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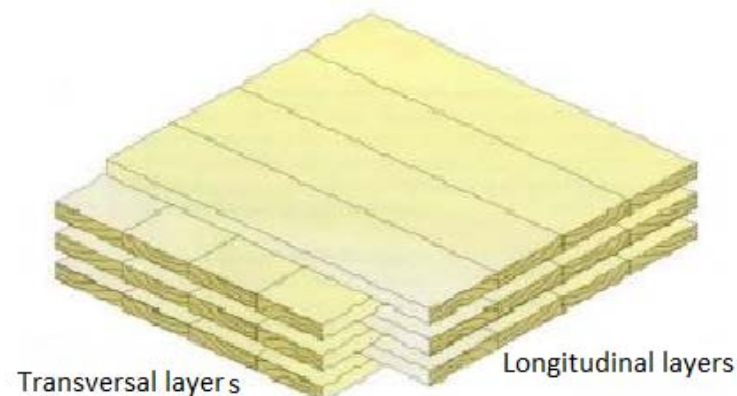
EXPERIMENTAL VERIFICATION OF DESIGN PROCEDURE FOR ELEMENTS FROM CROSS-LAMINATED TIMBER

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Main advantages of CLT

- Mechanical properties comparable with steel and reinforced concrete;
- Shorter manufacturing and construction time;
- CLT is suitable for structural elements subjected to flexure with spans from 4 to 9 m;
- CLT is suitable for high (up to 30 floors) and middle raised buildings;
- Reduced CO² emissions.





Aim of the work

- The aim of the current work is a comparison of the existing methods for the designing of CLT load-bearing elements, subjected to flexure and choice of the method, which is characterized by the less workability and enough precision.
- All the considered methods must be verified by the FEM and laboratory experiment.
- The design procedure for design realization by the selected method must be explained.



Design methods of CLT elements subjected to flexure

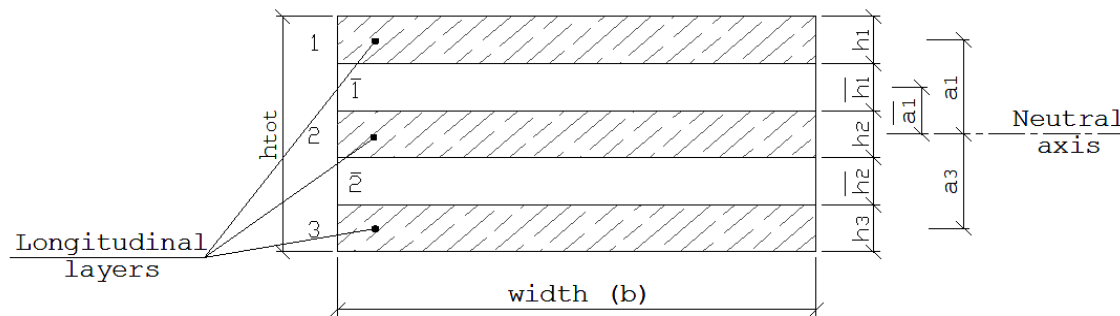
Gamma method

- ❑ Developed by Professor Karl Möhler.
- ❑ Initially it was used for the designing of composite beams with T, I or closed box-type cross-sections.

Assumptions

- ❑ The parts of the beams cross-sections are joined together by the compliant bonds;
- ❑ Material is working in the elastic stage.

Designation of the layers of CLT plate



h_{tot} – total thickness of the plate; h_i – thickness of the i -th longitudinal layer; \hat{h}_i – thickness of the i -th transversal layer; b – width of the plate; a_i – distance from the neutral axis of the whole plate to the neutral axis of separate layer



Design methods of CLT elements subjected to flexure

Gamma method

The effective stiffness $(EI)_{ef}$ is a major parameter which has influence at the elements behaviour.

$$(EI)_{ef} = \sum_{i=1}^n (E_i \cdot I_i + \gamma_i \cdot E_i \cdot A_i \cdot a_i^2)$$

E_i – mean value of modulus of elasticity of separate board material in fiber direction;

I_i – moment of inertia of the separate layer relative to its own main axis;

a_i – distance from the middle plane of the whole cross-section to the middle plane of the separate layer;

A_i – area of cross-section of the separate layer;

γ_i – reduction factors, which takes in to account compliance of the bonds.



Design methods of CLT elements subjected to flexure

Gamma method

The factors γ_i in case of the plate, which consists from the five layers:

$$\gamma_1 = \frac{1}{1 + \frac{\pi^2 \cdot E_1 \cdot A_1 \cdot \bar{h}_1}{L^2 \cdot G_R \cdot b}} \quad \gamma_2 = 1 \quad \gamma_3 = \frac{1}{1 + \frac{\pi^2 \cdot E_3 \cdot A_3 \cdot \bar{h}_2}{L^2 \cdot G_R \cdot b}}$$

L – span of the slab;

G_R – shear modulus of board material perpendicular to fiber direction



Design methods of CLT elements subjected to flexure

K - method

- The composite method (K-method) was developed by German scientists Hans Joachim Blass and Peter Fellmoser.
- This method initially was oriented at the design of plywood members, which are subjected to flexure.

Assumptions

- All layers of the slab must be taken into account;
- Span to height ratio of the slabs must not be less than 30, so as shear deformations are not taken into account;
- Strength and stiffness of the layers must be determined using the factor k_i , which depends from the scheme of loading and structure of the panel.
- The effective stiffness $(EI)_{ef}$ of the slab is determined with taking into account of all it layers.

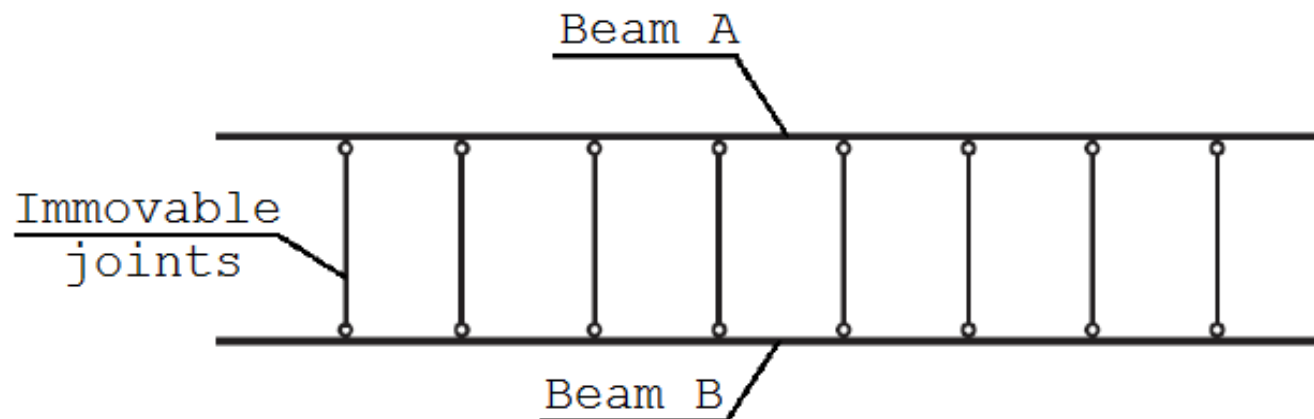


Design methods of CLT elements subjected to flexure

Method of shear analogy

- ❑ The method of shear analogy is considered as one of the most precise method for analyze of CLT plates so as elastic and shear modulus of all the layers are taken into account.
- ❑ The method of shear analogy was developed by German scientist Heinrich Kreuzinger.
- ❑ The slab is divided at two virtual beams, A and B, which are joined together by the immovable joints so that the deformations of the both beams are coinciding.

Model of the CLT slab by the method of shear analogy





Design methods of CLT elements subjected to flexure

Method of shear analogy

- ❑ The beam A is characterized by the infinitely big shear stiffness.
- ❑ Beam's bending stiffness $(EI)_A$ is determined as a sum of the bending stiffness of separate layers relatively their own neutral axis.

The total bending stiffness of the CLT slab $(EI)_{ef}$:

$$(EI)_{ef} = (EI)_A + (EI)_B = \sum_{i=1}^n E_i \cdot I_i + \sum_{i=1}^n E_i \cdot A_i \cdot z_i^2$$

$(EI)_B$ – the bending stiffness of the beam B;

z_i – the distance between the neutral axis of the i -th layer and neutral axis of the whole slab.



Design methods of CLT elements subjected to flexure

Transformed sections method

- ❑ Transformed method is characterized by the simplified design procedure in comparison with the methods, which were mentioned above.
- ❑ Transformed cross-section method is joined with the replacement of real cross-section of element by the equivalent transformed cross-section.

Checks of ultimate limit state (ULS)

$$\sigma_{max,d} \leq f_{m,d}$$

$$\tau_{max,d} \leq f_{V,R,d}$$

Checks of serviceability limit state (SLS)

$$w_{fin} \leq \delta_{max}$$

w_{fin} – final deflection of CLT slab;

δ_{max} – maximum available value for the final deflection of CLT plate, which is limited as a 1/300 part of the span.



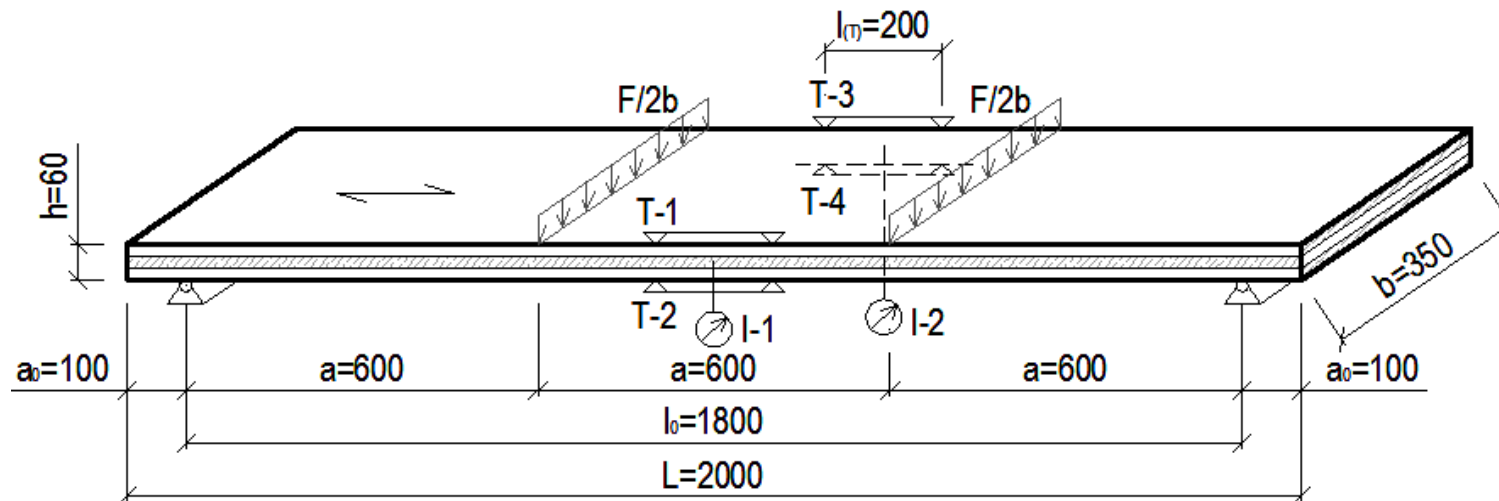
Verification of transformed section method (TSM) by experiment and FEM

- 8 CLT plates were considered.
- Dimensions of the CLT plates: length – 2 m; width – 0.35 m, thickness – 0.06 m.
- All plates were formed by three layers of boards.
- Thicknesses of external and internal layers of boards are equal to 20 mm.
- Pine wood with strength class C24 was chosen as a base material.
- The value of total vertical load change within the limits from 1 to 7 kN with the step equal to 1.0 kN.
- Maximum available value for the final deflection of CLT plate is limited as a $1/300$ part of the span



Verification of transformed section method (TSM) by experiment and FEM

Design scheme and measuring devices placement for CLT plates in four point bending



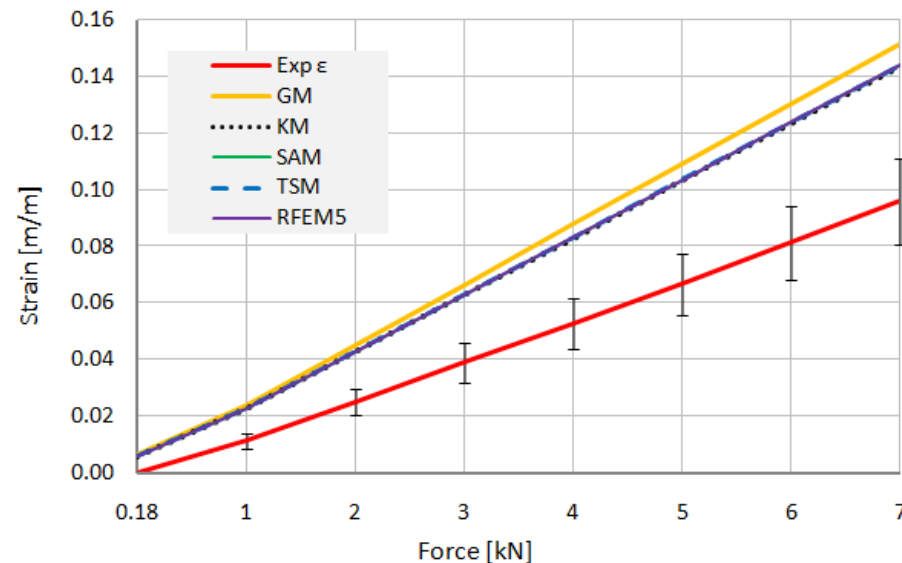


Verification of transformed section method (TSM) by experiment and FEM

Results, which were obtained for the considered CLT plate by:

- K-method
- gamma method
- shear analogy method
- transformed section method
- experiment
- software RFEM 5.0

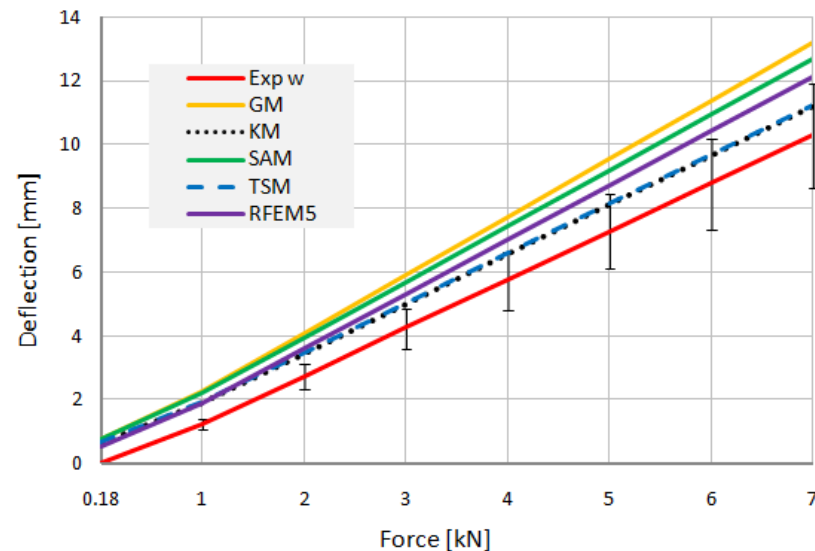
**The strain in the edge fibers of outer layers as a function from the
vertical load's intensity**





Verification of transformed section method (TSM) by experiment and FEM

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



Material properties used for CLT plate calculation:

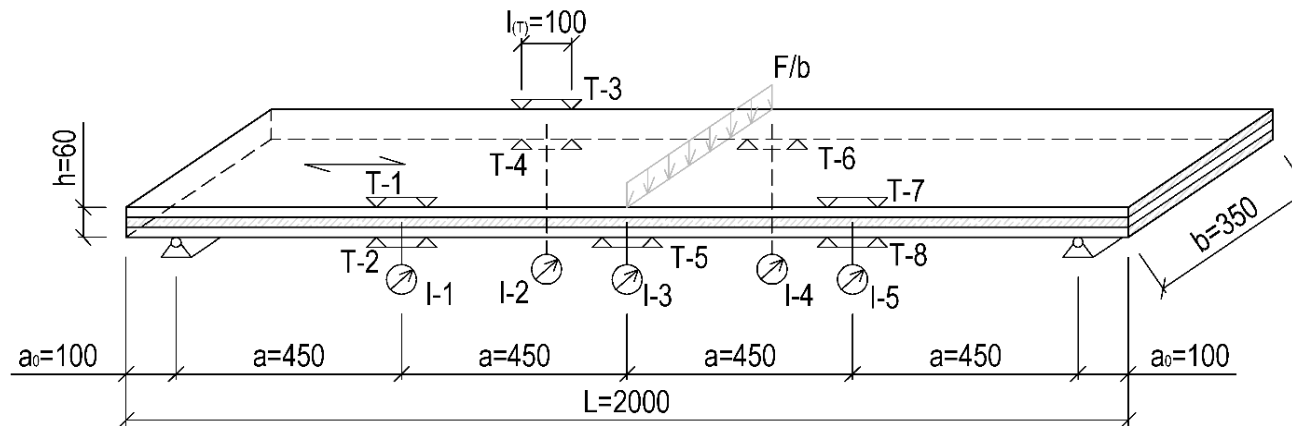
- mean modulus of elasticity $E_{0,mean} = 11$ GPa, $E_{90,mean} = 0.37$ MPa;
- 5% fractile and mean bending strength $f_{m,k,0.05} = 24$ MPa, $f_{m,k,mean} = 35.8$ MPa.



Benchmark study of transformed section method (TSM)

- ❑ The additional benchmark study was carried out to check the transformed section method for behaviour prediction of CLT plate under different loading type.
- ❑ One of the eight CLT plates was experimentally tested in three point bending up to the failure.

Design scheme and measuring devices placement for CLT plates in three point bending





Benchmark study of transformed section method (TSM)

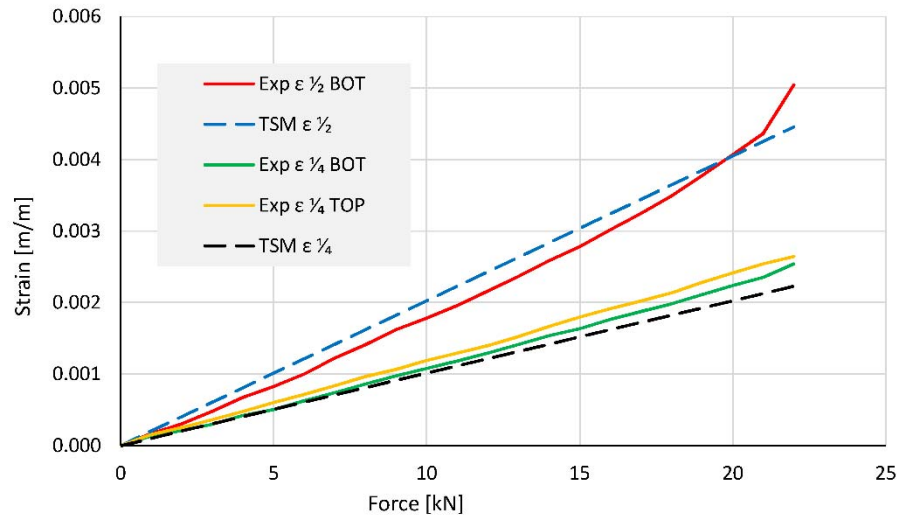
Plate under loading nearly collapse stage



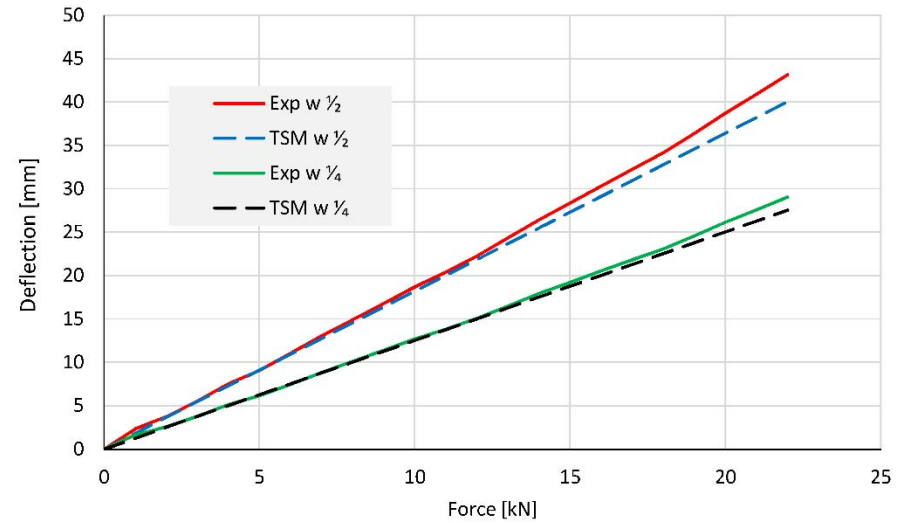


Benchmark study of transformed section method (TSM)

Dependence of force on strain



Dependence of force on deflection





Benchmark study of transformed section method (TSM)

Collapse of CLT slab





Conclusions

The design procedure for the elements from cross-laminated timber was verified.

K-method, gamma method, shear analogy method and transformed section method were compared analytically and by the experiment for behaviour prediction of statically loaded CLT panels in cases of three and four point bending.

□ The differences between the maximum vertical displacements in the middle of the span of CLT plates obtained by the K-method, gamma method, shear analogy method, transformed section method, software RFEM 5.0 and experiment were equal to 3.30, 13.90, 9.50, 3.30 and 6.00%, correspondingly.

The additional benchmark study was carried out to check the transformed section method for behaviour prediction of CLT plate under the three point bending up to the failure.

□ It was stated, that the difference of deflections between calculated using transformed section method and experimentally obtained does not exceed 7%.

□ The maximum difference between calculated and experimentally obtained strains is 20% in the half-span and 12% in the quarter-span.

□ It was stated, that the transformed sections method is characterized by simplicity of design procedure and reasonable precision in comparison with the K-method, gamma method and shear analogy method.



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