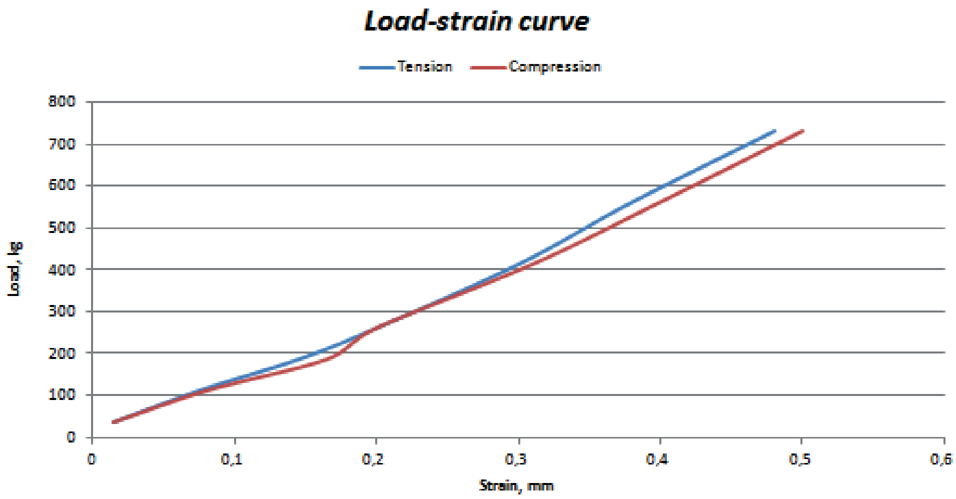

Figure 3. Load-strain curves for the CLT panel

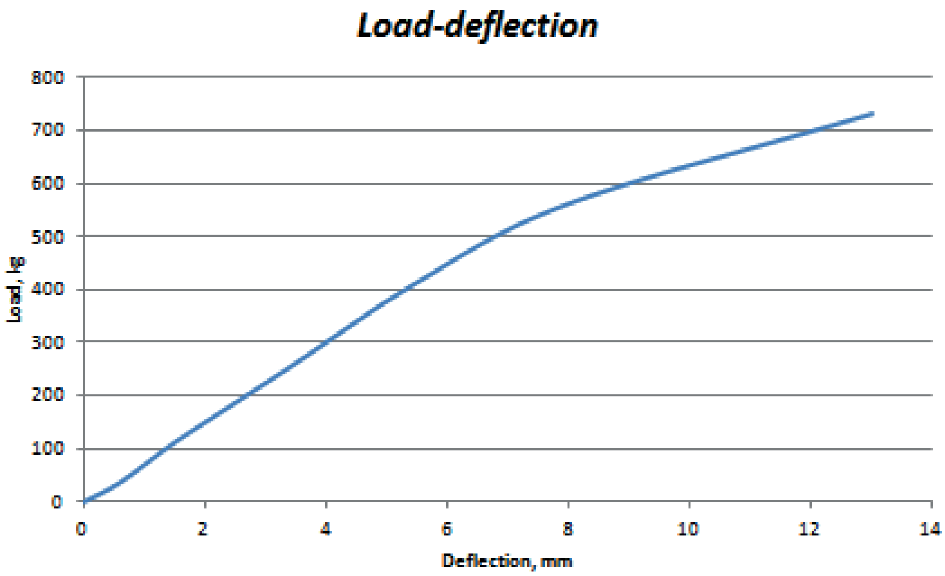

Figure 4. Load-deflection diagram

The design parameters of cross-section are $t_1 = 0.04\,\text{m}$, $t_2 = 0.02\,\text{m}$, $t_3 = 0.04\,\text{m}$, $b_y = 0.50$ m, $h = 0.10\,\text{m}$, $l = 3.00\,\text{m}$. If we consider the codified design, the following values can be taken $E_1 = E_2 = E_{mean} = 10\,\text{GPa}$, $\sigma_{ult} = 21$ MPa. Based on this values, the ultimate bending moment by eq. (3) is $M_{ult} = 34.7\ \text{kN·m}$.

As can be seen from above, the linear function can be adopted for the load-deflection and load-strain relationships at the elastic stage of CLT-panels behavior.

The variation coefficient of elasticity modulus for coniferous wood is about to 15-20 percent [11].

Ten control samples of wood were taken from every layer of CLT panel for standard tests.

The empirical distribution functions $F_E^{emp}(E)$ and the estimated cumulative distribution functions $F_E(E)$ are presented on the Fig. 5 for upper and lower layers of the CLT panel.

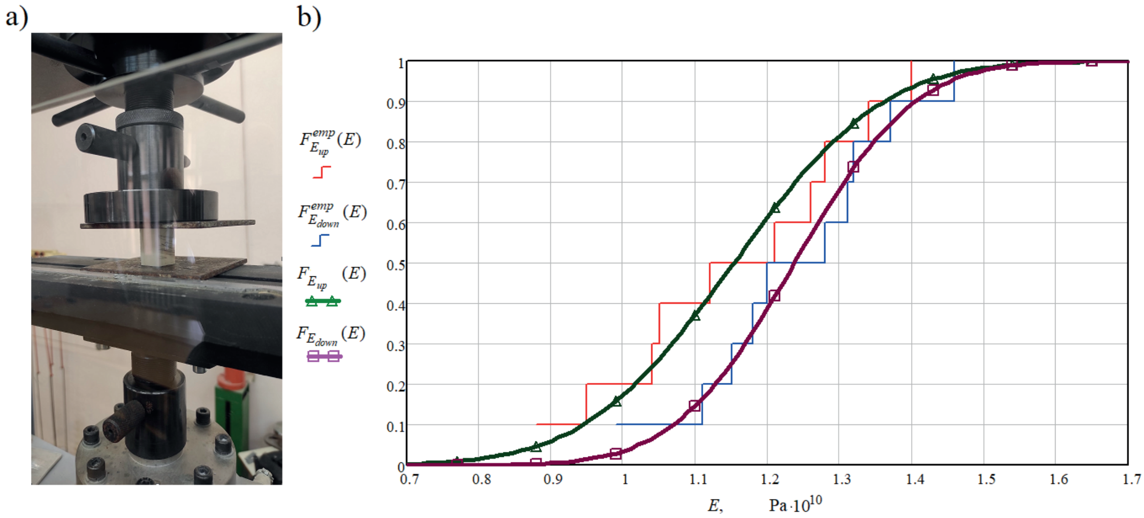

Figure 5. Statistical tests for elasticity modulus of the CLT panel's upper and lower layers: a) Test of a control sample; b) Cumulative density functions for elasticity modulus

As can be seen from Fig. 5(b), the random variable models for the elasticity modulus of upper and lower layers of the CLT panel are quite different. The coefficient of variation is higher and the expected value is lower for upper layer. The graphs in Fig. 5 also reflect the fact that the lower and upper layers of the CLT panel can be made of different timber, which can lead to a shift of the neutral axis and a redistribution of stresses. As a rule, the variability of this value is small and can be ignored at the first analytical stage of calculation. Probabilistic design can take into account such aspects. It will be taken into account in numerical calculations.

Normal distribution is adopted for the elasticity modulus of upper and lower layers. Following parameters are taken: $m_{E,up} = 11.53\,\text{GPa}$, $S_{E,up} = 1.63\,\text{GPa}$, $m_{E,down} = 12.37\,\text{GPa}$, $S_{E,down} = 1.31\,\text{GPa}$.

Ten control samples were also tested on bending. By the same way, following sample parameters were obtained: $m_{\sigma,ult} = 38.93\,\text{MPa}$, $S_{\sigma,ult} = 4.85\,\text{MPa}$.

It should be noted that for more accurate modeling of random variables by a small sample, it is necessary to use alternative models, for example, such as p-boxes [10]. However, to demonstrate the method, the hypothesis is used that the sample parameters estimates correspond to the parameters of the population.

Next, 100'000 values of random variables are generated in PTC MathCAD by the above statistical data. The number of failures is calculated on given value of the bending moment for tested CLT panel. Substituting the bending moment values according to Table 1 into the g function (3) for each of the 100,000 cases, it is possible to obtain the number of failed CLT panels for the total number of generations and to estimate the failure probability P_f and the corresponding reliability index β.

The relationship between reliability (probability of non-failure $P_s = 1 - P_f$) and bending moment is presented on Fig. 6.

Table 1. Reliability of the tested CLT panel

Bending moment M, kN·m	Reliability index β	Failure probability P_f
30.00	5.00	0.00004
35.00	3.40	0.00033
40.00	2.74	0.00312
45.00	2.12	0.01709
50.00	1.53	0.06253

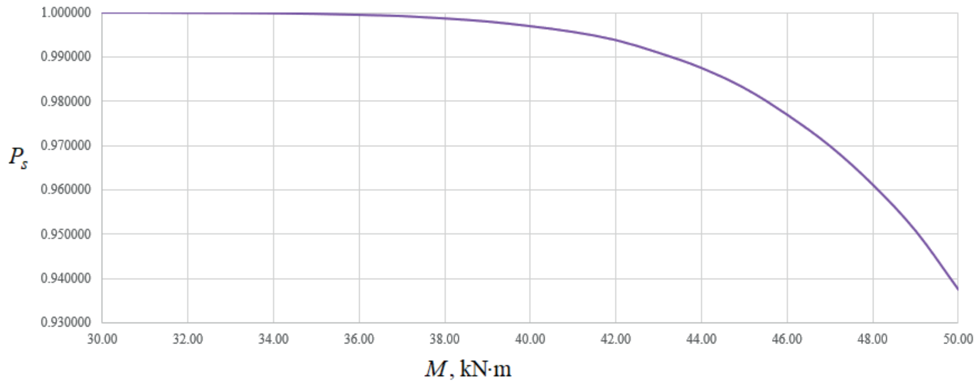

Figure 6. Relationship between reliability and test load on the CLT panel

To obtain a more accurate solution, it becomes necessary to take into account the inhomogeneities of each individual board in each layer of the CLT element. The solution of such problems is the domain of numerical solutions, for example, the finite element method [12-15]. The task is to build a model in a FEM program, and then simulate inhomogeneities by generating initial data (elasticity modulus, timber strength, etc.) using the Monte Carlo method. Reliability will also be determined by the ratio of the number of non-failure FEM models to the total number of initial data generations. However, as a rule, the use of such algorithms is associated with high costs of time and computing power.

CONCLUSIONS

Cross-laminated timber (CLT) is an innovative timber product that was introduced in the early 1990s in Austria and Germany and has been gaining popularity in many civil applications. The article presents a probabilistic approach to estimate the reliability level (reliability index or failure probability) of a CLT element in bending according to the strength criterion of normal cross-sections. The elasticity modulus and bending strength of wood have a high coefficient of variation (up to 20-25%), which is important to model in CLT elements, since they consist of many sub-elements (glued boards). The Monte Carlo method based on wood test data can be used in both analytical and numerical methods for structural design of CLT elements to further assess their reliability in probabilistic terms. P-boxes as random variables models can be used in case of limited statistical data.

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