Project Nr.3.
Risk consideration for safe, effective and sustainable structures

Task Nr.3.

To develop innovative smart structure with using of removable natural resources with the increased durability and reliability for structural and infrastructural purposes

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Content

Time frame for core task 3

	2014		2015				2016				2017			
	1	2	1	2	3	4	1	2	3	4	1	2	3	4
1. Development of design procedure for load-bearing elements from cross-laminated timber	x	x	x	x	x	x	x	x	x	x				
1.1. Data generalization for development of design procedure for load-bearing elements from cross-laminated timber	x	x	x											
1.2. Development of design procedure for load-bearing elements from cross-laminated timber			x	x	x	x	x	x						
1.3. Experimental testing of design procedure for load-bearing elements from cross-laminated timber				x	x	x	x	x	x	x				
2. Topology optimization for structure from cross-laminated timber and evaluation of it rational, from the point of view of it materials expenditure, parameters							x	x	x	x	x	x	x	x
2.1. Model of behaviour for structure from cross-laminated timber							x	x	x	x				
2.2. Development of optimization algoritme for structure from cross-laminated timber							x	x	x	x	x	x	x	x
2.3. Evaluation of it rational parameters for structure from cross-laminated timber							x	x	x	x	x	x	x	x
3. Development of load-bearing structure which consists from the main tensioned members and secondary cross-laminated timber members subjected to flexture							x	x	x	x	x	x	x	x
3.1. Development of numerical model of the structure							x	x	x	x	x	x	x	x
3.2. Development of physical model of the structure											x	x	x	x
4. Conferences, papers						1/3 1/4				1/1 1/3*				1 2
5. Supervision of doctoral and masters thesis	x	x	x	x	x	x	x	x	x	x	x	x	x	x

2. Aim and tasks of activity

Aim of activity:

To develop innovative smart structure with using of removable natural resources with the increased durability and reliability for structural and infrastructural purposes

Tasks:

- Development of design procedure for load-bearing elements from cross-laminated timber.
- Topology optimization for structure from cross-laminated timber and evaluation of it rational, from the point of view of it materials expenditure, parameters.
- Development of load-bearing structure which consists from the main tensioned members and secondary cross-laminated timber members subjected to flecture.

3. Design methods for CLT elements.

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 vailable value for the final deflection of CLT plate, which is limited as a 1/300 part of the span.

3.1. Transformed section method verification for CLT elements subjected to flexure

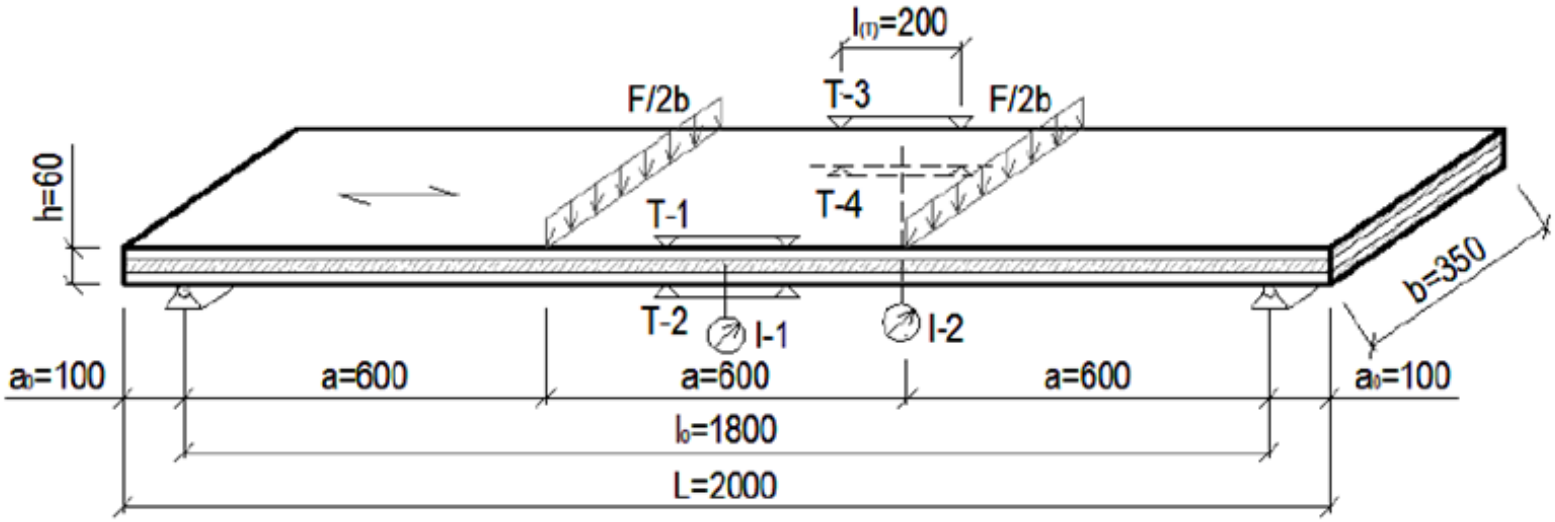
Verification of transformed section method (TSM) by experiment and FEM

- 8 CLT plates were considered.
- Dimensons 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

3.1. Transformed section method verification for CLT elements subjected to flexure

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

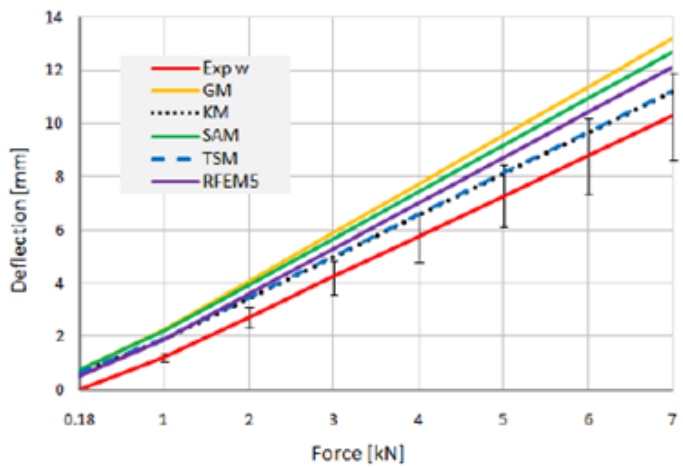
Design scheme and measuring devices placement for CLT plates in four point bending



3.1. Transformed section method verification for CLT elements subjected to flexure

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:

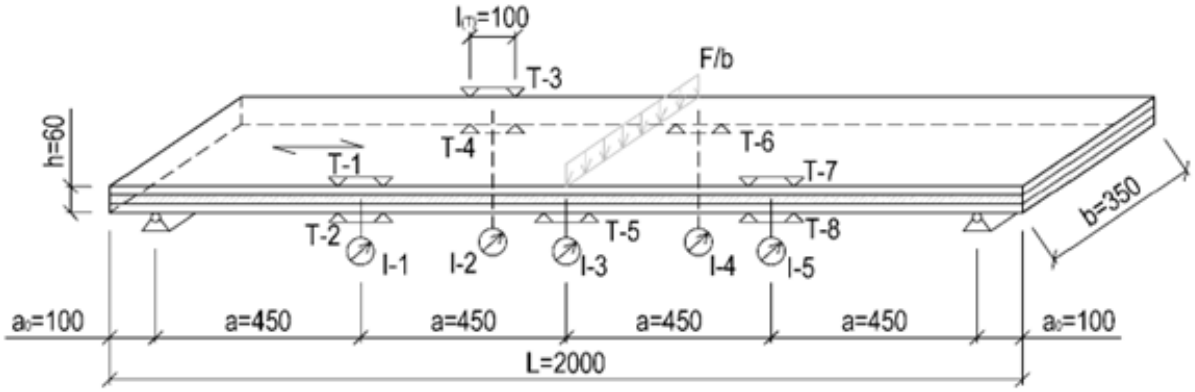
- mean modulus of elasticity $E_{0,mean}$ = 11 GPa, $E_{90,mean}$ = 0.37 MPa;
- 5% fractile and mean bending strength $f_{m.k,0.05}$ = 24 MPa, $f_{m,k,mean}$ = 35.8 MPa.

3.1. Transformed section method verification for CLT elements subjected to flexure

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.

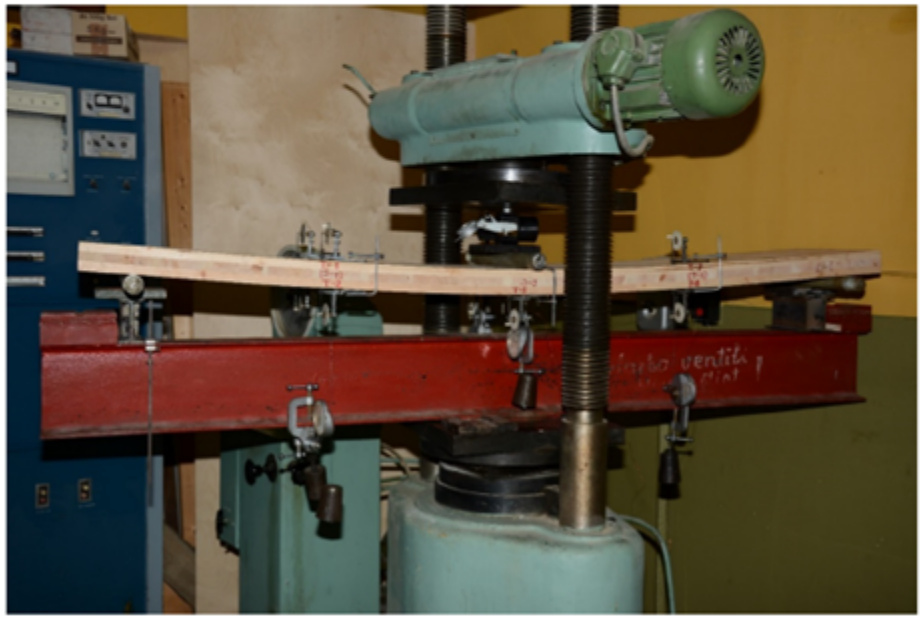
Design scheme and measuring devices placement for CLT plates in three point bending



3.1. Transformed section method verification for CLT elements subjected to flexure

Benchmark study of transformed section method (TSM)

Plate under loading nearly collapse stage



Collapse of CLT slab

3.2. Transformed section method verification CLT 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.

3.2. Transformed section method verification CLT 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:

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

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_{crit} and k_c are the factors, which take into account the reduced bending and compression strengths.

3.2. Transformed section method verification CLT elements subjected to compression with the bending.

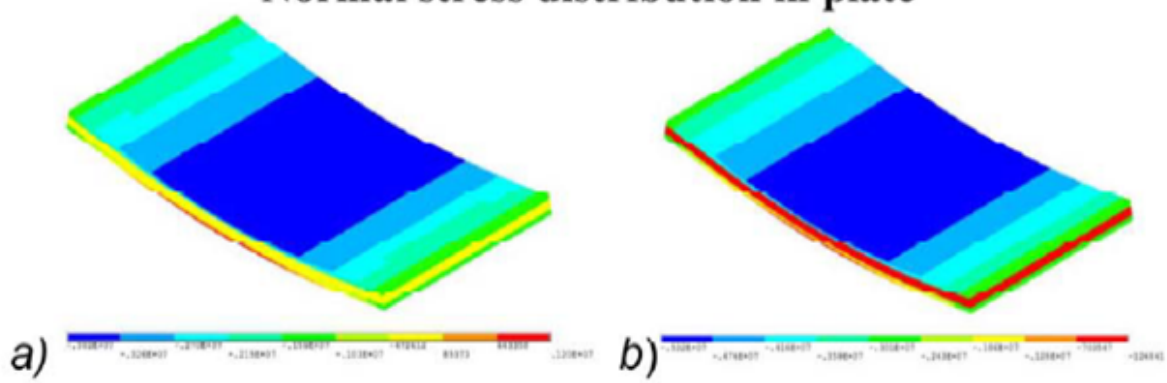
The cross-laminated timber plate, which was detaily described above, was considered. A freely supported beam with the span equal to 1.9 m, which is loaded by the uniformly distributed load and axial force, was considered as a design scheme. The intensity of uniformly distributed load was equal to 7.5kN/m^2. 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.

3.2. Transformed section method verification CLT elements subjected to compression with the bending.

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



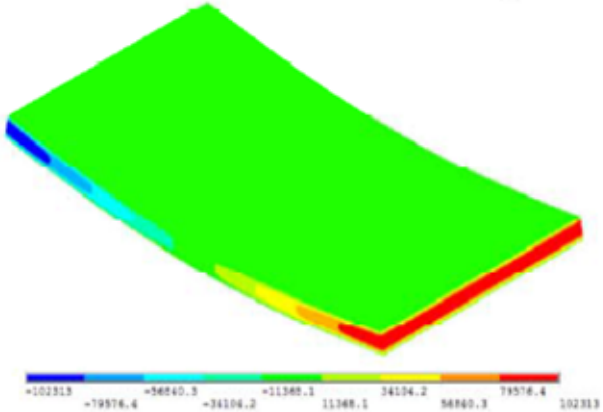
a) in case of dominating bending stresses; *b)* in case of dominating compression stresses

3.2. Transformed section method verification CLT elements subjected to compression with the bending.

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



3. Transformed section method verification for CLT elements

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.

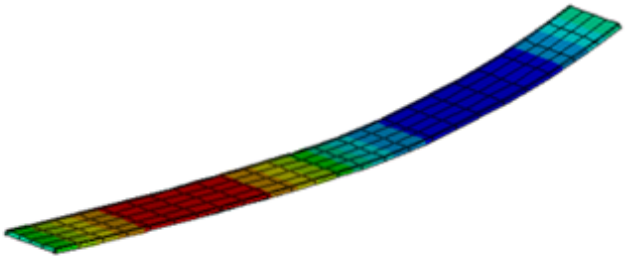
- It was stated, that the difference of deflections between calculated using transformed section method and experimentally obtained does not exceed 7%.
- The maximum difference between calculated and experimentally obtained strains is 20% in the half-span and 12% in the quarter-span.
- It was stated, 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.

4. Topology optimization for structure from cross-laminated timber

4.1. Model of behaviour for structure from cross-laminated timber

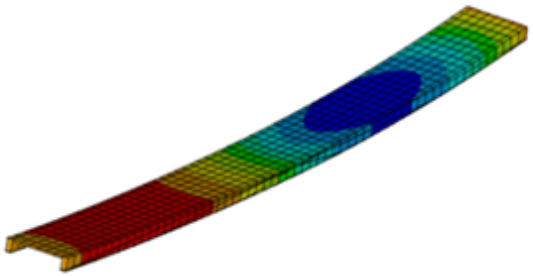
Comparison of different types

Ribbon type
Prestressed by cables CLT based curved deck:



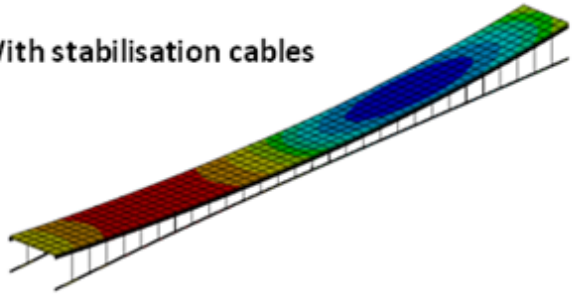
Characteristic: too flexible, prestressing is not influencing kinematical displacements

Ribbon type
Prestressed by cables CLT based curved deck with additional beams:



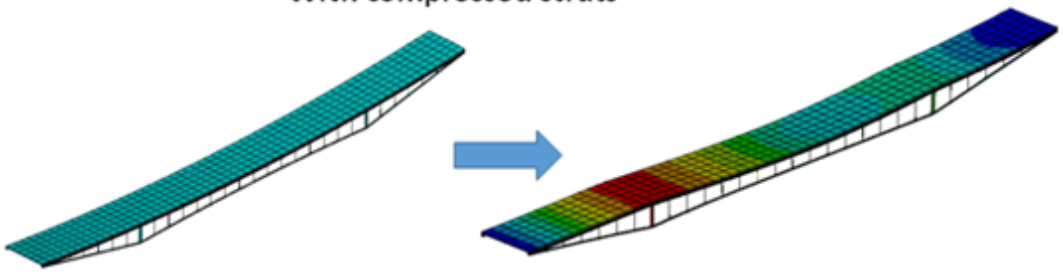
Characteristic: increased material consumption

With stabilisation cables



Characteristic: satisfactory

With compressed struts



Characteristic: too flexible

4.2. Development of optimization algoritme for structure from cross-laminated timber

Optimization:

Parametric ANSYS FE model

Design variables:
- diameter of main cable
- diameter of stabilisation cable
- diameter of suspenders

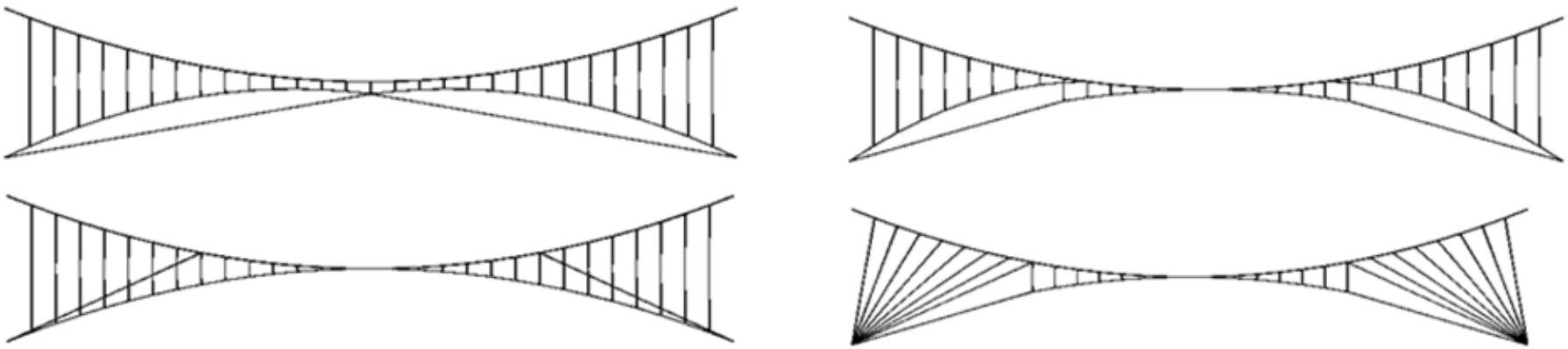
State variables:
- total displacements < 1/200 L
- stresses in cables < 850 MPa

Objective function:
- material consumption on mail and stab. cables and suspenders.

Optimization type:
- First order optimization method by ANSYS

4.3. Evaluation of rational parameters for structure from cross-laminated timber

Different subtypes, which seemed to be perspective



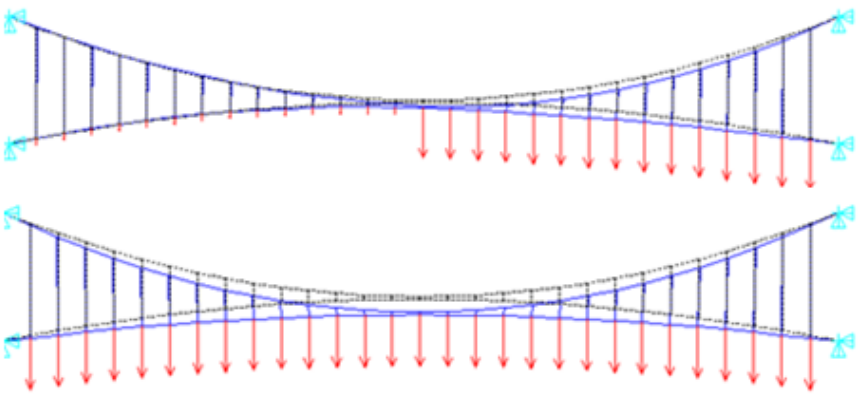
No significant difference

The best type:

4.3. Evaluation of rational parameters for structure from cross-laminated timber

Connect or not main and stabilisation cable?

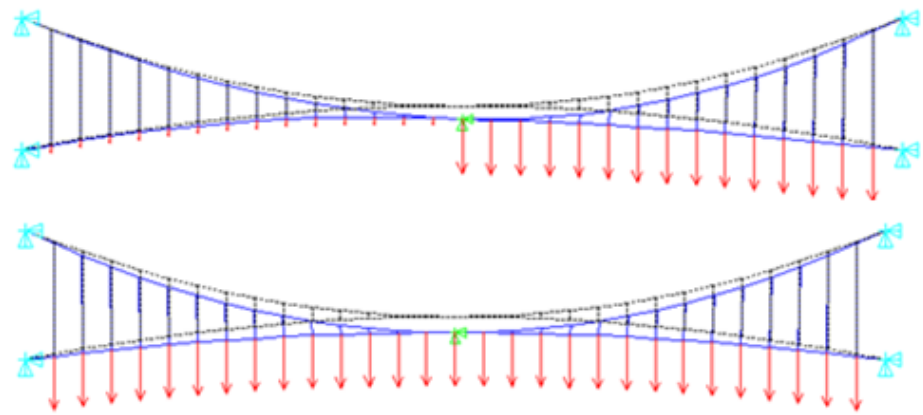
The distance between main and stabilisation cable: **0.2 m**



Displacements in case of half span loading:
w=0.586m or **1/102** L

Displacements in case of full span loading:
w=0.299m or 1/200 L

The distance between main and stabilisation cable: 0.0 m



Displacements in case of half span loading:
w=0.298m or **1/200** L

Displacements in case of full span loading:
w=0.299m or 1/200 L

Other parameters are the same, stresses in cables are below limits

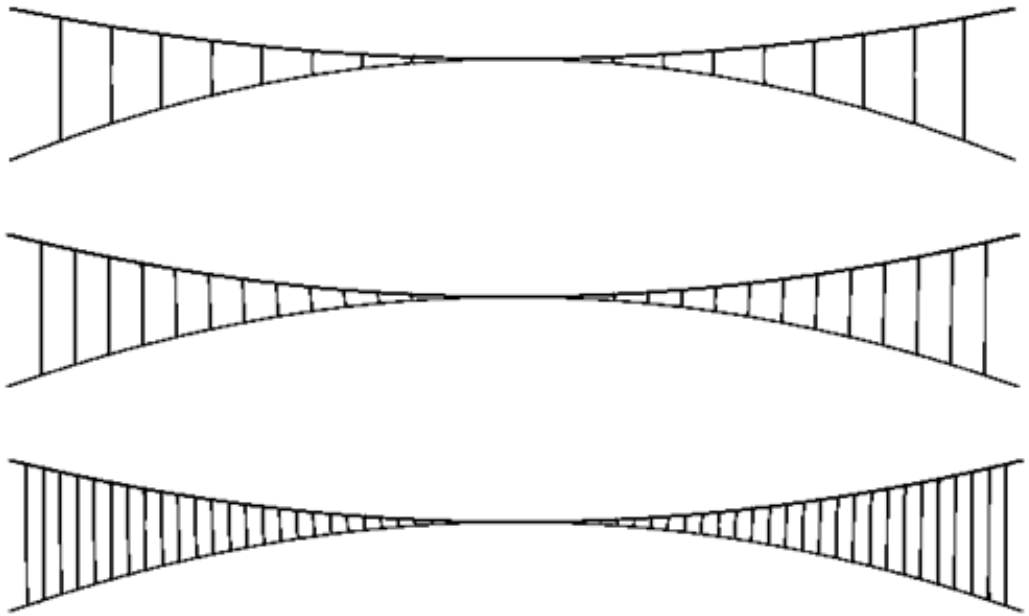
4.3. Evaluation of rational parameters for structure from cross-laminated timber

Step of suspenders?

s=3m

s=2m

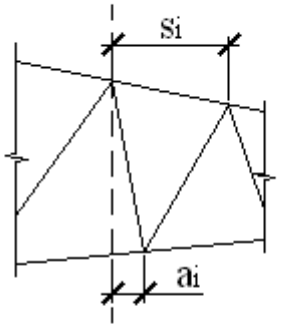
s=1m



No significant difference,
step 2m will be used

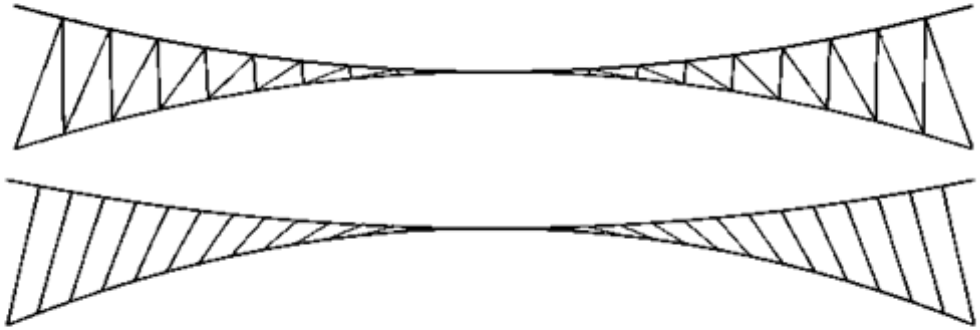
4.3. Evaluation of rational parameters for structure from cross-laminated timber

Types of web?



$a_i = b - c \cdot i$

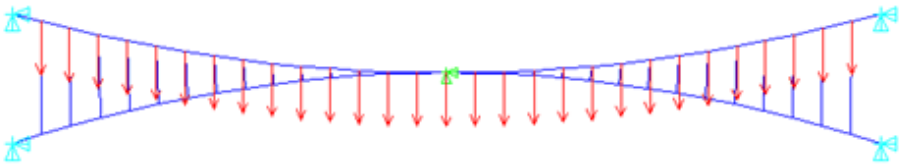
b and c found by optimisation

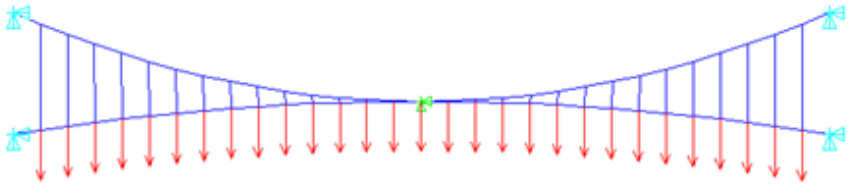


No significant difference,
vertical suspenders will be used as most simplest

4.3. Evaluation of rational parameters for structure from cross-laminated timber

Apply the load to main or stabilisation cable?





Weight of main and stabilisation cables and suspenders:

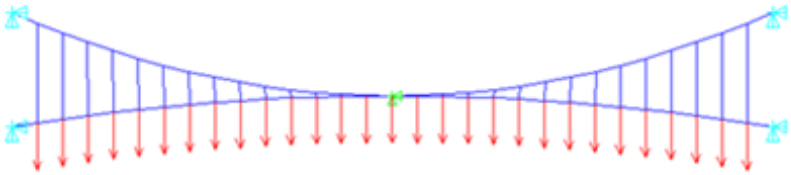
g = 2993 kg **g = 2432 kg**

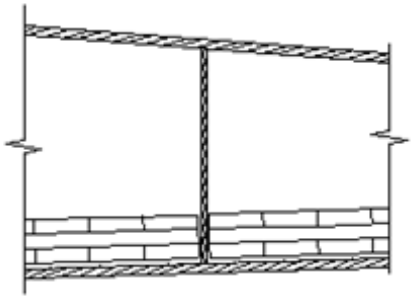
Difference in material consumption: 16.7 % or 23.1% depending on the structure compared with.

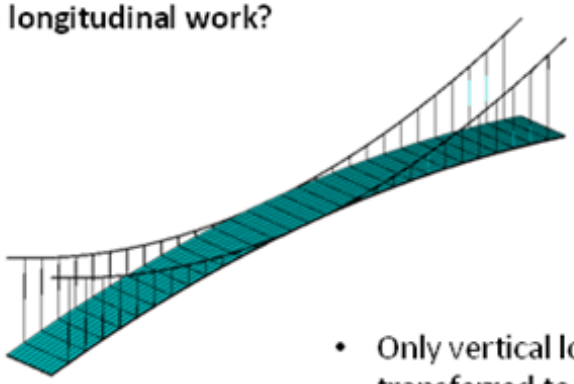
Both structures are optimized

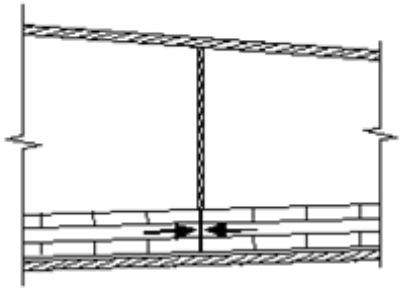
5. Development of load-bearing structure which consists from the main tensioned members and secondary cross-laminated timber members subjected to flexture

Include or not CLT deck to the longitudinal work?









- Only vertical loads are transferred to CLT.
- CLT is included to the work after prestressing is performed.
- CLT works as an arch, which could not loose stability due to cables.

Weight of main and stabilisation cables and suspenders:

g = 4864 kg

g = 4025 kg

Difference in material consumption: 17.3 % or 20.8% depending on the structure compared with.

Both structures are optimized, material consumption of CLT is the same.

Stresses and displacements are below the limit.

THANK YOU FOR YOUR ATTENTION

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Izglītības un zinātnes ministrija

imateh

Studiju un zinātnes administrācija