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Design Methodology Analysis of Cross-Laminated Timber Elements Subjected to Flexure

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Design Methodology Analysis of Cross-Laminated Timber Elements Subjected to Flexure

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Behavior and mechanical properties of cross-laminated timber are analyzed for case of static loading. Two panels with thickness 95mm consisting from three layers were tested in laboratory. Freely supported panels with span equal to 2m, which is loaded by the uniformly distributed load was a design scheme of considered panels. The panel's width was equal to 1m. Analytical FEM design method, which is based on the using of computational program ANSYSv14 and RFEM5.0, was checked by the experiment. The comparison of stresses acting in the edge fibers and vertical displacements shows that the considered design methodology can be used for engineering calculations.

Comparing methodology of calculations and experimental results the difference between results were up to 30%. Result difference for cross and parallel laminated timber plates – load bearing capacity, horizontal displacement and deflection varies up to 10%, it can be concluded that the middle layer does not give a significant effect on the load – bearing capacity loss. The transversal layer provides a homogeneous and solid system.

Finite element program for the calculation of accurate results in comparison with the calculation methodology showed RFEM5.0 program with differences up to 10% and 15%The program ANSYS up to 15%. RFEM5.0 increased accuracy of results increases built up functions for both EN1995-1-1 and GEM. Comparison of results between cross and parallel laminated timber in relative deformations, the difference is up to 6%. The cross – laminated timber middle layer does not affect load – bearing capacity. The middle layer decreases only 10 % of load – bearing capacity.

Introduction

Timber is one of the oldest and most traditional building materials, which combines interesting and aesthetics looks, variable textures, combined with proper strength and flexibility. Timber as a structural material is environmentally friendly in relation to bio-recovery and with minimal resources for providing it. [3] Wood is one of the world's most sustainable building material. Unlike concrete and steel, wood has almost zero "embodied carbon" (the amount of carbon used in the process of manufacturing a building product).

Cross – laminated timber attracts interest of civil engineers because it has new perspectives as a structural material. The cross – laminated timber possess the mechanical properties, which enable to decrease structural cost and time in comparison with analogous structures made of steel and reinforced concrete. CLT also has excellent thermal qualities, in some instances reducing

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the amount of energy needed to heat building by approximately 40 per cent, subsequently lowering costs for occupiers while also reducing CO_2 emissions.

Using of cross – laminated timber enables to obtain reliable load – bearing members and meets and aesthetic and architectural requirements at the same time. [2]

Two probable 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 orthotropic material. It matrix of stiffness will contain nine independent constants. It fibers of all the layers will be oriented in one direction, we will get anisotropic material which matrix of stiffness will contain twenty – one independent constants.

CLT panels are widely used for structures of floors and roofs. So, the aim of this paper is design methodology analysis of CLT elements subjected to flexure. Design methodology which is described in EN 1995-1-1 must be compared with methodology of mechanics of laminated materials and verified by laboratorian experiments and FEM to obtain identified aim.

CLT panel structure is mainly used for load-bearing structures and components of the system. CLT panels are used for walls, intermediate floors and roof structures.

Design methodologies of cross – laminated timber elements subjected to flexure

According to methodology we can offer two design methods for bending calculations of CLT:

_ Method of effective cross section;

_ Effective strength and stiffness method

The study includes six stages, where the slab layer dimensions chosen by the recommended literature and information available. [2] The slab is considered as freely supported beam with span equal to 2 m. The beam is considered under load with certain step 1, 2, 3, 4, 4.5, 5, 6, 7, and 7.5 kN/m2. The load steps chosen from the studies carried out by the available resources and opportunities.

1 First experiment with the first CLT plate;

2 Second experiment with second CLT plate;

3 Third stage is analytical calculations and drafting of methodology for elements subjected to flexure according EN 1995-1-1;

4 Calculations of parallel laminated timber according EN 1995-1-1;

5 Analytical experiments of CLT and parallel laminated timber with the finite element program RFEM5.0;

6 Analytical experiments of CLT and parallel laminated timber with the finite element program ANSYSv14.0.

The CLT subjected to flexure requires calculation consideration of the calculation steps:[2,4]

1 The ultimate limit state (ULS);

_ Calculation in shear;

_ Bending calculations;

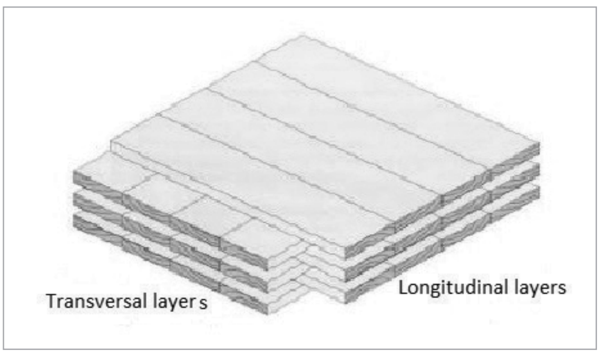

Fig. 1

Cross – laminated timber

2 Serviceability limit state (SLS);

_ Deflection of independent regulatory load;

_ Deflection of useful regulatory load;

_ The total deflection;

_ The stiffness calculation.

Verification of design methodologies Physical experiment

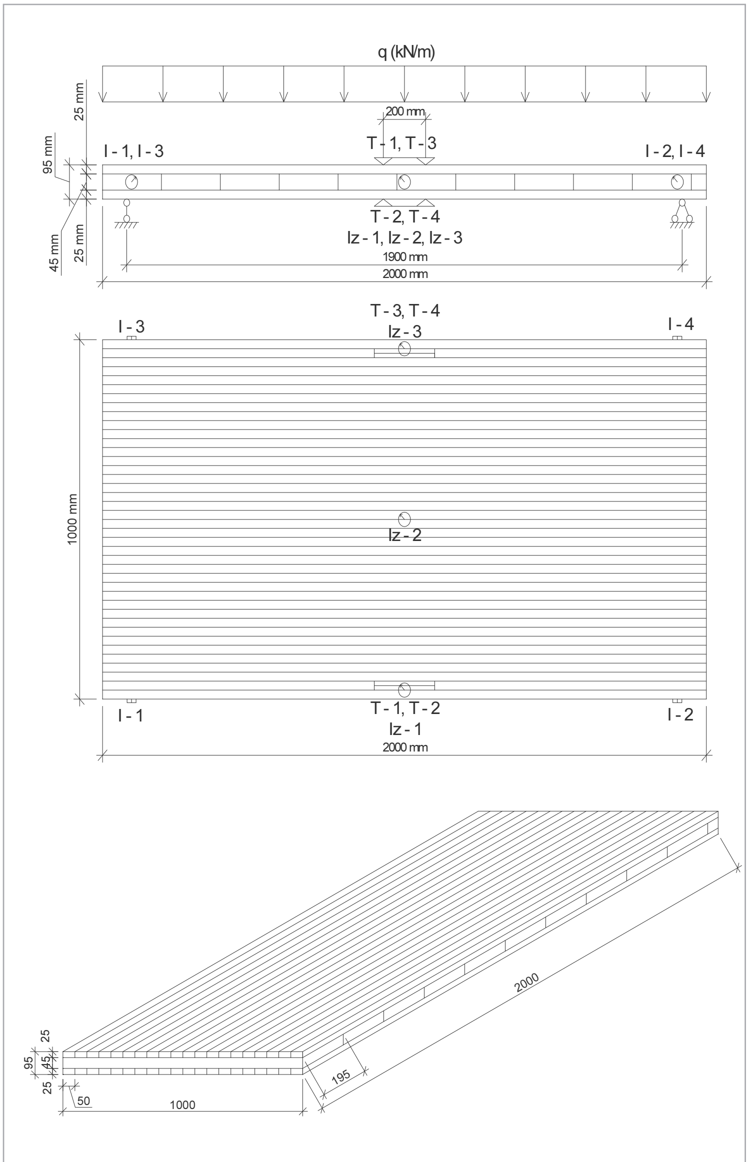

Fig. 2

CLT representation of the experimental

Physical experiment

The experiment is carried out to verify the accuracy of the calculation methodology in real usage conditions. The goal is to determine mismatch of analytical calculations and experiment.

For testing of cross – laminated timber are used strain gauges T-1, T-2, T-3, T-4, deflection meter Iz - 1 Iz - 2 Iz – 3 and indicators I – 1, I – 2, I – 3, I – 4. q – distributed load.

For making cross – laminated timber plate is used timber with cross – sections:

_ 25x50 (external layers);

_ 45x195 (middle layer).

_ Wood class EN 338 - C18.

Plates making process:

_ Preparing place;

_ Inlay the first external layer 25x50;

_ Applied polyurethane adhesive on first layer (glue usage quantity, 0.3kg/m^2);

_ Second layer is laid 45x195 and a glue is applied (0.3kg/m^2);

_ On the second layer is laid last layer 25x50;

_ The pressure (400kg/m^2) is applied.

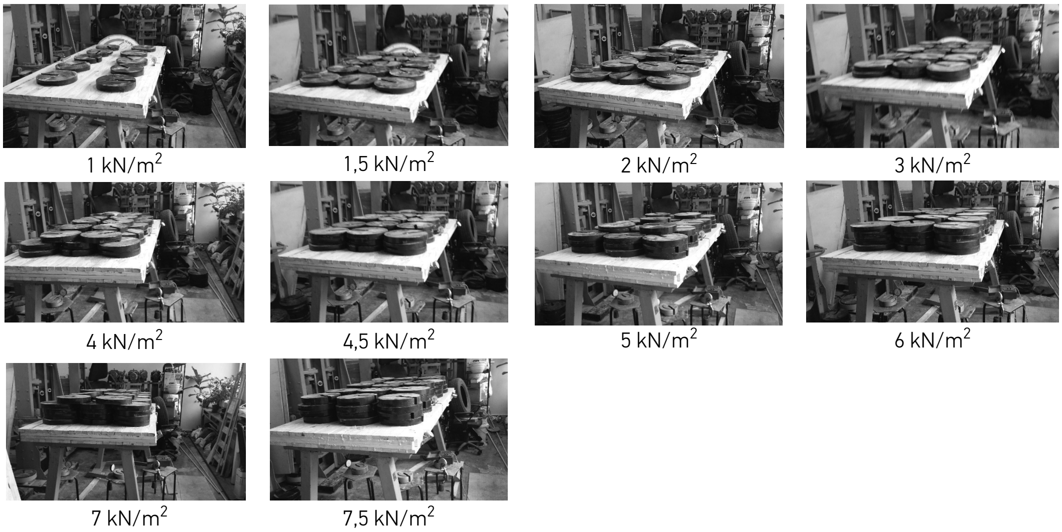

Fig. 3

CLT plate

Methodology of a analytical calculations

The plate is freely supported with span equal 2 m and loaded with distributed load. The plate is analyzed in one-way bending. If the plate would be based on the contour, it should be considered in two – way bending. The experimental procedure adapted to the available resources and opportunities to realize it.

Shear stresses acting in the CLT plates are determined basing on the recommendations of [3] and deformations of CLT plates due to shear stresses action are shown in **Fig. 5**.

Shear stresses acting in the CLT plate must be calculated by the following equation.

$$\tau(z_o) = \frac{V_z \cdot \int_{A_o} E(z) \cdot z \cdot dA}{K_{clt} \cdot b(z_o)} \quad [10] \tag{1}$$

The following condition must be satisfied [3]:

$$\left(\frac{\tau_d}{f_{v,d}}\right)^2 + \left(\frac{\tau_{drill,d}}{f_{v,d}}\right)^2 \leq 1.0 \tag{2}$$

where τ_d – tangential longitudinal stresses, N/mm²;

$\tau_{drill,d}$ – tangential transversal stresses, Nmm²;

$f_{v,d}$ – shear calculation value.

Normal stresses acting in the CLT plates are determined basing on the recommendations of [3] and distribution of normal stresses in the middle and outer layers of CLT plates is shown in **Fig. 6**. The fibers of second

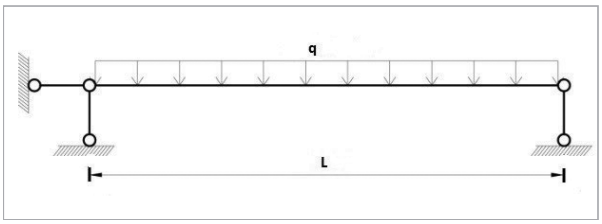

Fig. 4

Design scheme

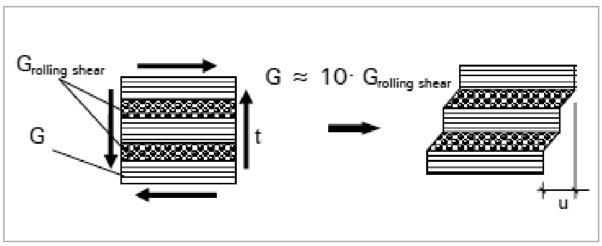

Fig. 5

Shear deformations in CLT

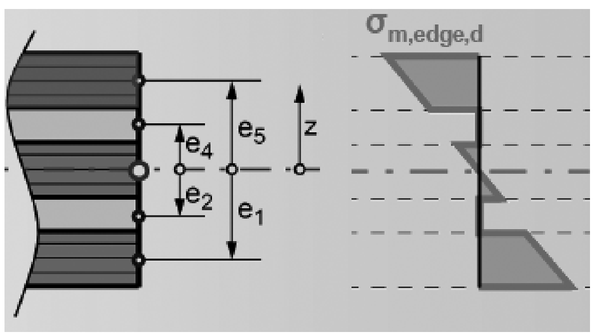

Fig. 6

Normal stresses in cross – section ($e_{1,2,3,4}$ – distance from center axis, $\sigma_{edge,d}$ – normal stress at edge) layer are oriented perpendicular to the direction of fibers for outer layer.

Bending stresses, acting at the distance z from the middle plane are calculated by the following equation:[2]

$$\sigma(z) = \frac{M_y}{K_{clt}} \cdot z \cdot E(z) \tag{3}$$

The following condition must be satisfied [3]:

$$\frac{\sigma_{edge,d}}{f_{m,clt,d}} \leq 1.0 \tag{4}$$

where:
$\sigma_{edge,d}$ – bending stresses in edge, N/mm^2;
$f_{m,clt,d}$ – bending strength calculation value, N/mm^2.

Two considered methods for analysis of cross-laminated timber elements subjected to flexure are based on the equation 4). Let us to consider reduced cross section method. Reduced 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:[1]

$$n = \frac{E_o}{E_{90}} \tag{5}$$

where:
E_0 – elastic module in longitudinal direction, N/mm^2;
E_{90} – elastic module in transversal direction, N/mm^2.

Moment of inertia of transformed cross-section should be determined by the equation:

$$I_{yy,transformed} = \\ = \left\{ \frac{b \cdot t_{CLT}^3}{12} - \frac{(-b_1 + b) \cdot t_2^3}{12} \right\} \tag{6}$$

where:
b – CLT plate width, mm;
h_{CLT} – CLT plate height, mm;
b_1 – the middle layer width, mm;
h_2 – middle layer height, mm.

Maximum value of normal stresses acting in the edge fibers of outer layers of CLT panels is determined by the equation:

$$\sigma_{edge,d} = \frac{Mz_{CLT}}{I_{yy,transformed}} \tag{7}$$

where:
$z_{CLT} = \frac{h_{CLT}}{2}$.

In accordance with the effective strength and stiffness method, maximum value of normal stresses acting in the edge fibers of outer layers of CLT panels must be determined by the equation:[5,6]

$$\sigma_{edge,d} = \frac{M_{\max,d}}{K_{CLT}} \cdot \frac{a_{CLT}}{2} \cdot E_{i=5} \tag{8}$$

where:
$M_{\max,d}$ – maximum bending moment, kNm;
a_{CLT} – CLT plates height;
K_{CLT} – safety factor;
$E_{i=5}$ – modulus of elasticity.

The value of factor K must be found by the equation:

$$K_{CLT} = \sum_{i-1}^{n} (J_i \cdot E_i) + \sum_{i=1}^{n} (A_i \cdot e_i^2 \cdot E_i) = (EI)_{ef} = E_0 \cdot \frac{h^3 \cdot a_{CLT}}{12} \cdot k_{(1,2,3,4)} \tag{9}$$

Effective values of composition factor $k_{(1,2,3,4)}$ must be determined by the well-known equations [2] depending on the CLT layer placement **(Fig. 8.)**.

The value of the composition factor $k_{(1,2,3,4)}$ depends from direction how load is apllied on structure and from layers layout.

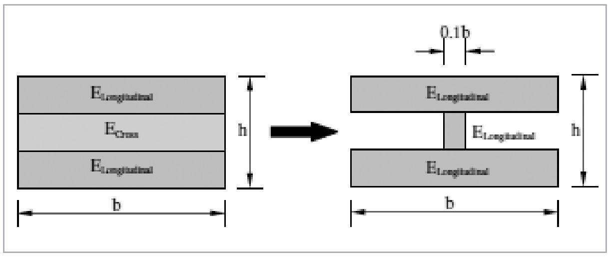

Fig. 7

Cross – section area transformations

Maximum vertical displacements of the CLT panels must be calculated by the following equation:[7,8,9]

$$w = \frac{1}{K_{CLT}} \int \left(M \cdot \overline{M} \right) dx + \frac{1}{S_{CLT}} \int \left(V \cdot \overline{V} \right) dx \qquad (10)$$

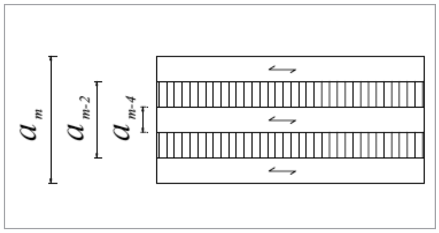

Fig. 8

Layer placement (a_{m-x} – plate and layer thickness)

In case if static scheme of the CLT panel is a freely supported beam, the above mentioned equation will be simplified:

$$w = \frac{5 \cdot q \cdot I_{ef}^{4}}{384 \cdot K_{CLT}} + \frac{q \cdot I_{ef}^{4}}{8 \cdot S_{CLT}}, \qquad (11)$$

where:
q – linear load;direction, N/mm^2;
I_{ef} – inertia moment;
S_{CLT} – shear stiffness.

The value of shear stiffness is determined by the equation:

$$S_{CLT} = k \cdot S_{tot} = k \cdot \sum \left(G \cdot b \cdot a_m \right) = k \sum \left(G \cdot A \right), \qquad (12)$$

where:
k - reduction coefficient;
G - shear modules, N/mm^2;
A - cross section of plate, mm^2.

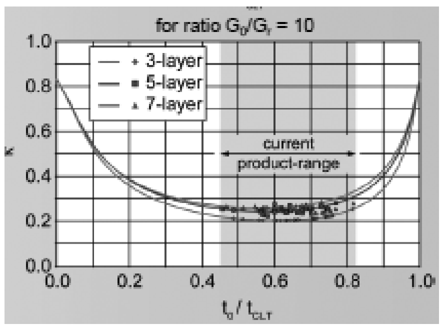

Fig. 9

Relative shear module proportion (To G0/Gr = 10) [3]

FEM design methodology

CLT panel 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.10**. The target of the calculation is verification of the results, obtained by the reduced cross-section method and effective strength and stiffness method.

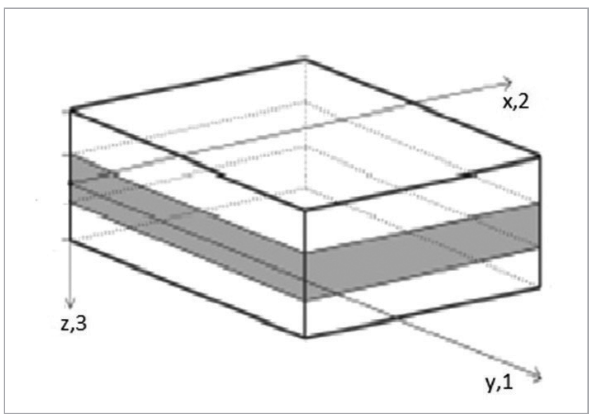

Fig. 10

Coordinate system for software

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:

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

where E_1, E_2, E_3 – moduli of elasticities in directions 1, 2 and 3;
υ_{ij} - Poisons ratio;
G_{23}, G_{31}, G_{12} – shear modules in 2-3, 3-1 and 1-2 planes,
γ_{23} γ_{31} γ_{12}, - shift deformations.

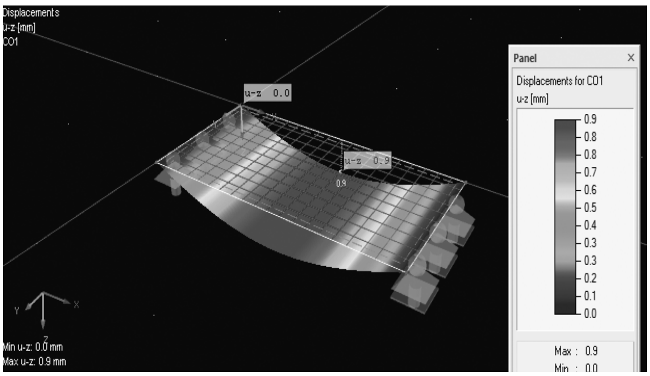

Fig. 11

Deflections in FEM software REFM5.0

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 11** and **12**.

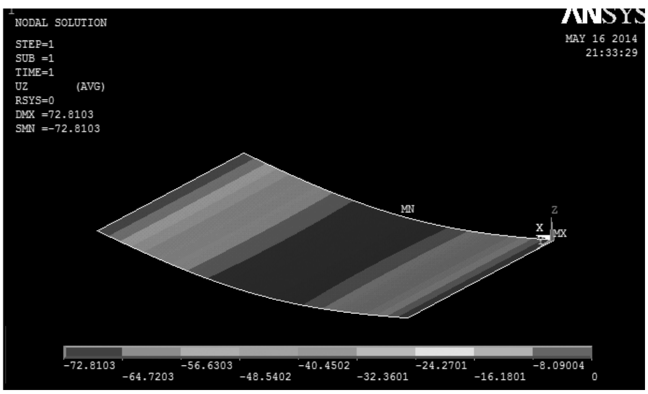

Fig. 12

Deflections in FEM software ANSYSv14

Design methods analysis of CLT elements subjected to flexure

The main cross – laminated timber proportion should be considered in relation to the calculation methodology:

1 Physical experimental results;

2 Finite element software.

The cross – laminated timber proportion between calculation methodology and experiments:

- relative deformation of 22%;
- horizontal deflection by 17%;
- deflection by 31%.

The cross – laminated timber proportion between calculation methodology and FEM:

- relative deformation of 10%;
- horizontal deflection to 7%;
- deflection to 3%.

Comparison of results between cross and parallel laminated timber in relative deformations, the difference is up to 6%. The cross – laminated timber middle layer does not affect load – bearing capacity. The middle layer decreases only 10 % of load – bearing capacity.

Deflection between two plates varies up to 20%, but for the deflection to the applied loads is less than ½ of the allowable deflection of 8 mm.

The graph shows results for strain of plate. The results form RFEM, ANSYS, first experiment and methodology are curved linearly, but the second experiment is curved cubicle.

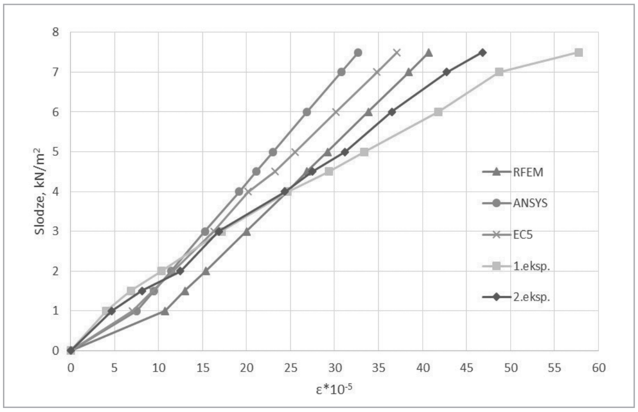

Fig. 13

Strain of CLT

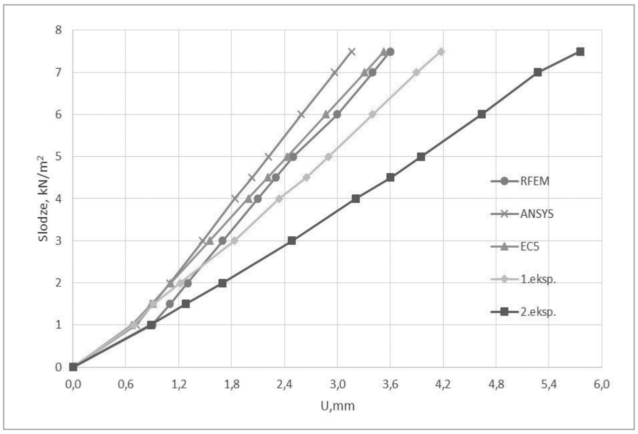

Fig. 14

Vertical deflections of CLT

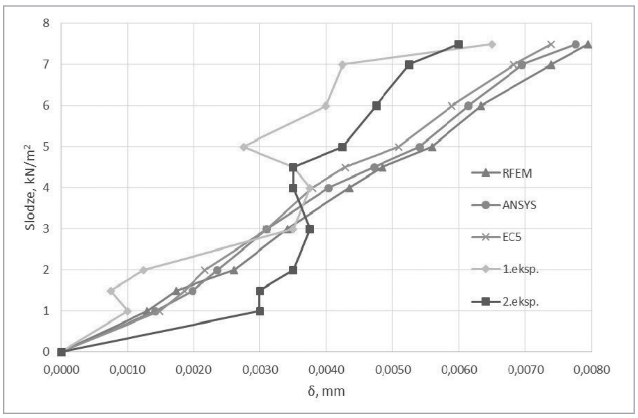

Fig. 15

Horizontal displacements of CLT

Conclusions

Cross – laminated timber, which is a durable, strong and sustainable solid wood alternative to concrete, is considered in the paper.

Design methodology analysis of cross-laminated timber elements subjected to flexure was carried out. The method of reduced sections and effective strength and stiffness methods were checked analytically and experimentally for cross laminated and parallel laminated timber panels.

Comparing methodology of calculations and experimental results the difference between results were up to 30%. Result difference for cross and parallel laminated timber plates – load bearing capacity, horizontal displacement and deflection varies up to 10%, it can be concluded that the middle layer does not give a significant effect on the load - bearing capacity loss. The transversal layer requires a homogeneous and solid system.

Finite element program for the calculation of accurate results in comparison with the calculation methodology showed RFEM5.0 program with differences up to 10% and 15%The program ANSYS up to 15%. RFEM5.0 increased accuracy of results increases built up functions for both EN1995-1-1 and GEM.

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