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Design Methods of Elements from Cross-Laminated Timber Subjected to Flexure

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Abstract

Design methods of cross-laminated timber elements subjected to bending is considered. The methods are based on LVS EN 1995–1–1. The presented methods were checked by the experiment and analytically. Two cross-laminated timber plates with the total thickness of 95 mm were tested under action of static load. The considered cross-laminated timber plates were analysed by FEM method, which is based on the using of computational program ANSYSv14. The comparison of stresses acting in the edge fibres of the plate and the maximum vertical displacements shows that the considered methods can be used for engineering calculations so as the difference between the experimentally and analytically obtained results does not exceed 20%.

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Keywords: Load-bearing elements; cross-laminated timber plate; static loading; normal stresses; maximum vertical displacement ned element; hybrid composite suspender; long span steel structure; static loading

1. Introduction

Cross – laminated timber (CLT) is a structural material which cause rising interest at the present moment. Cross – laminated timber attracts interest of civil engineers because it possesses the mechanical properties, which enable to decrease structural cost and time of building erection in comparison with analogous structures made of steel and reinforced concrete. Using of cross – laminated timber enables to obtain reliable load – bearing members and meets aesthetic and architectural requirements at the same time [1–3].

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Cross-laminated timber is used for load-bearing walls and plates in one-storey and multi-storey timber buildings. The maximum amount of storey for existing buildings, which is made with the using of cross-laminated timber, is equal to nine. It is a residential building in London. The main vertical load-bearing elements of this building are external walls and structural core, which are made of CLT. Horizontal load-bearing elements are CLT plates [4–9].

The structural solutions of multi-storey buildings, with the load-bearing elements made of CLT, can be divided in to three groups. These are solution with the structural core and glulam columns at curtain walls, solution with a structural core and internal walls with glulam columns at curtain wall and solution with external walls and a structural core. Amount of storey can reach twelve for the first solution. But it rise up to twenty for the second and third solutions, correspondingly [10].

Cross-laminated timber plates are used for decking for pedestrian and road bridges [11–13]. Pedestrian bridge which is created in Feldbach, Austria is one of such bridges examples.

Two variants of CLT can be obtained dependently from the orientation of fibers for separate layers (timber boards), which must be glued together. If fibers of each second layer will be oriented perpendicular to the fibers direction of the first layer, we will get an orthotropic material. If fibers of all separate layers are oriented in one direction, we will get second variant of CLT.

So, it can be concluded, that CLT is widely used for the structural members subjected to flexure [11]. CLT plates are used for structures of floors and roofs. So, the aim of this paper is to consider and analyse design methodology of CLT elements subjected to flexure. Design methodology which is described in EN 1995–1–1 must be compared with the methodology of mechanics of laminated materials and verified by laboratorian experiments and FEM to obtain identified aim. Influence of the middle layer fibers orientation on the load carrying capacity of elements made from laminated timber must be evaluated also.

2. Design methods of cross – laminated timber elements subjected to flexure

Two following methods are used for the designing of CLT structural members subjected to flexure [1, 14–15]: effective strength and stiffness method and transformed section method. But both the methods are based on the well-known approach for the designing of structural members subjected to flexure, which is described in [14]. The ultimate limit state (ULS), which includes checks of bending stresses and check of shear stresses so as serviceability limit state (SLS) must be checked for the CLT structural member subjected to flexure [14].

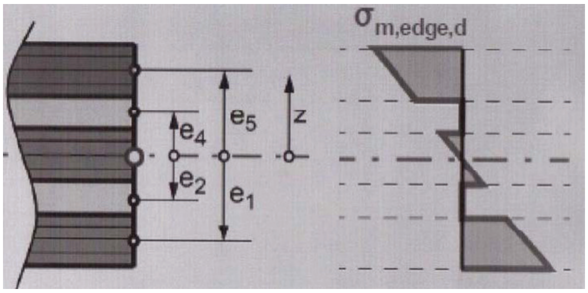

Fig. 1. Distribution of normal stresses in the CLT element's cross-section: $e_{1,2,3,4}$ – distances from the neutral axis to the middle of current layer; $\sigma_{m,\ edge,\ d}$ – normal stresses acting in the edge fiber [15].

Bending stresses acting in the CLT plates are determined basing on the recommendations of [14] and distribution of normal stresses in the middle and outer layers of CLT plates is shown in Fig. 1. The fibers of second layer are oriented perpendicular to the direction of fibers for outer layer.

Let us consider peculiarities of effective strength and stiffness method. In accordance with the effective strength and stiffness method, maximum value of bending stresses acting in the edge fibers of outer layers of CLT panels must be determined by the equation:

$$\sigma_{edge,d} = \frac{M_{\max,d}}{K_{CLT}} \cdot \frac{a_{CLT}}{2} \cdot E_{i=5}, \tag{1}$$

where $M_{max,d}$ – design value of maximum bending moment; a CLT – CLT plates height; K_{CLT} – effective stiffness of CLT plate; $E_{i=5}$ – modulus of elasticity of the each layer in longitudinal direction.

Effective stiffness of CLT plate K_{CLT} can be determined by the equation (2):

$$K_{CLT} = \sum_{i-1}^{n}\left(J_i \cdot E_i\right) + \sum_{i=1}^{n}\left(A_i \cdot e_i^2 \cdot E_i\right) = \left(EI\right)_{ef} = E_0 \cdot \frac{h^3 \cdot a_{CLT}}{12} \cdot k_i, \tag{2}$$

where, E_i , A_i – modulus of elasticity and area of cross-section of separate layer; I_i – moment of inertia of separate layer relatively it own main axis; E_0 – modulus of elasticity of timber in longitudinal direction; h – total thickness of the plate; k_i – composition factor which depends from the certain loading conditions.

Composition factor also is used for determination of shear stresses and maximum vertical displacements taking in to account bending and shear deformations. Equation (1) is written for the CLT plate, which consists of the five layers. So, checks of ultimate limit state (ULS) and serviceability limit state (SLS) must be conducted by taking effective stiffness of CLT plate in to account.

Let us consider transformed cross-section method [15]. Transformed cross-section method is joined with the replacement of real cross-section of element by the equivalent reeducated cross-section. This method can be used in the case, when fibers of each second layer of CLT are oriented perpendicular to the fibers direction of the first layer. Transformation of cross – section is based on the relation of modulus of elasticity of the layers in longitudinal direction:

$$n = \frac{E_{90}}{E_0}, \tag{3}$$

where E_0 – modulus of elasticity of timber in longitudinal direction ; E_{90} – modulus of elasticity of timber in transversal direction.

The width of the layer which fibers is oriented in transversal direction must be multiplied by the relation of moduli of elasticity.

a) b)

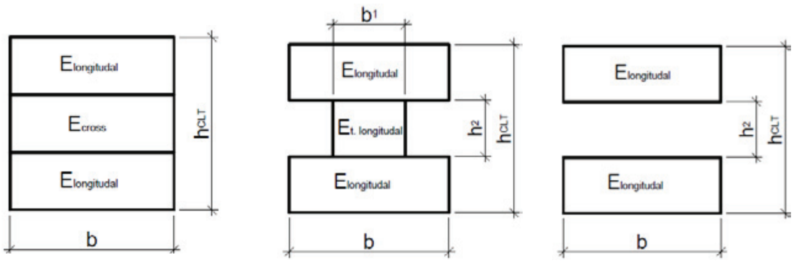

Fig. 2. Transformation of cross – section: (*a*) middle layer is taked in to account; (*b*) middle layer is not taked in to account.

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 basing on the recommendations of [14].

The filling of the glued joints between the boards of the layer(s) with orientation of fibers in transversal direction is a very significant moment. If middle layer(s) can not be considered as a monolithic one, this layer can not be taked in to account in the transformed section.

Verification of transformed section and effective strength and stiffness methods analytically and by the experiment is explained in the next chapter.

3. Verification of design methods by experiment and FEM

The experiment is carried out to verify the accuracy of the calculation methodologies for current structural member, which is subjected to flexure. Two CLT plates with the length and width equal to 2 and 1m, correspondingly and thickness in 95 mm were considered. The both plates were formed by three layers of boards. Thicknesses of external and internal layers of boards were equal to 25 and 45 mm, correspondingly. Pine wood with strength class C18 [17–20] was chosen as a boards material. Dimensions of the board's cross-sections for outer and middle layers were equal to 25x50 and 45x195 mm, correspondingly. All layers were joined together by the polyurethane glue under pressure in 400kg/m^2. A freely supported beam, which is loaded by the uniformly distributed load, was chosen as a design scheme for both plates, because this statical scheme is widely used for CLT plates in practice. A span of freely supported beam was equal to 1.9 m (Fig. 4). The both specimens were statically loaded by the pieces of steel with approximate weight in 20 kg each, which were uniformly distributed by the plate's surfaces. Intensities of uniformly distributed loads changes within the limits from 1 to 7.5 kN/m^2 with the step equal to 0.5 or 1.0 kN/m^2. The loading stage, when the plate was loaded by the uniformly distributed load with intensity equal to 7.5 kN/m^2, is shown in Fig. 3. Maximum bending stresses, acting in the edge fibers 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.

Fig. 3. Loading of CLT plate by the load with intensity equal to 7.5 kN/m^2.

Four strain gauges T-1, T-2, T-3, T-4, three deflectometers Iz – 1, Iz – 2, Iz – 3 and four indicators I – 1, I – 2, I – 3, I – 4 were used for this purpose (Fig. 7). Measurements by the apparatus were made in the each stage of specimens loading. Parameters of laboratorial experiment and thicknesses of the slabs layers were chosen in accordance with the literature recommendations [10, 17, 19].

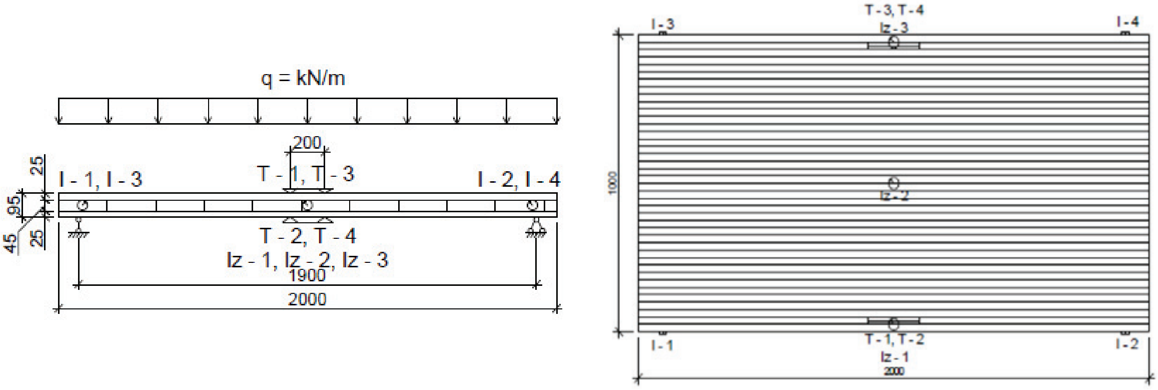

Fig. 4. Design scheme and apparatus placement for f CLT plates.

Second stage of considered methodologies verification was joined with calculation of maximum bending stresses, acting in the edge fibers of outer layers, maximum vertical displacements in the middle of the span and horizontal relative displacements of outer and middle layers of CLT plate by the softwares ANSYSv14 and REFM 5.0. CLT plate with dimensions in plan 2x1 m and thickness in 95 mm was calculated with the using of softwares ANSYSv14 and REFM 5.0. Calculations of CLT plate by the softwares ANSYSv14 and REFM 5.0 are based on mechanics of laminated materials. The coordinate system and axis designation are shown on Fig. 5.

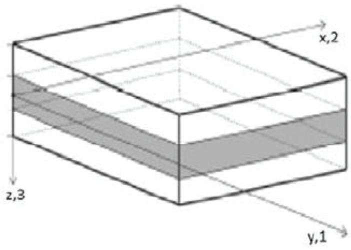

Fig. 5. Coordinate system for considered element.

The target of the calculation is verification of the results, obtained by the reduced cross-section method and effective strength and stiffness method.

The dependence between stress and strains for considered CLT panel can be described by the generalized Hooke's law, which is written for orthotropic model:

$$
\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{bmatrix} =
\begin{bmatrix}
\frac{1}{E_1} & -\frac{\upsilon_{21}}{E_2} & -\frac{\upsilon_{31}}{E_3} & 0 & 0 & 0 \\
-\frac{\upsilon_{12}}{E_1} & \frac{1}{E_2} & -\frac{\upsilon_{32}}{E_3} & 0 & 0 & 0 \\
-\frac{\upsilon_{13}}{E_1} & -\frac{\upsilon_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G_{31}}
\end{bmatrix}
\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{bmatrix} \quad (4)
$$

where E_1, E_2, E_3 – moduli of elasticity in directions 1, 2 and 3; ν_{12}, ν_{13}, ν_{23} – Poisons ratious;G_{23}, G_{31}, G_{12} – shear modules in 2–3, 3–1 and 1–2 planes.

The results, obtained by the FEM softwares REFM 5.0 and ANSYS v14 for the CLT plate with dimensions in plan 2x1 m and thickness in 95 mm, are given in figures 6 and 7.

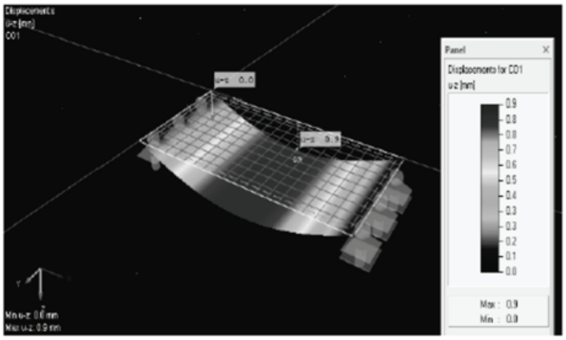

Fig. 6. Maximum vertical displacements of CLT plate, which was determined by the software REFM5.0.

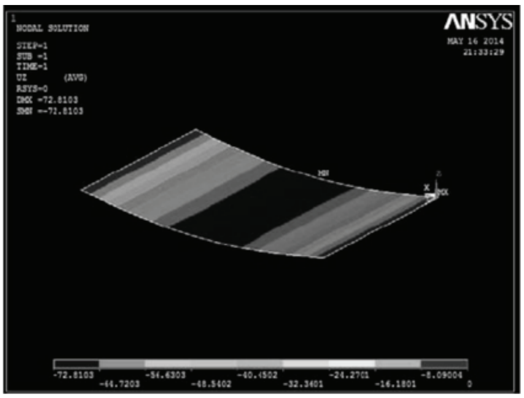

Fig. 7. Maximum vertical displacements of CLT plate, which was determined by the software ANSYSv14.

The results, which were obtained for the considered CLT plate by the transformed section and effective strength and stiffness method, physical experiment and softwares REFM 5.0 and ANSYS v14, were compared in the next chapter of this study.

4. Design methodologies analysis of CLT elements subjected to flexure

The verification of transformed section method and effective strength and stiffness method was carried out by the comparison of maximum bending stresses, acting in the edge fibers of outer layers, maximum vertical displacements in the middle of the span and horizontal relative displacements of outer and middle layers of CLT plate, which were determined by this methods with the results of physical experiment and results obtained by the softwares REFM 5.0 and ANSYS v14. The difference between the results obtained by the transformed section method and effective strength and stiffness method was insufficient. So, next these results will be mentioned as the results, obtained by the design methods. The maximum differences between the results obtained by the design methods and physical experiment are following:

- maximum bending stresses, acting in the edge fibers – 22%;
- horizontal relative displacements of outer and middle layers of CLT plate –17%;
- maximum vertical displacements in the middle of the span –31%.
- The maximum differences between the results obtained by the design methods and softwares REFM and ANSYS v14 are following:
- maximum bending stresses, acting in the edge fibers – 10%;
- horizontal relative displacements of outer and middle layers of CLT plate –7%;
- maximum vertical displacements in the middle of the span – 3%.

The differences between the results obtained by the design methods and physical experiment can be explained by the deviation from the technological requirements during producing of both specimens. So, necessary pressure during gluing of the CLT panels must be at least 600kN/m^2, but in reality it was 33% less and, probably, necessary quality of glue joints was not provided.

Two plates which are differed by the direction of fibers orientation for the middle layer were analyzed by the design methods and softwares REFM and ANSYS v14. Direction of the first specimen's middle layers fibers was perpendicular to the direction of outer layers (cross-laminated timber). Direction of the second specimen's middle layers fibers was parallel to the direction of outer layers (parallel-laminated timber). Comparison of results between cross and parallel laminated timber specimens shows, that the difference between maximum bending stresses is up to 6%. Influence of middle layer of CLT panels on it load carrying capacity, basing on the ultimate limit state, is insufficient. So, absence of middle layer cause load bearing capacity decrease at 10% only for considered specimens. Deflection between two plates varies up to 20%.

The dependence of strains in edge fibers of CLT plates as a function from the load's intensity is shown in Fig. 8.

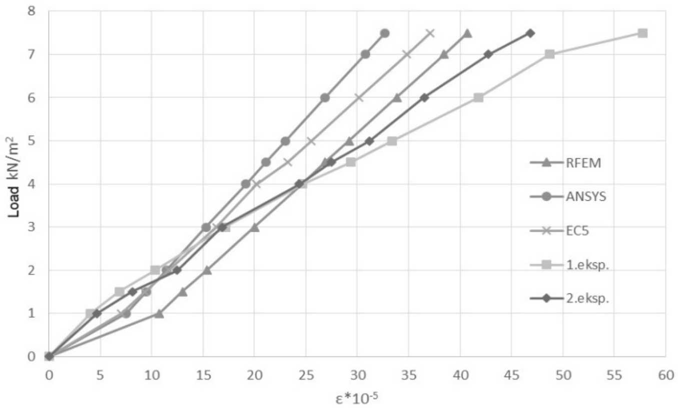

Fig. 8. The dependence of strains in edge fibers of CLT plates as a function from the load's intensity.

Results obtained by the considered methods are designated as EC 5. The dependences of maximum vertical displacements in the middle of the span of CLT plates as a function from the load's intensity and the dependence of relative displacements of outer and middle layers of CLT plate as a function from the load's intensity are shown in Fig. 9 and 10, correspondingly.

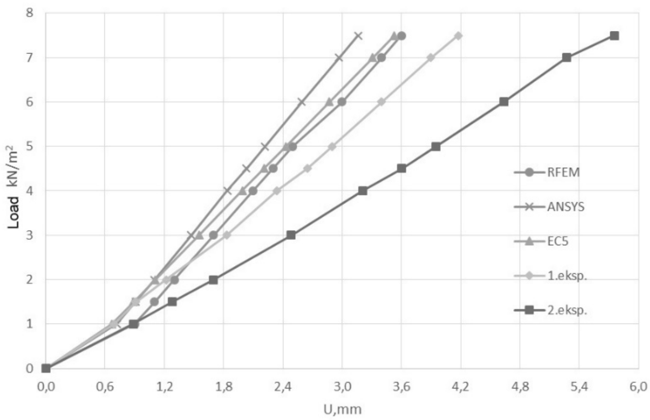

Fig. 9. The dependence of maximum vertical displacements in the middle of the span of CLT plates as a function from the load's intensity.

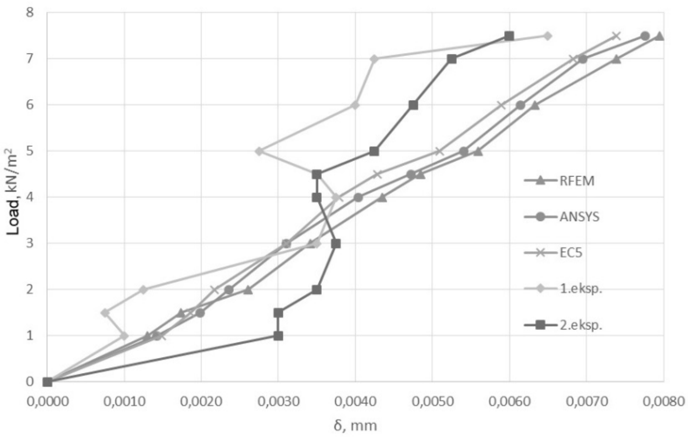

Fig. 10. The dependence of relative displacements of outer and middle layers of CLT plate as a function from the load's intensity.

5. Conclusions

Analysis of design methods of cross-laminated timber elements subjected to flexure was carried out. The transformed sections and effective strength and stiffness methods were checked analytically and experimentally for cross laminated timber panels.The maximum differences between the results obtained by the design methods, physical experiment and softwares REFM 5.0 and ANSYS v14 were equal to 31 and 10%, correspondingly. So, the transformed sections and effective strength and stiffness methods enable to describe behaviour of CLT elements subjected to flexure with the available accuracy. Result difference for cross laminated timber plates for load bearing capacity, relative displacements of outer and middle layers and maximum vertical displacements varies up to 10%. It can be concluded that the middle layer does not give a significant influence on the load - bearing capacity of CLT elements.

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