Design Methods for Load-bearing Elements from Cross-laminated Timber

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Abstract. Cross-laminated timber is an environmentally friendly material, which possesses a decreased level of anisotropy in comparison with the solid and glued timber. Cross-laminated timber could be used for load-bearing walls and slabs of multi-storey timber buildings as well as decking structures of pedestrian and road bridges. Design methods of cross-laminated timber elements subjected to bending and compression with bending were considered. The presented methods were experimentally validated and verified by FEM. Two cross-laminated timber slabs were tested at the action of static load. Pine wood was chosen as a board’s material. Freely supported beam with the span equal to 1.9 m, which was loaded by the uniformly distributed load, was a design scheme of the considered plates. The width of the plates was equal to 1 m. The considered cross-laminated timber plates were analysed by FEM method. The comparison of stresses acting in the edge fibres of the plate and the maximum vertical displacements shows that both considered methods can be used for engineering calculations. The difference between the results obtained experimentally and analytically is within the limits from 2 to 31\%. The difference in results obtained by effective strength and stiffness and transformed sections methods was not significant.

1. Introduction
Cross-laminated timber (CLT) is a structural material, which at the present moment is widely used for several structural purposes. Cross-laminated timber possesses the mechanical properties, which enable to decrease structural cost and time of building erection in comparison with analogous structures made

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of steel and reinforced concrete. Using of cross-laminated timber enables to obtain reliable load-bearing members and meet aesthetic and architectural requirements at the same time [1–3].

Multi-storey buildings of 4 to 10 storeys constructed entirely in timber, such as numerous structures recently constructed in Europe, are innovative and effective [4].

Buildings where timber is used as a structural material across the world are becoming more popular, because timber is one of the oldest and most traditional structural materials, which fulfills aesthetic requirements and is environmentally friendly. Timber is an efficient building material, not only regarding its mechanical properties, but also because it is a highly sustainable material considering all phases of the life cycle of timber structures: production, use and decommissioning [4]. Cross-laminated timber is used for load-bearing walls and plates in one-storey and multi-storey timber buildings. The maximum number of storeys for existing buildings, which are made 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 the structural core, which are made of CLT. Horizontal load-bearing elements are CLT plates [2–7]. These load-bearing elements are subjected to compression with the bending and flexure.

![Figure 1. Structures with CLT load-bearing elements: a) model of residential building; b) pedestrian bridge with the CLT deck in Feldbach, Austria [4].](image)

The structural solutions of multi-storey buildings with the load-bearing elements made of CLT can be divided in to three groups. These are the solution with the structural core and glulam columns at curtain walls, the solution with a structural core and internal walls with glulam columns at curtain wall and the solution with external walls and the structural core. The number of storeys can reach twelve for the first solution. But it rises up to twenty for the second and third solutions, correspondingly [8].

Cross-laminated timber plates are used for decking for pedestrian and road bridges [9–11]. The pedestrian bridge created in Feldbach, Austria, is an example of that kind of bridges (figure 1).

So, it can be concluded that CLT is widely used for the structural members subjected to flexure and compression with bending [9]. CLT plates are used for structures of floors, roofs and load-bearing walls. Thus, the aim of this paper is to consider and analyse design methods of CLT elements subjected to flexure and compression with bending. Effective strength and stiffness methods must be compared and verified by the laboratory experiments and FEM to obtain the identified aim.
2. Design methods for cross-laminated timber elements

2.1. Design methods for cross-laminated timber elements subjected to flexure

Two following methods are used for designing of CLT structural members subjected to flexure [1, 14–15]: effective strength and stiffness method and transformed section method. Both methods are based on the well-known approach to the design of structural members subjected to flexure, which is described in [12]. The ultimate limit state (ULS), which includes checks of bending stresses and the check of shear stresses, as well as serviceability limit state (SLS) must be checked for the CLT structural member subjected to flexure [12].

Bending stresses acting in the CLT plates are determined based on the recommendations of [14]. The stresses acting in the middle layers of CLT plates can be neglected in the case when the fibers of these layers are oriented perpendicular to the direction of the fibers of the 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 the outer layers of CLT panels must be determined by the equation:

\[ \sigma_{\text{edge},d} = \frac{M_{\text{max},d} \cdot a_{\text{CLT}}}{K_{\text{CLT}}} \cdot \frac{E_i}{2} \]

(1)

where \( M_{\text{max},d} \) – design value of maximum bending moment; \( a_{\text{CLT}} \) – CLT plates height; \( K_{\text{CLT}} \) – effective stiffness of CLT plate; \( E_i \) – modulus of elasticity of each layer in longitudinal direction.

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

\[ K_{\text{CLT}} = \sum_{i=1}^{n} (J_i \cdot E_i) + \sum_{i=1}^{n} (A_i \cdot e_i^2 \cdot E_i) = (EI)_{ef} = E_0 \cdot \frac{h^3 \cdot a_{\text{CLT}} \cdot k_i}{12} \]

(2)

where, \( E_i, A_i \) – modulus of elasticity and area of cross-section of a separate layer; \( I_i \) – moment of inertia of the separate layer relative to its own main axis; \( E_0 \) – modulus of elasticity of timber in longitudinal direction; \( e_i \) – the distance from the middle plane of the element to the middle of the \( i \)-th layer; \( h \) – total thickness of the plate; \( k_i \) – composition factor which depends on certain loading conditions.

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

Let us consider the transformed cross-section method [13]. The transformed cross-section method is joined with the replacement of real cross-section of the element by the equivalent transformed 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:

\[ n = \frac{E_{90}}{E_0} \]

(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 whose fibers are oriented in transversal direction must be multiplied by the relation of moduli of elasticity.

$\sigma_{c,0,d} \geq \sigma_{m,d}$

where $\sigma_{c,0,d}$ and $\sigma_{m,d}$ are the normal stresses which were determined for the transformed cross-section of the cross-laminated timber element due to compression force and bending moment, correspondingly.

Stability of cross-laminated timber element can be checked by equations (6.23) and (6.24) [12] in the most common case, when relative slenderness of considered load-bearing elements exceeds the value 0.3. Otherwise strength of cross-laminated timber element must be checked by equations (6.19) and (6.20) [12]. The first sub-case can take place for load bearing walls where axial force is dominating.
The second sub-case takes place when bending moment is the dominating internal force and condition (4) is not satisfied. Stability of cross-laminated timber element can be checked by equation (6.35) in [12].

\[
\left( \frac{\sigma_{m,d}}{k_{crit} \cdot f_{m,d}} \right)^2 + \frac{\sigma_{c,0,d}}{k_c \cdot f_{c,0,d}} \leq 1
\]

(5)

where \(\sigma_{c,0,d}\) and \(\sigma_{m,d}\) – design bending stress, which is determined for the transformed cross-section of cross-laminated timber element due to compression force and bending moment, \(f_{m,d}\) and \(f_{c,0,d}\) – design bending and compressive strengths parallel to grain; \(k_{crit}\) and \(k_c\) are the factors, which take into account the reduced bending and compression strengths.

All components of equation (5) must be determined for the transformed cross-section of the cross-laminated timber element. The second sub-case can occur in the horizontal load-bearing elements such as floor or roof plates, when non-sufficient axial forces took place. Checks of ultimate limit state (ULS) and serviceability limit state (SLS) must be conducted based on the recommendations of [12].

3. Verification of design methods of cross-laminated timber element subjected to flexure by experiment and FEM

3.1. General approach

The experiment has been carried out to verify the accuracy of the design method for current structural member, which is subjected to flexure. Two CLT plates with the length and width equal to 2 and 1 m, correspondingly, and thickness of 95 mm were considered. Both plates were formed by three layers of boards. Thicknesses of external and internal layers of boards are equal to 25 and 45 mm, correspondingly. Pine wood with strength class C18 [15–17] was chosen as a base 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/m². Both 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 1.9 m (figure 3).

Figure 3. Design scheme and apparatus placement for CLT plates.
Both specimens were statically loaded by pieces of steel with approximate weight of 20 kg each, which were uniformly distributed by the plate surfaces. Intensities of uniformly distributed loads changed within the limits from 1 to 7.5 kN/m² with the step equal to 0.5 or 1.0 kN/m². The maximum intensity of the applied load is equal to the half from the design load-bearing capacity of the considered plates. The loading stage, when the plate was loaded by the uniformly distributed load with intensity of 7.5 kN/m², is shown in figure 3. Maximum bending stresses acting in the edge fibers of the 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 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 (figure 3). Measurements by the apparatus were made in each stage of specimen loading. The parameters of the laboratory experiment and thicknesses of the slab layers were chosen in accordance with the literature recommendations [8, 15]. The second stage of the verification of the methodologies considered was joined with the calculation of maximum bending stresses, acting in the edge fibers of the outer layers, maximum vertical displacements in the middle of the span by the software ANSYSv14 and RFEM 5.0 [18–19]. CLT plate with dimensions 2x1 m and thickness of 95 mm was calculated using software ANSYSv14 and RFEM 5.0. Calculations of CLT plate using ANSYSv14 and RFEM 5.0 are based on mechanics of laminated materials. 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 strain for the considered CLT panel can be described by the generalized Hooke’s law, which is written for the orthotropic model. The results obtained by the FEM software RFEM 5.0 and ANSYS v14 for the CLT plate with dimensions 2x1 m and thickness of 95 mm are given in figures 4 and 5.

The results, which were obtained for the considered CLT plate by the transformed section and effective strength and stiffness method, physical experiment and software RFEM 5.0 and ANSYS v14, were compared in the next chapter of this study.
3.2. Analysis of design methods of CLT elements subjected to flexure

The verification of the 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 the outer layers, maximum vertical displacements in the middle of the span and horizontal relative displacements of the outer and middle layers of CLT plate, which were determined by these methods with the results of physical experiment and results obtained using RFEM 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, further 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 the following:

- maximum bending stresses acting in the edge fibers – 22%;
- horizontal relative displacements of the 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 software RFEM and ANSYS v14 are the following:

- maximum bending stresses acting in the edge fibers – 10%;
- horizontal relative displacements of the 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. Thus, the necessary pressure during gluing of the CLT panels must be at least 600kN/m², but in reality it was 33% less and, probably, the necessary quality of glue joints was not provided.

The dependence of strains in the edge fibers of CLT plates as a function from the load intensity is shown in figure 6. The results obtained by the considered methods are designated as EC 5. The dependence of maximum vertical displacements in the middle of the span of CLT plates as a function of the load intensity is shown in figure 7.

![Figure 6. The dependence of strains in the edge fibers of CLT plates as a function of the load intensity.](image1)

![Figure 7. The dependence of maximum vertical displacements in the middle of the span of CLT plates as a function of the load intensity.](image2)
4. Verification of the transformed sections method for cross-laminated timber element subjected to compression with bending by FEM

The cross-laminated timber plate, which was described in details in chapter 3.1, was considered. A freely supported beam with the span equal to 1.9 m, which was loaded by the uniformly distributed load and axial force, was considered as a design scheme. The intensity of uniformly distributed load was equal to 7.5kN/m\(^2\). The value of axial force was equal to 70 and 150kN. The values of axial force were taken to consider both probable cases for the cross-laminated timber elements subjected to compression with bending. When the value of axial forces is equal to 150kN, the compressive normal stresses are dominating. When the value of axial forces is equal to 70kN, the bending normal stresses are dominating.

The plate was modeled by the software ANSYS v15 using layered shell elements SHELL181 and orthotropic material properties. In case of dominating bending stresses, the maximum obtained stress by FEM is equal to 3.82 MPa (figure 8 (a)). The maximum stress, which was obtained by the transformed section method, is equal to 3.86 MPa. In case of dominating compressive stresses, the maximal obtained stress by FEM is equal to 5.32 MPa (figure 8 (b)); the stress obtained by the transformed section method is equal to 5.41 MPa.

![Stress distribution in the plate](image)

**Figure 8.** Stress distribution in the plate: (a) in case of dominating bending stresses; (b) in case of dominating compression stresses.

Comparison of the results obtained by the transformed section method and FEM, which was performed by the software ANSYS v15, indicates that the difference between the obtained results does not exceed 1.7 % for the cases with dominating compressive and bending normal stresses. It allows us to make a conclusion that the transformed section methods can be used to predict behaviour of cross-laminated timber elements subjected to compression with bending.
Distribution of shear stresses obtained by FEM is shown in figure 9. The level of shear stresses is much lower than shear strength. Shear stresses must be calculated using the transformed section method as for elements subjected to flexure.

5. Conclusions
Design methods of cross-laminated timber elements subjected to flexure and compression with bending were analyzed. The transformed sections and effective strength and stiffness methods were checked analytically and experimentally for cross-laminated timber panels. It was stated that the maximum differences between the results obtained by the transformed section method, physical experiment and software RFEM 5.0 and ANSYS v14 were equal to 31 and 10%, respectively, for the CLT panels subjected to flexure. The maximum differences between the results obtained by the transformed section method and software ANSYS v15 does not exceed 2% for the CLT panels subjected to compression with bending for the cases of dominating compressive and bending stresses. Therefore, the transformed sections and effective strength and stiffness methods enable to describe the behaviour of CLT elements subjected to flexure and compression with bending with the relative accuracy.

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