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Experimental verification of design procedure for elements from cross-laminated timber

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Abstract

Cross-laminated timber is widely used for load-bearing walls and slabs of multi-storey timber buildings as well as for decking structure of pedestrian and road bridges. Design procedure for elements from cross-laminated timber was considered and validated by the experiment and FEM. The design procedure is based on the transformed section method. Eight cross-laminated timber slabs with span equal to 1.8 m were experimentally checked under the action of static load. The difference between the experimentally and analytically obtained results is within the limits from 3.3 up to 20%.

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Keywords: Transformed section method;brittle damege; plates in bending

1. Introduction

Cross – laminated timber (CLT) is a perspective structural material which is widely used for walls and plates of multistory residential buildings so as for decking structures of road and pedestrian bridges [1-5]. Main load-bearing elements in these structures are subjected to flexure or compression with bending. Evaluation of the main rational parameters of these structures very often is joined with consideration and analyse of large variants amount of considered structure. The results of variants analyse are necessary for obtaining the dependences between parameter of optimization and variables, were rational levels must be determined in course of optimization tasks solution [6].

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Nomenclature

A_i	area of cross-section of the separate layer
E_i	mean value of modulus of elasticity of separate board material in fibre direction
(EI)	bending stiffness
$(EI)_{ef}$	effective stiffness
I_i	moment of inertia of the separate layer relative to its own main axis
I	moment of inertia
W	resistance moment
L	span of the slab
G_R	shear modulus of board material perpendicular to fibre direction
E_0	modulus of elasticity of timber in longitudinal direction
E_{90}	modulus of elasticity of timber in transversal direction
a_i	distance from the neutral axis of the whole plate to the neutral axis of separate layer
b	width of the plate
$f_{m,d}$	design bending strength of external timber boards
$f_{V,d}$	design resistance in shear of middle timber board
h_{tot}	total thickness of the plate
h_i	thickness of the *i*-th longitudinal layer
$\hat{h}_i$	thickness of the *i*-th transversal layer
γ_i	reduction factors, which takes in to account compliance of the bonds
δ_{max}	maximum available value for the final deflection of CLT plate
$\sigma_{max,d}$	maximum normal stresses acing in the edge fibre due to the maximum bending moment
$\tau_{max,d}$	maximum shear stresses acing in the middle board due to the maximum shear force
w_{fin}	final deflection of CLT slab

Simple and enough precise method, which enables prediction of the behaviour of load-bearing elements from cross-laminated timber, subjected to flexure is necessary in this connection [7]. The stress and stiffness method (K-method) and transformed sections method were compared and verified by the FEM, which was realized by the computational programs RFEM 5.0 and ANSYS v 14, and laboratory experiment in the previous investigations [8, 9]. The maximum difference between the analytically and experimentally obtained maximum vertical displacements for simply supported CLT slabs with the total thickness of 95 mm and the span equal to 1.9 m, which were loaded by the statically applied uniformly distributed load in 7.5 kN/m^2 , exceeds 31% [8, 9]. The difference can be explained by the deviations of the technological requirements during the producing of the specimens. The maximum surface pressure during the producing of the both slabs with length and width equal to 2 and 1m, correspondingly and thickness of 95 mm was equal to 400kg/m^2 instead of the necessary 600kg/m^2. Calibration of the board sizes was not conducted also [10, 11]. It the current investigation the specimens were produced in the industrial conditions by SCONTO ENTERPRISE.

The aim of the current work is a comparison of the existing methods for the design of CLT load-bearing elements, subjected to flexure and choice of the method, which is characterized by the less workability and enough precision. All the considered methods must be verified by the laboratory experiment. The design procedure for design realization by the selected method must be explained.

2. Design methods of CLT elements subjected to flexure

2.1. Short description of K-method, gamma method and shear analogy method

Let us to consider the main peculiarities of the methods, which can be used for the design of the load-bearing elements from the CLT subjected to flexure. These methods are stress and stiffness method (K-method), gamma method, shear analogy method and transformed section method [12]. The main differences between the methods are joined with the determination of effective stiffness of the CLT plate. So these differences will be mentioned below.

The gamma method was developed by Professor Karl Mőhler. Initially it was used for the design of composite beams with T, I or closed box-type cross-sections. This method is based on the assumption that the parts of the beams cross-sections are joined together by the compliant bonds and material is working in the elastic stage. Designation of the layers of CLT plate is shown in the Fig. 1 for the case, when total amount of the layers is equal to five. The fibres direction of the each second layer is perpendicular to the longitudinal axis of the plate [12].

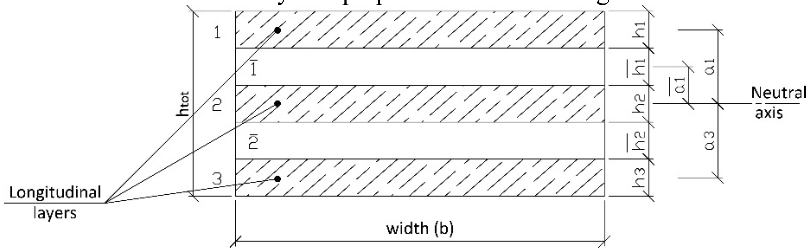

Fig. 1. Designation of the layers of CLT plate [12].

The effective stiffness (EI)ef is a major parameter which has influence at the elements behaviour. It can be found by the following equation:

$$\left(EI\right)_{ef} = \sum_{i=1}^{n}\left(E_i \cdot I_i + \gamma_i \cdot E_i \cdot A_i \cdot a_i^2\right) \tag{1}$$

The factors γi can be determined by the following equations in case of the plate, which consists from the five layers (Fig. 1):

$$\gamma_1 = \frac{1}{1+\dfrac{\pi^2 \cdot E_1 \cdot A_1 \cdot \bar{h}_1}{L^2 \cdot G_R \cdot b}} \tag{2}$$

$$\gamma_2 = 1 \tag{3}$$

$$\gamma_3 = \frac{1}{1+\dfrac{\pi^2 \cdot E_3 \cdot A_3 \cdot \bar{h}_2}{L^2 \cdot G_R \cdot b}} \tag{4}$$

The value of the effective stiffness depends from the factor γ, which reflect the compliance of the bonds and reduction of transversal layers stiffness. Elastic behaviour of the bonds in current shear plane for the composite beam is replaced by the shear deformations between the load-bearing layers to take into account peculiarities of the CLT slabs [12].

The composite method (K-method) was developed by German scientists Hans Joachim Blass and Peter Fellmoser. This method initially was focused on the design of plywood members, which are subjected to flexure. The following simplifications must be taken into account during the design of CLT slabs by the composite method: all layers of the slab must be taken into account; span to height ratio of the slabs must not be less than 30, so as shear deformations are not taken into account; strength and stiffness of the layers must be determined using the factor ki, which depends on the scheme of the loading and structure of the panel. The effective stiffness (EI)ef of the slab is determined by taking into account all layers [12].

The method of shear analogy is considered as one of the most precise method for analyse of CLT plates due to elastic and shear modulus of all the layers are taken into account. The method of shear analogy was developed by German scientist Heinrich Kreuzinger. The slab is divided in two virtual beams, A and B, which are joined together by the immovable joints so that the deformations of the both beams are coinciding (Fig. 2).

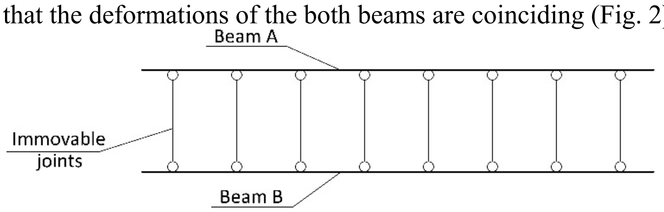

Fig. 1. Designation of the layers of CLT plate [12].

The beam A is characterized by the infinitely large shear stiffness and it's bending stiffness (EI)A is determined as a sum of the bending stiffness of separate layers relatively to their own neutral axis. The total bending stiffness of the CLT slab (EI)ef is determined by the following equation:

$$\left(EI\right)_{ef}=\left(EI\right)_{A}+\left(EI\right)_{B}=\sum_{i=1}^{n}E_i\cdot I_i+\sum_{i=1}^{n}E_i\cdot I_i\cdot z_i^2 \tag{5}$$

2.2. Short description of design procedure of transformed sections method

Let us consider transformed cross-section method [13]. Transformed method is characterized by the simplified design procedure in comparison with the methods, which were mentioned above. Transformed cross-section method is joined with the replacement of the real cross-section of element by the equivalent transformed cross-section. This method can be used in the case, when fibres of some internal layer of CLT are oriented perpendicular to the fibres direction of the outer layers. Transformation of cross – section is based on the ratio of modulus of elasticity of the layers in longitudinal and transverse direction:

$$n=\frac{E_{90}}{E_0} \tag{6}$$

The width of the layer were fibres are oriented in transversal direction must be multiplied by the relation of modulus of elasticity. Obtained transformed double-tee cross-section then is considered as glued homogenous cross-section. Checks of ultimate limit state (ULS) and serviceability limit state (SLS) must be conducted based on the recommendations of [12]. Check of ultimate limit state is joined with the checks of normal and shear stresses. The value of the partial factor for a material property is equal to 1.25 [14]. The system strength factor k_{sys} depends from the width of the boards. It is taken equal to 0.90 for the boards with the width less than 250 mm. The factor k_{sys} changes within the limits from 1.00 to 1.20 for the boards with the width bigger than 250 mm. Serviceability limit state very often becomes as a determinant due to enough high specific strength of CLT.

3. Verification of transformed section method (TSM) by experiment and FEM

3.1. General approach

The results which were obtained for the current structural elements subjected to flexure by the K-method, gamma method, shear analogy method and transformed section method were compared with the results obtained by the experiment and FEM. Eight CLT plates with the length and width equal to 2 and 0.35m, correspondingly and thickness of 60 mm were considered. All plates were formed by three layers of boards. Thicknesses of external and internal layers of boards are equal to 20 mm.

Pine wood with strength class C24 [15–17] was chosen as a base material. Dimensions of the board's cross-sections for outer and middle layers were equal to 20x50mm. All plates were freely supported by the short sides and loaded by the uniformly distributed load. This static scheme is widely used for CLT plates in practice. A span of freely supported plates was equal to 1.8 m (Fig. 3).

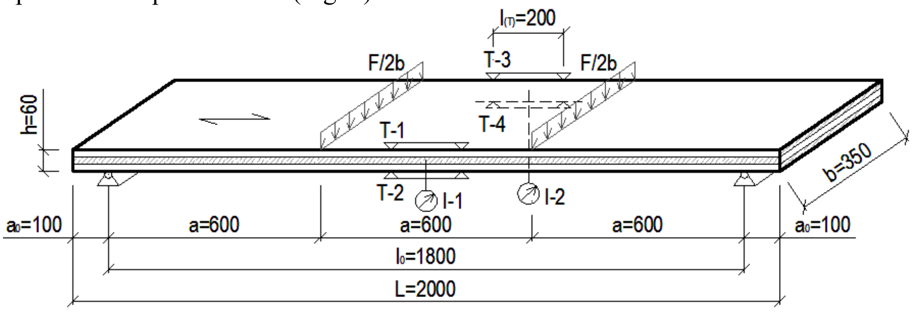

Fig. 3. Design scheme and measuring devices placement for CLT plates in four point bending.

All specimens were statically loaded by pieces of steel with approximate weight of 20 kg each, which were applied as two concentrated forces which divide the span of the plate at three equal sections with the length in 600mm each. The value of total vertical load changes within the limits from 1 to 7 kN with the step equal to 1.0 kN. The maximum intensity of the applied load is equal to the design load-bearing capacity of the considered plates. Maximum bending stresses, acting in the edge fibres of outer layers, maximum vertical displacements in the middle of the span and horizontal relative displacements of outer and middle layers of CLT plate were the main objectives of measurements. The local deformations in supports are not significant and were neglected. Four strain gauges and two deflectometers were used for this purpose (Fig. 3). Measurements by the apparatus were made in the each stage of specimens loading.

Second stage of considered methodologies verification was joined with calculation of maximum bending stresses, acting in the edge fibres of outer layers, maximum vertical displacements in the middle of the span by the software RFEM 5.0 [18, 19].

The results, which were obtained for the considered CLT plate by the K-method, gamma method, shear analogy method and transformed section method, physical experiment and software RFEM 5.0 were compared in the next chapter of this study.

3.2. Design methods analysis of CLT elements subjected to flexure

The verification of K-method, gamma method, shear analogy method and transformed section method was carried out by the comparison of maximum bending stresses, acting in the edge fibres of outer layers, maximum vertical displacements in the middle of the span with the results of physical experiment and results obtained by the software RFEM 5.0. The results of physical experiment are mean values of the bending stresses, acting in the edge fibres of outer layers and maximum vertical displacements in the middle of the span, which were determined for the eight plates and include double standard deviation. The mean value of the bending stresses, acting in the edge fibres of outer layers changes within the limits from 1.69 to 14.11MPa when the value of total vertical load change within the limits from 1 to 7 kN, correspondingly.

The differences between the maximum bending stresses, acting in the edge fibres of outer layers obtained by the K-method, shear analogy method, transformed section method and software RFEM 5.0 is equal to zero. Comparison of these results with the results obtained by the experiment show, that the difference was equal to 12.20% when the plate was loaded by the maximum vertical load equal to 7kN. The difference increases till 17.90% for the results obtained by the gamma method. The strains in the edge fibres of outer layers obtained by the K-method, gamma method, shear analogy method and transformed section method, physical experiment and software RFEM 5.0 as a function from the vertical load are shown in Fig. 4 (a).

The mean value of the maximum vertical displacements in the middle of the span of CLT plates changes within the limits from 1.40 to 11.40mm when the value of total vertical load change within the limits from 1 to 7 kN, correspondingly. The maximum vertical displacements in the middle of the span of CLT plates, obtained by the K-method, gamma method, shear analogy method and transformed section method, physical experiment and software RFEM 5.0 as a function from the vertical load are shown in Fig. 4 (b).

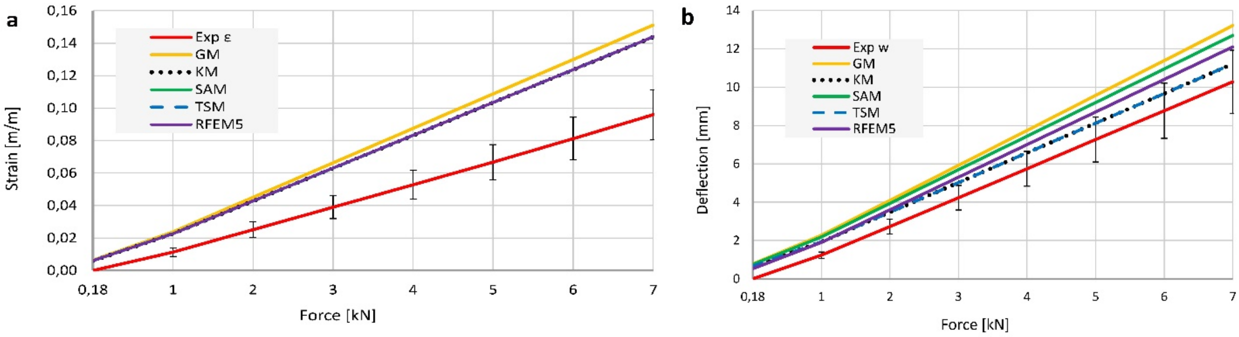

Fig. 4. (a) Strain in the edge fibres of outer layers obtained by the K-method, gamma method, shear analogy method and transformed section method, physical experiment and software RFEM 5.0 as a function from the vertical load's intensity; (b) Dependence of maximum vertical displacements in the middle of span of CLT plates as a function from the load's intensity.

The differences between the maximum vertical displacements in the middle of the span of CLT plates obtained by the K-method, gamma method, shear analogy method, transformed section method, software RFEM 5.0 and experiment were equal to 3.30, 13.90, 9.50, 3.30 and 6.00%, correspondingly. Comparison of obtained results indicates that transformed section method enables to predict the behaviour of CLT plates subjected to flexure with the better accuracy than gamma method and shear analogy method. The results obtained by the transformed section method and K-method are practically equal, what was mentioned in the previous investigations [7, 8]. So, transformed section method will be considered for the behaviour prediction of CLT plate, which will be loaded up to failure in the next chapter of this study.

4. Benchmark study of transformed section method (TSM)

The additional benchmark study was carried out to check the transformed section method for behaviour prediction of CLT plate under the different loading type [20]. One of the eight CLT plates, which was described in details in the chapter 3 of this study, was experimentally tested in three point bending up to the failure. The design scheme of the considered plate is depicted on Fig. 5. The load was controlled by deformations. The overview of tested plate with placement of measuring devices is shown on Fig. 6 (a).

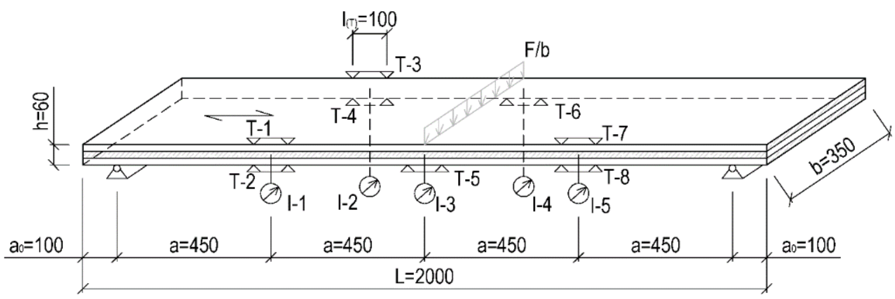

Fig. 5. Design scheme and measuring devices placement of CLT plate in three point bending.

Eight strain gauges and five deflectometers were used for measuring of vertical displacements and deformations of edge fibres. The value of total vertical load changes within the limits from 1 to 22.6 kN. The minimum step of loading was equal to 0.20 kN.

Fig. 6. (a) Plate under loading nearly collapse stage; (b) Collapse of CLT slab.

Simplified equation of the moment of inertia for transformed cross-section of three-layered slab with layer thickness h_i and width b were derived (Eqs. 7). Material properties used for CLT plate calculation are following: mean modulus of elasticity E_0 = 11 GPa, E_{90} = 0.37 MPa; the 5% fractile and mean bending strength $f_{m.k,0.05}$ = 24 MPa, $f_{m,k,mean}$ = 35.8 MPa. The dependence of calculated and experimentally obtained strains and deflections depending on force are shown on Fig. 6. The dependences are obtained for the points in the half and quarter of the plates span.

$$I_y = \frac{bh_i^3}{12}\left(\frac{E_{90}}{E_0} + 26\right) \quad (7)$$

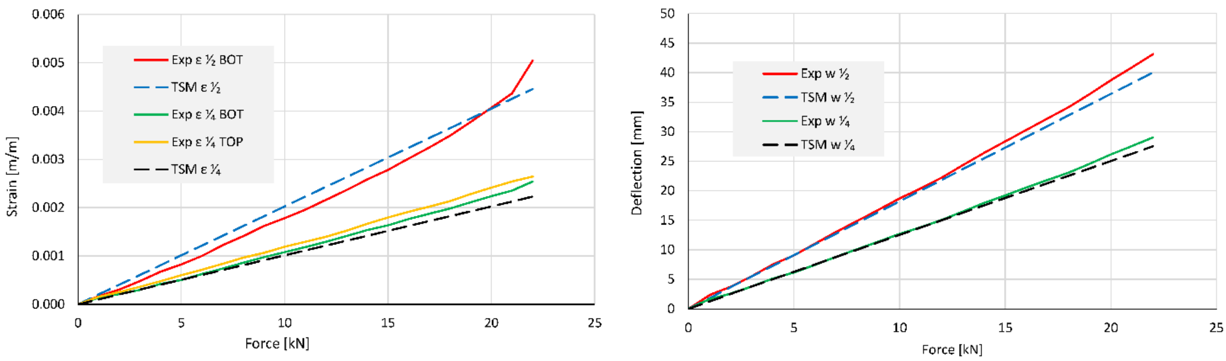

Fig. 6. (a) Dependence of force on strain; (b) Dependence of force on deflection.

The ultimate force is equal to 22.6 kN. Ultimate stress is equal to 50.3 MPa, that is by 40% large than mean value of bending strength. Ultimate displacement in the centre of span is equal to 44.5 mm, which is equal to 1/40 from span. The collapse of the CLT plate is brittle. Post-failure behaviour was not observed. The damage of the CLT slab happened in timber boards and glued connection at the same time in zone of the biggest moments (Fig. 6 (b)).

The difference of deflections between calculated using transformed section method and experimentally obtained does not exceed 7%. The maximum difference between calculated and experimentally obtained strains is 20% in the half-span and 12% in the quarter-span. The difference in strains could be described by the non-homogeneous structure of timber material and timber defects. So, the results obtained in the experiments realized in course of current and previous studies [7, 8] indicates, that transformed sections method is characterized by simplicity of design procedure and reasonable precision in comparison with the K-method, gamma method and shear analogy method.

5. Conclusions

The design procedure for the elements from cross-laminated timber was verified. K-method, gamma method, shear analogy method and transformed section method were compared analytically and by the experiment for behaviour prediction of statically loaded CLT panels in cases of three and four point bending. The differences between the maximum vertical displacements in the middle of the span of CLT plates obtained by the K-method, gamma method, shear analogy method, transformed section method, software RFEM 5.0 and experiment were equal to 3.30, 13.90, 9.50, 3.30 and 6.00%, correspondingly.

The additional benchmark study was carried out to check the transformed section method for behaviour prediction of CLT plate under three point bending up to failure. It was stated, that the difference of deflections between calculated using transformed section method and experimentally obtained does not exceed 7%. The maximum difference between calculated and experimentally obtained strains is 20% in the half-span and 12% in the quarter-span.

It was stated, that the transformed sections method is characterized by simplicity of design procedure and reasonable precision in comparison with the K-method, gamma method and shear analogy method.

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