DE GRUYTER OPEN

DOI: 10.1515/sspjce-2018-0027

Structural analysis of cross-laminated timber slabs subjected to bending – state of the art

Viktoria Bajzecerova, Maros Kovac, Jan Kanocz

Technical University of Košice, Slovakia
Faculty of Civil Engineering, Institute of Structural Engineering
Faculty of Art, Department of Architecture
e-mail: viktoria.bajzecerova@tuke.sk, maros.kovac@tuke.sk, jan.kanocz@tuke.sk

Abstract

Compared to solid or laminated timber, the main point of the design of cross-laminated timber (CLT) is very low resistance and stiffness of the CLT cross layers. For the modeling and analyzing of the load distribution in CLT, various methods are available. The aim of this paper is to present the possible ways for load-bearing analysis of structural members subjected to uniaxial and biaxial bending in various software products and using various methods. A parametric analysis was performed with the aim to compare the results obtained by the analytical method, the model of the orthotropic slab, the grillage model and using the software based on the finite element method. The values of maximum deflection obtained by selected methods were compared. The mid-span deflection of beams subjected to uniaxial bending differs only slightly. In the case of slabs subjected to biaxial bending, more visible differences in results occurred. The simplified methods give the highest values on the safe side.

Key words: cross-laminated timber, software modeling, parametric analysis

1 Introduction

Cross-laminated timber (CLT or X-lam) is a relatively new, innovative material that was developed at the end of the 20th century in Austria and Germany. It is mainly used for bearing structures of multi-story residential and non-residential buildings such as administrative buildings, schools, exhibition or gallery space. Elements of the bearing structure are fully prefabricated, which rapidly speeds up the construction of the building. Other benefits include high material resistance compared to the weight, high fire resistance, the structural and spatial variability of individual segments. The most commonly used compositions are three-, five- or seven-layer panels. These consist of two, three or four layers with longitudinally oriented lamellas, and the rest of the cross section are cross-oriented lamellas.

The cross layers of the panels have relatively low strength and stiffness properties, which affects the strength and stiffness of the overall cross-section of the CLT. The solving of this phenomena in the structural design software is influenced by the computing capabilities of the respective software. The software based on the finite element method are suitable ([1],[2]), but within the modeling, it is necessary to take into account the flexibility of the cross layers. Cross-laminated timber can also be designed according to analytical methods using simplified equations. Several analytical methods are available for calculating CLT cross-sectional strength and stiffness, such as the modified γ-method [3], the shear analogy method [4] and the Timoshenko method [5]. Cross-laminated timber is able to transfer the load in both directions of the panel. The choice of the calculation model also depends on the support conditions and static behavior. In the case of a beam behavior, the bending occurs only about one axis. In the case of slab behavior, biaxial bending occurs, and the calculation model must take into account the different stiffness properties of the CLT panel about both axes.

As mentioned above, for the modeling and analyzing of the load distribution in cross-laminated slabs subjected to bending, various methods are available. For this reason, parametric analysis of selected types of beam and slab elements was performed in several design software and using various calculation methods. The aim of the analysis was to compare the results of the structural behavior using various selected methods.

2 Modeling of CLT panels subjected to bending

2.1 Beam behavior

If the distribution of the load in a ceiling or a roof CLT panel is performed in one dominant direction, the panel can be analyzed as a beam with the cross-section width of one meter. For this case, cross-sectional characteristics for uniaxial stresses are determined. Verification of the ultimate limit state can be performed using the net cross-sectional characteristics [6], [3]. It means, that in the calculation of the characteristics the cross layers are considered as a separating layer between the longitudinal layers and the Young modulus of elasticity of the cross layers is taken as E_{90} = 0 MPa (Fig. 1).

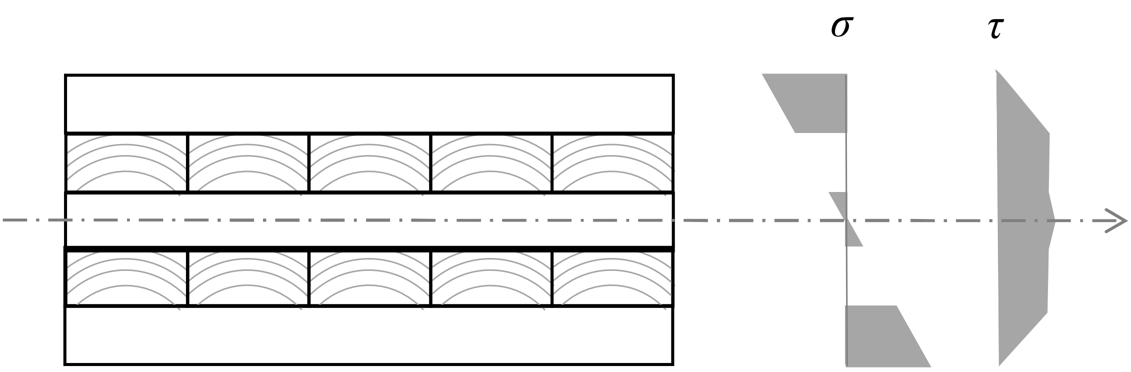

Figure 1: The CLT cross-section, normal and shear stress diagram

For the service limit state, the low stiffness of the cross-layers must be taken into account by determining either the effective stiffness of the cross-section according to the γ-method [7] or by the calculation of the shear deformation according to the Timoshenko method [5]. The γ-method is the most commonly used method for determining the effective stiffness of the CLT cross-section. The calculation procedure is analogous to the procedure for calculating the effective stiffness of the built-up timber beams with semi-rigid composite action according to [8]. The γ-method allows taking into account the slip between the individual layers. The equations for the calculation included in Annex B, Eurocode 5 [7] are sufficient for three- and five-layer panels. For the seven-layer panels, a modified γ-method [3] was derived.

2.2 Slab behavior

In some cases, biaxial bending of CLT panels occurs. For example, this is the case of a point load, openings in the panel, double side cantilever slabs or a point support. Verification of the ultimate limit state can be performed with the net cross-sectional characteristics in the respective direction. The internal forces and stresses in the panel are obtained from the plate model. In the calculation model, the low stiffness of the cross layers is necessary to take into account in the verification of the service limit state within the calculation of the slab deformation.

The biaxial bending of CLT panels can be relatively easy analyzed in software, such as [2], which include a subroutine for the modeling of multilayer slabs with considering the flexible shear connection. In other finite element based calculation software without special subroutines such as [1], it is possible to analyze the multilayer panels such as CLT using the orthotropic panel, whose stiffness characteristics in two directions can be defined in following ways:

Orthotropic slab with effective thicknesses. Effective thicknesses of the panel d_y a d_x (Fig. 2) can be calculated from the values of effective moment of inertia in respective directions. The effective moment of inertia can be determined using the γ-method.

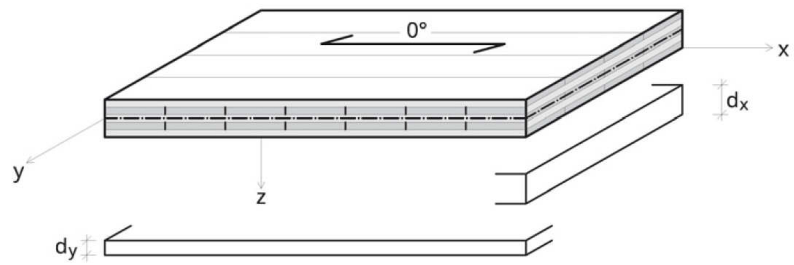

Figure 2: Effective thicknesses of the orthotropic slab [3]

Grillage model. The CLT panel can be substituted by the grillage consisted of homogenous timber beams. The substituted beams have the same stiffness as the CLT panel in respective directions. The cross-section dimensions of the grillage beams are calculated from the cross-sectional characteristics of CLT panel, which are usually determined by analytical methods, for example by the γ-method. The recommended distance of the grillage beams is 0.4 to 0.8 m according to [3]. The torsional stiffness of the grillage beams is much smaller than of the CLT panel. This usually leads to a slightly larger deformation of the grillage model.

Direct definition of the stiffness matrix. The flexibility of the CLT cross-layers can be taken into account according to Mindlin theory [3, 9]. The stiffness matrix can be determined independently of the static system. In calculating matrix members, the shear stiffness is taken into account by shear factors according to Timoshenko's theory of beams [3].

3 Parametric analysis

For a comparison of above-mentioned methods, the parametric analysis was performed. Various type of beams and slabs elements were considered. The maximum deformations of selected CLT panels with a different span and support configuration were compared. The aim was to evaluate the differences between the uses of individual methods.

3.1 Selected software products for CLT modeling

As mentioned before, modeling of members from CLT and following calculation of strain and verification of limit states can be performed by several software products based either on finite element method or on analytical computational procedures. For the parametric analysis, 3 various software were used: Calculatis developed by Storaenso [10], DLUBAL RFEM [2] with the add-on module RF-LAMINATE [9] and the software SCIA Engineer [1].

Calculatis is a software provided by CLT producer Storaenso online [10]. The design and verification of individual structural elements are carried out using analytical methods. For most of the CLT beam panels, Timoshenko's theory of beams is used. The stiffness characteristics according to the γ-method are used for slabs and walls. For the design and verification of the slabs subjected to biaxial bending within the relevant module of the software, relations derived from the grillage model are used.

The other SCIA Engineer [1] and DLUBAL RFEM [2] software are based on finite element method. The DLUBAL RFEM software includes an RF-LAMINATE add-on module that can analyze the stresses and deflections of multi-layer slabs [9]. The calculation is carried out according to the laminate theory, taking into account the shear bonding of the layers. Based on the defined layer structure, the total local stiffness matrix for the respective slab defined in the RFEM software is created. Within the parametric analysis, orthotropic panels were defined by effective thicknesses as well as grillage in the SCIA Engineer software. Appropriate stiffness properties of CLT were calculated by γ-method.

3.2 Parameters of the analyzed elements

For the analysis, three types of Storaenso panels were used: CLT 120 L3s (three-layer panel with the depth of 120 mm), CLT 140 L5s (5-layer panel with the depth of 140 mm) and CLT 180 L7s (7-layer panel with the depth of 180 mm). The beam elements had a span of 4 m, 5 m and 6 m. The geometry of the slab elements is shown in Fig. 3. These are double side cantilever slabs with a length of 1 m. Geometry and support position were chosen based on the constraints of the respective calculation module in Calculatis. The dimensions of the inner part are 4.0 x 1.8 m, the floor plan is 5 x 2.8 m. Supports in other software were modeled as hinged. The loads were considered in all cases with a value of 5 kN/m^2 without considering the elements self-weight.

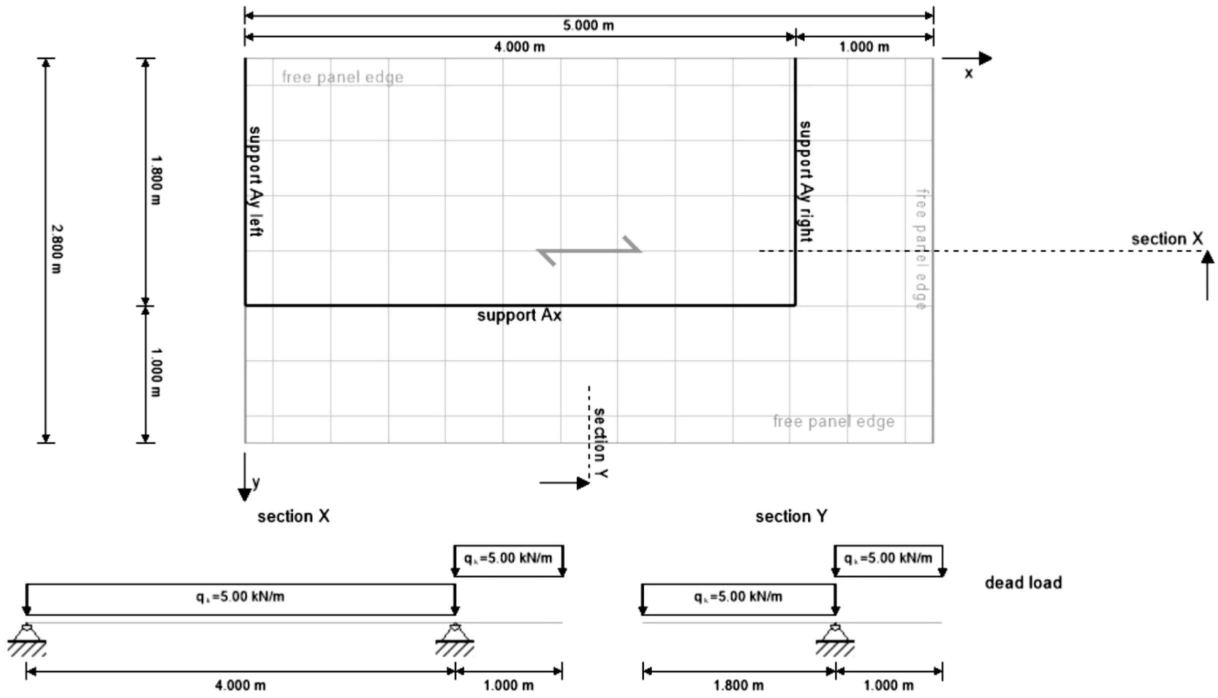

Figure 3: The geometry and load of the CLT slab – software Calculatis [9]

3.3 Results and discussion

The calculated maximum deflections of the analyzed elements and the percentage differences between these values are shown in Table 1 and Table 2. The reference values for the comparison were the values from RF-LAMINATE (DLUBAL RFEM), as we suppose this calculation should be the most accurate. The maximum deflections of slab elements were obtained at the corner of the cantilever part.

By comparing the results of the beams in Table 1, it can be seen that the values obtained by the various methods differ only slightly. The maximum deviation is 5% for the 7-layer panel with the span of 4 m. However, it should be pointed out that the values obtained by the finite element method in RF LAMINATE are the lowest. If we take this method as the most accurate, other approximate methods give results on the safe side. All methods, therefore, appear to be appropriate and equivalent for the analysis of CLT beams.

In the case of slab behavior analysis (Table 2), there are larger deviations between the results of respective methods. The largest deflection of the corner was calculated by the grillage model in SCIA Engineer. This could be due to the neglecting of the CLT torsional stiffness in this model. The lowest values were calculated in Calculatis. This is caused by the default grillage raster, which caused that there was no network node at the corner of the cantilever. The values are therefore not on the safe side.

Table 1: Calculated mid-span deflection w of beams with the span of L. The difference Δ in comparison with the values obtained by RF-LAMINATE.

Method (software)	L	CLT 120 L3s		CLT 140 L5s		CLT 180 L7s	
		w (mm)	Δ (%)	w (mm)	Δ (%)	w (mm)	Δ (%)
Analytical method (Calculatis)	4 m	11,0	2,8%	7,3	2,8%	4,2	5,0%
Effective thicknesses (SCIA Engineer)		10,9	1,9%	7,2	1,4%	4,1	2,5%
Grillage model (SCIA Engineer)		11,0	2,8%	7,3	2,8%	4,2	5,0%
RF-LAMINATE (DLUBAL RFEM)		10,7	0%	7,1	0%	4,0	0%
Analytical method (Calculatis)	5 m	25,6	1,6%	16,9	1,8%	9,6	3,2%
Effective thicknesses (SCIA Engineer)		25,4	0,8%	16,8	1,2%	9,5	2,2%
Grillage model (SCIA Engineer)		25,5	1,2%	16,9	1,8%	9,6	3,2%
RF-LAMINATE (DLUBAL RFEM)		25,2	0%	16,6	0%	9,3	0%
Analytical method (Calculatis)	6 m	51,8	1,4%	34,1	1,2%	19,2	2,1%
Effective thicknesses (SCIA Engineer)		51,5	0,8%	33,9	0,6%	19,1	1,6%
Grillage model (SCIA Engineer)		51,7	1,2%	34,1	1,2%	19,2	2,1%
RF-LAMINATE (DLUBAL RFEM)		51,1	0%	33,7	0%	18,8	0%

Table 2: Calculated maximum deflection w of slabs. The difference Δ in comparison with the values obtained by RF-LAMINATE.

Method (software)	CLT 120 L3s		CLT 140 L5s		CLT 180 L7s	
	w (mm)	Δ (%)	w (mm)	Δ (%)	w (mm)	Δ (%)
Analytical method (Calculatis)	18,8	1,6%	8,4	-5,6%	2,5	-10,7%
Effective thicknesses (SCIA Engineer)	21,2	14,6%	9,3	4,5%	2,8	0,0%
Grillage model (SCIA Engineer)	23,9	29,2%	10,9	22,5%	4,0	42,9%
RF-LAMINATE (DLUBAL RFEM)	18,5	0,0%	8,9	0,0%	2,8	0,0%

For the preliminary structural design, the most appropriate and most affordable software Calculatis software seems to be suitable. It offers the possibility of designing individual building segments such as a beam, walls with openings or double side cantilever panels. However, in the case of spatial modeling, this software has considerable limitations. It is necessary to divide the spatial model into individual planes and to design and verify the elements separately. The spatial construction modeling seems most accurate in the DLUBAL RFEM software with the RF-LAMINATE add-on module. Based on a defined layer structure, the total local stiffness matrix for the respective slab defined in the RFEM software is created. It is possible to directly analyze the stresses and deflections of multilayer panels.

In standard software based on the finite element method, it is relatively easy to model CLT panels using orthotropic slabs with effective thicknesses or grillage analogy. But the user should respect, that the software calculated self-weight of the modeled slab does not correspond to the real weight of the panel. In addition, for the verifying the ultimate limit state, only the internal forces are available. The respective stresses have to be calculated using the net cross-section characteristics. On the other hand, the obtained deformations will be on the safe side.

4 Conclusion

The article summarizes methods of structural analysis of the load distribution in cross-laminated slabs subjected to uniaxial and biaxial bending. The available methods of software modeling of cross-laminated timber elements are presented. A parametric analysis was performed to compare the deformations of the selected types of panels calculated using various methods and to evaluate the possibilities, advantages or disadvantages of CLT modeling in selected software.

On the basis of the performed analyses, we can conclude that the approximate simplified analytical methods and models of the orthotropic slab or grillage give comparable results to the finite element method. The differences are more visible in the case of slabs subjected to biaxial loading. The differences in deflections obtained by various methods reached almost 43%. But on the other hand, the analytical methods almost in all cases give larger deflection compared to the finite element model, on the safe side.

In terms of availability, the Calculatis software from Storaenso can be recommended for preliminary calculation. The DLUBAL RFEM software with the RF-LAMINATE add-on module is more suitable for spatial models, with the possibility of direct stress and deformation analysis of multi-layer slabs. The CLT modeling in SCIA Engineer can be performed relatively easy using orthotropic slabs, but the stress analysis is then more time-consuming.

Acknowledgements

This paper is prepared with supporting of the grant VEGA No. 1/0477/15 “Numerical analysis and modeling of interactive problems in multilayered composite structural members.” and the grand VEGA No. 1/0538/16 “Analysis of progressive parametric designed spatial structural systems created from wood-based composites” supported by the Scientific Grant Agency of Ministry of Education of Slovak Republic and Slovak Academy of Sciences.

References

[1] (2017). SCIA Engineer 17.1.2029 – student version [computer software]. Munich, Germany: Nemetschek.

[2] (2016) DLUBAL RFEM 5.07.13 – student version [computer software]. Tiefenbach, Germany: Dlubal Software GmbH.

[3] Novak, M.W., Koppelhuber, J. & Pock, K. (2014). *Cross-Laminated Timber Structural Timber: Basic design and engineering principles according to Eurocode*. Vienna, Austria: proHolz Austria.

[4] Mestek, P., Kreuzinger, H. & Winter S. (2008). Design of Cross Laminated Timber (CLT). In 10th World Conference on Timber Engineering, 2-5 June 2008 (pp. 156-163). Miyazaki, Japani: Curran Associates, Inc..

[5] Harris, R., Ringhofer A. & Schickhofer G. (2013). *Focus Solid Timber Solutions - European Conference on Cross Laminated Timber (CLT)*. Graz, Austria: Graz University of Technology.

[6] Demschner, T. (2016). *CLTengineer: The Stora Enso CLT design software, User Manual.* Stora Enso Wood Products GmbH. Ybbs a.d. Donau. Retrieved January 15, 2016, from https://calculatis.clt.info/Dokumentation/CLT-Engineer_Manual.pdf.

[7] EN 1995-1-1. (2004). Eurocode 5: Design of Timber Structures–Part 1–1: General Rules and Rules for Buildings. European Committee for Standardization Brussels. Belgium.

[8] K. Möhler. (1956). *Über das Tragverhalten von Biegeträgern und Druckstäben mit zusammengesetzem Querschnitt und nachgiebigen Verbindungsmitteln*. Habilitationsschrift, Karlsruhe, Germany.

[9] *RF-Laminate, Design of Laminate Surfaces. Program Description*. Dlubal Software GmbH, Retrieved September 30, 2016, from https://www.dlubal.com/en/products/rfem-and-rstab-add-on-modules/others/rf-laminate.

[10] (2018) Caltulatis 2.15.0, Stora Enso [computer software], from https://calculatis.clt.info/.