Computational Modelling of Cross-Laminated Timber Panels

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Abstract. The paper is dedicated to the qualitative and quantitative analysis of cross-laminated timber (CLT) panels within the theory of orthotropic laminated plate theory. Short description of CLT panels and assumptions of the theory is followed by the selection of examples with some parametric analysis within the Abaqus finite element software. The main conclusion is that the average values for orthotropic parameters of the material (usually used in practice) provides to overestimation of the results and can cause mistakes in the design.

1. Introduction

Cross-laminated timber (CLT) is a wood-based material consisting of layers glued to each other. Layers are placed alternately, usually in perpendicular directions to each other. It is also possible to make panels in which the layers cross at an angle other than 90°. In particular, the successive layers can be arranged parallel to each other to form a double layer. This solution is used, for example, to improve the strength and stiffness of panels in a selected direction [1]. The most common panels have 3 to 7 layers and are presented in figure 1.

Figure 1. Typical layers of CLT panels

CLT panels can carry loads acting both in the panel plane and perpendicular to it. Thanks to this, it is possible to use them in building constructions as load-bearing elements such as walls, ceilings or roof constructions. When used as a wall, a layer system is used in which most laminates are laid in a vertical direction. In roof and roof elements, working mainly on bending, external lamina are laid in the direction of the action of a larger bending moment [2].

An important aspect in determining the cross-section characteristics is to take into account the orthotropic properties of the wood [3]. In addition, due to the arrangement of layers in different directions and the possibility of using laminates with different parameters, these properties may be different in each layer.

Cross-laminated wood can be used in the construction of small building objects such as single-family houses. Most often, in this case, the entire above-ground part of the building structure is made...
as a wooden one. Often a solution is used in which the walls are made of cross-laminated wood, while the ceilings and roof are made of panels with a box section, usually with insulation filling.

At the stage of panel production, openings for windows and doors as well as openings for stairwells and installation shafts are prepared. Thanks to this, it is possible to significantly shorten the time of construction works - the panels only need to be assembled on the construction site and no additional processing is necessary. The panels can be covered with additional finishing layers or left uncovered. Example of using CLT in the construction of small building is shown in figure 2a.

For larger objects, often cross-laminated wood is combined with other materials. It is possible to use poles and beams made of laminated or steel laminated timber. In multi-storey buildings (figure 2b), a solution is often used, in which the horizontal forces from the wind carried by ceilings on reinforced concrete communication shafts. Some details of external and internal CLT solutions are presented in figure 2c,d.

Figure 2. Buildings in the CLT technology: family house (a), multi storey house (b), external walls (c), internal walls, seeings (d)
2. Mechanical properties of CLT panels

Mechanical properties of the CLT panels are estimated according to the theory of multi-layered plates described in [3]. The layers are orthotropic [4] without any limitations for the material directions, with the rules of transformation of the fourth order tensor. Following the theory an original programme in the Mathematica environment was developed to calculate mechanical properties of CLT panels.

The analysis is done within the finite element method [5] and commercial software. Material characteristic are applied to the Abaqus code [6]. Before the analysis the appropriate convergence analysis was performed. Selection of examples for estimation the influence of material parameters for the results are presented in the next chapter.

3. Computational analysis

In the Abaqus program a plate model (figure 3a) was made - the panel is simply supported and uniformly loaded perpendicular to its plane (figure 3b) – 10kN/m². The dimensions of the board were 3x6m, 25cm thick (5 layers by 5cm). A layer system was adopted in which every second is rotated by 90°. Three cases were analyzed: layers 1, 3, 5 arranged parallel to the long edge of the board; layers 1, 3, 5 arranged parallel to the short edge of the board, layers made of isotropic material.

In cases 1 and 2 it was assumed that the layers are made of spruce wood with the following elastic properties (1-longitudinal, 2-radial, 3-tangential direction):

\[
\begin{align*}
E_1 &= 10\,000\,\text{MPa} \\
E_2 &= 780\,\text{MPa} \\
E_3 &= 430\,\text{MPa} \\
v_{12} &= 0.372 \\
v_{13} &= 0.467 \\
v_{23} &= 0.435 \\
G_{23} &= 30\,\text{MPa} \\
G_{13} &= 610\,\text{MPa} \\
G_{12} &= 640\,\text{MPa} \\
v_{21} &= 0.029 \\
v_{31} &= 0.020 \\
v_{32} &= 0.420
\end{align*}
\]

For the case of 3 stiffnesses were assumed as average values:

\[
\begin{align*}
E &= \frac{E_1+E_2+E_3}{3} = 3736.67\,\text{MPa}, \\
v &= \frac{v_{12}+v_{21}+v_{13}+v_{31}+v_{23}+v_{32}}{6} = 0.260 \\
G &= \frac{E}{2(1+v)} = 1482.94\,\text{MPa}
\end{align*}
\]

In the Abaqus program, there are no components dedicated to orthotropic layered flat constructions. More general elements of double curvature are used. 8-node elements of medium thickness were selected for analysis.

![Figure 3. Finite element model: element mesh (a), boundary conditions (b)](image-url)
Figure 4. Vertical displacement [m]: orthotropy 1 (a), orthotropy 2 (b) and isotropy (c)

No qualitative differences are observed for the displacement distribution (figure 4). Maximum displacement in the case 1 is 50% bigger than in the case 2. Average values of mechanical properties provide the displacements 3-4 times lower.
Figure 5. Bending moment M-x [Nm/m]: orthotropy 1 (a), orthotropy 2 (b) and isotropy (c)

Qualitative as well as quantitative differences are observed in bending moments distribution (figure 5). Maximum values in the case 1 are 4 times bigger than in the case 2 and 2 times bigger than for average mechanical properties of the plate.
Qualitative as well as quantitative differences are observed in twisting moments distribution (figure 6). Maximum values in the case 1 are 25% bigger than in the case 2 and 50% bigger than for average mechanical properties of the plate.

Figure 6. Twisting moment $M_{xy}$ [Nm/m]: orthotropy 1 (a), orthotropy 2 (b) and isotropy (c)
Neither qualitative nor quantitative differences are observed for shear force distribution (figure 7).

The second model analyzed in the paper is a CLT box presented in figure 8a. A ceiling model with dimensions of 6x6m, based on 3m high walls, was made. A rigid connection of the ceiling with the walls was adopted. Assumptions regarding the material and thickness of the layers were the same as in
the previous example, with the difference that isotropic layers were not analyzed. In the walls, 1, 3, 5 layers were arranged vertically, while in the roof two cases were checked: in the direction of the x-axis and with the layers arranged along the diagonals (i.e. all layers rotated by 45° in relation to the first case). As in the previous examples, 8-node shell elements of medium thickness were used. Boundary conditions were assumed in the form of restraints on the lower edges of the walls (figure 8b). An uniformly distributed load of uniformly loaded perpendicular to its plane (figure 3b) – 10kN/m² was applied on the whole floor surface (figure 8b).

Figure 8. CLT box: finite element mesh (a) and load/support (b)

Figure 9. Vertical displacement [m] on upper surface: orthotropy 1 (a) and orthotropy 2 (b)

Figure 10. Bending moment M-x [Nm/m] on upper surface: orthotropy 1 (a) and orthotropy 2 (b)
Figure 11. Twisting moment $M_{xy}$ [Nm/m] on upper surface: orthotropy 1 (a) and orthotropy 2 (b)

Figure 12. Shear forces $Q_{x}$ [N/m] on upper surface: orthotropy 1 (a) and orthotropy 2 (b)

Displacements and shear forces in the ceiling plate (figure 9, 11) are similar for both cases analysed in the example. Bending and twisting moments (figure 10, 12) are 2.5 times bigger in the case 1.

Figure 13. Normal forces $N_{y}$ [N/m] on side surfaces: orthotropy 1 (a) and orthotropy 2 (b)

Normal forces in both cases (figure 13) are similar. Some qualitative differences are recognised.
4. Conclusions

Based on the obtained results, it can be concluded that there are basic qualitative as well as quantitative differences between the orthotropic and isotropic models, which is evident in the obtained displacement and internal force distributions. This is easy to see on the example of a rectangular ceiling plate, where with symmetrical design and loads, significantly different values of bending moments and lateral forces for the x and y directions are obtained. In an isotropic plate, these values would be the same.

There are also visible differences between orthotropic models with different layer layout. By changing the direction of the laminate, it is possible to control the stiffness of the panel, and thus, for example, to limit deflections or change the main direction of the board (e.g. to align the load of the walls supporting the plate). It gives the possibility to easily optimize the structure and adapt it to various requirements.

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