Scientific Seminar
Design of Steel and Timber Structures
SPbU, May 21, 2015

The research leading to these results has received the funding from Latvia state research programme under grant agreement "Innovative Materials and Smart Technologies for Environmental Safety, IMATEH". Project ID 1854 (task 3).

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

RIGA 2015
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1. Introduction;
2. Aim and tasks of investigation;
3. Design methods of CLT elements subjected to flexure;
4. Verification of design methods by experiment;
5. Verification of design methods by FEM;
6. Design methods Analysis of CLT elements subjected to flexure;
7. Design method of cross – laminated timber elements subjected to compression with the bending
8. Conclusions;
Introduction
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 CO\textsuperscript{2} emissions.
Introduction

Multy-stories buildings with the using of CLT

a) Residential buildings in London.

b) Design of residential buildings with up to 30 stories.
Introduction
Typical floor structure for multy-stories buildings with the using of CLT
Introduction

Bridge structures with the using of CLT

Pedestrian bridges with the decking made of CLT (Feldbach, Austria)
Aim and tasks of investigation

The **aim** of current investigation is to consider and analyse design methodology of CLT elements subjected to flexure.

Design methodology which is described in EN 1995–1–1 must be verified by laboratorian experiment and FEM.
Design methods of cross – laminated timber elements subjected to flexure

Two following methods are used for the designing of CLT structural members subjected to flexure:

- Effective strength and stiffness method.
- Transformed section method.

Checked for the CLT structural member subjected to flexure:

The ultimate limit state (ULS)

- Check of bending stresses;
- Check of shear stresses.

Serviceability limit state (SLS)
Design methods of cross – laminated timber elements subjected to flexure

**Effective strength and stiffness method**

Distribution of normal stresses in the CLT element's cross-section: $e_{1,2,3,4}$ – distances from the neutral axis to the middle of current layer; $\sigma_{m, \text{edge}, d}$ – normal stresses acting in the edge fiber
Design methods of cross – laminated timber elements subjected to flexure

**Effective strength and stiffness method**

Maximum value of bending stresses acting in the edge fibers of outer layers of CLT panels:

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

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; $E_{i=5}$ – modulus of elasticity of the each layer in longitudinal direction.

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

where, $E_i, A_i$ – modulus of elasticity and area of cross-section of separate layer; $I_i$ – moment of inertia of separate layer relatively it own main axis; $E_0$ – modulus of elasticity of timber in longitudinal direction; $h$ – total thickness of the plate; $k_i$ – composition factor which depends from the certain loading conditions.
Design methods of cross – laminated timber elements subjected to flexure

**Transformed cross-section method**

Transformation of cross – section is based on the relation of modulus of elasticity of the layers in longitudinal direction:

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

where \( E_0 \) – modulus of elasticity of timber in longitudinal direction ; \( E_{90} \) – modulus of elasticity of timber in transversal direction.
Design methods of cross – laminated timber elements subjected to flexure

**Transformed cross-section method**

Transformation of cross – section: 

- **a)** middle layer is taken into account;
- **b)** middle layer is not taken into account.

Obtained transformed double-tee cross-section then is considered as glued homogenous cross-section. Checks of ultimate limit state (ULS) and serviceability limit state (SLS) must be conducted basing on the recommendations of EN 1995–1–1.
Verification of design methods by experiment

Two CLT plates with the length and width equal to 2 and 1m, correspondingly and thickness in 95 mm were considered.

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.
Verification of design methods by experiment

Loading of specimens

Intensities of uniformly distributed loads changes within the limits from 1 to 7.5 kN/m\(^2\) with the step equal to 0.5 or 1.0 kN/m\(^2\).

\[ a) \quad \text{CLT plate before loading} \]

\[ b) \quad \text{CLT plate under the load in } 7.5 \text{ kN/m}^2 \]
Verification of design method by FEM method

The FEM softwares **REFM 5.0** and **ANSYS v14** were used for the CLT plate with dimensions in plan 2x1 m and thickness in 95 mm.

Maximum vertical displacements of CLT plate, which were determined by the softwares:

a) REFM5.0; b) ANSYS v14
Design methods analysis of CLT elements subjected to flexure

The dependence of strains in edge fibers of CLT plates as a function from the load's intensity.
Design methods Analysis of CLT elements subjected to flexure

The dependences of \textit{a}) maximum vertical displacements in the middle of the span of CLT plates and \textit{b}) relative displacements of outer and middle layers of CLT plate as a function from the load's intensity.
**Design methods Analysis of CLT elements subjected to flexure**

The maximum differences between the results obtained by the design methods and physical experiment are following:

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

- maximum bending stresses, acting in the edge fibers – 10%;
- horizontal relative displacements of 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. So, necessary pressure during gluing of the CLT panels must be at least 600kN/m², but in reality it was 33% less and, probably, necessary quality of glue joints was not provided.
Design methods of cross – laminated timber elements subjected to compression with the bending

Transformed section method is considered for cross-laminated timber elements, subjected to compression with the bending. The method is divided in to two sub-cases dependently from the dominating internal force. The first sub-case takes the place in the case when compression internal force is dominating and condition is satisfied.

\[
\sigma_{c,0,d} \geq \sigma_{m,d},
\]

where \(\sigma_{c,0,d}\) and \(\sigma_{m,d}\) are the normal stresses which were determined for the transformed cross-section of cross-laminated timber element due to compression force and bending moment, correspondingly.
Design methods of cross – laminated timber elements subjected to compression with the bending

The **second sub-case** takes the place in the case when bending moment is dominating internal force and condition (4) is not satisfied. Stability of cross-laminated timber element can be checked by the equation:

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

where \(\sigma_{c,0,d}\) and \(\sigma_{m,d}\) – is the 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 \(f_{c,0,d}\) – are design bending and compressive strengths parallel to grain; \(k_{\text{crit}}\) and \(k_c\) are the factors, which take into account the reduced bending and compression strengths.
Verification of transformed sections method for cross-laminated timber element subjected to compression with the bending by FEM

The cross-laminated timber plate, which was detaily described above, was considered. A freely supported beam with the span equal to 1.9 m, which is 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/m². 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 the 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.
**Verification of transformed sections method for cross-laminated timber element subjected to compression with the bending by FEM**

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

*Normal stress distribution in plate*

*a) in case of dominating bending stresses; b) in case of dominating compression stresses*
Verification of transformed sections method for cross-laminated timber element subjected to compression with the bending by FEM

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 exceeds 1.7 % for the cases with dominating compressive and bending normal stresses.

Shear stress distribution in plate
Conclusions

Analysis of design methods of cross-laminated timber elements subjected to flexure and compression with the bending was carried out. The transformed sections and effective strength and stiffness methods were checked analytically and experimentally for cross laminated timber panels.

The maximum differences between the results obtained by the design methods, physical experiment and softwares REFM 5.0 and ANSYS v14 were equal to 31 and 10%, correspondingly.

So, the transformed sections and effective strength and stiffness methods enable to describe behaviour of CLT elements subjected to flexure with the available accuracy. Result difference for cross laminated timber plates for load bearing capacity, relative displacements of outer and middle layers and maximum vertical displacements varies up to 10%.
Acknowledgement

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Materials Consumption Decrease for Long-Span Prestressed Cable Roof

RIGA 2015
Content

10. Introduction;
11. Aim and tasks of investigation;
12. Approach to solution of the problem;
13. Materials consumption decrease for long-span prestressed cable roof;
14. Evaluation of rational parameters of cable net prestressing;
15. Conclusions;
Introduction

Prestressed Long-Span Cable Structures

\begin{itemize}
\item[a)] one-chord roofs,
\item[b)] saddle-shaped roofs,
\item[c)] combined roofs.
\end{itemize}
Aim and tasks of investigation

The **aim of the work** is to check possibility to decrease materials consumption for saddle-shaped cable roof with the rigid contour by the prestressing of the cables by the different forces. The following **tasks** must be solved to obtain the aim:

- Possibility to obtain a cable net, where stresses, acting in the all cables are the same also should be considered.

- Rational amount of the cables groups in the net, which are differed by the level of prestressing and the level of prestressing of cables in the each group, should be evaluated also.
**Approach to solution of the problem. Structural solution of long-span prestressed cable roof**

Prestressed saddle-shaped cable roof 60X60 m in plan was considered as an object of investigation.

**Scheme of cable net for roof with rigid supporting contour**

1 – supporting contour, 2 – catenary cables, 3 – stressing cables, \( l_s \) and \( l_n \) spans of main suspension and stressing cables, \( f_s \) and \( f_n \) – initial deflections of suspension and stressing cables, \( F_v \) and \( F_h \) – vertical and horizontal support reactions, \( N_1 \) and \( N_2 \) – maximum axial forces in suspension and stressing cables of the net.
Approach to solution of the problem. Method of analysis

**Scheme of cable net loading**

Metallic cross-sections of catenary and stressing cables were determined by the following equation:

\[ A_{m,n(s)} \geq 1.5 \cdot \frac{n_{n,(s)} \cdot \gamma_R}{f_{uk}} \]

Where

- \( A_{m,n(s)} \) – metallic cross-section of catenary and stressing cables;
- \( n_{n,(s)} \) – maximum axial forces, acting in catenary and stressing cables;
- \( \gamma_R \) – partial factors;
- \( f_{uk} \) – characteristic value of tensile strength of steel wire.
Approach to solution of the problem. Method of analysis

The dependences of cable net materials' consumption ($G$), coefficient of effectiveness of cable net materials using ($\psi$), maximum vertical displacements of the cable net ($\delta_{\text{max}}$) on the main parameters of the cable net prestressing were determined.

\[
G = b_0 + b_1 \cdot n + b_2 \cdot N_{0,n} + b_3 \cdot N_{0,s} + \\
+b_{12} \cdot n \cdot N_{0,n} + b_{13} \cdot n \cdot N_{0,s} + b_{23} \cdot N_{0,n} \cdot N_{0,s} + \\
+b_{11} \cdot n^2 + b_{22} \cdot N_{0,n}^2 + b_{33} \cdot N_{0,s}^2,
\]

Where $G$ – cable net materials' consumption;
$n$ – amount of the cables groups, which are differed by the level of prestressing;
$N_{0,n}$ – prestressing level of catenary cables; $N_{0,s}$ – prestressing level of stressing cables.
Approach to solution of the problem. Method of analysis

Rational from the point of view of materials consumption amount of the cables groups, which are differed by the level of prestressing, prestressing levels of catenary and stressing were determined by the systems of equations, which was written for cable net materials consumption ($G$).

\[
\begin{align*}
\frac{\partial G}{\partial n} &= b_1 + b_{12} \cdot N_{0,n} + b_{13} \cdot N_{0,s} + 2 \cdot b_{11} \cdot n = 0, \\
\frac{\partial G}{\partial N_{0,n}} &= b_2 + b_{12} \cdot n + b_{23} \cdot N_{0,s} + 2 \cdot b_{22} \cdot N_{0,n} = 0, \\
\frac{\partial G}{\partial N_{0,s}} &= b_3 + b_{13} \cdot n + b_{23} \cdot N_{0,n} + 2 \cdot b_{33} \cdot N_{0,s} = 0.
\end{align*}
\]
Materials Consumption Decrease for Long-Span Prestressed Cable Roof

Tension stresses distribution in the cables of the net for the variant with the four cables groups

The values of tension stress changes within the limits from 535.83 to 1470MPa. The values of tension stresses for variants with one and twenty seven groups of cables changes within the limits from 242.5 to 1129.6 MPa and from 104.9 to 1843.1MPa, correspondingly.
Materials Consumption Decrease for Long-Span Prestressed Cable Roof

It was stated, that materials volume was equal to 3.71, 3.24 and 2.67 m$^3$ for the variants which contains 1, 4 and 27 groups of cables, which are differed by the prestressing level, correspondingly. So, increase of cable groups amount with the different level of prestressing from 1 to 4 and 27 enables to decrease cable net materials consumption by 21.3 and 39.2%, correspondingly.
### Evaluation of rational parameters of cable net prestressing

#### The coefficients of second power polynomial equations

<table>
<thead>
<tr>
<th>Coefficients of second power polynomial equations</th>
<th>Dependence for materials' consumption (G)</th>
<th>Dependence for coefficient of effectiveness of cable net materials using (ψ)</th>
<th>Dependence for maximum vertical displacements of the cable net (δ_{max})</th>
</tr>
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<tbody>
<tr>
<td>$b_0$</td>
<td>$1.08 \cdot 10^{-3}$</td>
<td>374.70</td>
<td>489.52</td>
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<tr>
<td>$b_1$</td>
<td>$-5.14 \cdot 10^{-5}$</td>
<td>26.88</td>
<td>12.86</td>
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<td>$b_2$</td>
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<tr>
<td>$b_3$</td>
<td>0</td>
<td>-6.92</td>
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<tr>
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<tr>
<td>$b_{22}$</td>
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</tr>
<tr>
<td>$b_{23}$</td>
<td>0</td>
<td>0.06</td>
<td>-0.02</td>
</tr>
<tr>
<td>$b_{33}$</td>
<td>$1.08 \cdot 10^{-3}$</td>
<td>0.03</td>
<td>-0.01</td>
</tr>
</tbody>
</table>
Evaluation of rational parameters of cable net prestressing

The dependence of the effectiveness of cable net materials using from the prestressing level of catenary and stressing cables of the net
Evaluation of rational parameters of cable net prestressing

The dependence of cable net prestressing level of catenary and stressing cables on maximal vertical deflection
Evaluation of rational parameters of cable net prestressing

The dependence of the cable net materials consumption on the amount of cables groups

The dependence was obtained when the prestressing levels of catenary and stressing cables of the net were equal to 57 % and 80% from its load-carrying capacity, correspondingly.
Conclusions

Possibility to decrease materials consumption by the changing of prestressing forces for cables of the roof was checked on the example of saddle-shaped cable roof with the rigid support contour and dimensions 60x60 m in the plan. So, increase of cable groups amount with the different level of prestressing from 1 to 4 and 27, enables to decrease cable net materials consumption by 21.3 and 39.2%, correspondingly. Values of prestressing forces, which were applied to the groups of cables, changes within the limits from 20 to 80% from the cables breaking force.

Rational from the point of view of cable net material's consumption amount of cables groups, which are differed by the levels of prestressing and prestressing level for catenary and stressing cables, were determined. It was stated, that division of suspension and stressing cables on the 18 groups enables to decrease cables material consumption by 19.2%. Values of prestressing forces for suspension and stressing cables of the roof were equal to 57 and 80 %, from it load-carrying capacity, correspondingly.
Acknowledgement

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