Compression perpendicular to the grain of Cross-Laminated Timber

Influence of support conditions of CLT on compressive strength and stiffness

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Abstract

Cross-Laminated Timber (CLT) has recently become a popular construction material for building timber structures. One advantage of CLT is, that it can be used as floor, beam and wall element. As the arrangements of layers in CLT is in perpendicular direction to each other, it exhibits remarkable strength properties in both in-plane directions. However, the low stiffness and strength properties in compression perpendicular to the grain hinder application of CLT in high rising building, since forces are usually transferred from the wall elements through floor elements perpendicular to the grain. Thus, the aim of this thesis is to get a thorough understanding of the mechanical properties of such connections for different setups, including wood-wood connections, connections with acoustic layers and connections with screws. In addition, the wall was placed at different positions on the CLT-floor element. Mechanical tests and numerical simulations, by means of finite element modelling (FEM) were carried out. CLT floor elements, consisting of 5-layers, were loaded by 3-layered CLT wall elements. Displacement and deformation were continuously measured by Potentiometers/LVDTs and an optical measurement system, respectively. Based on the experimental results compressive strength, slip curve and stiffness of the CLT connections were evaluated. Subsequently, results from FE-modelling were compared with experimental findings, which show a good agreement in elastic stiffness. Experimental results exhibited a pronounced influence of the wall position and connection setup on strength and stiffness. Central position of the wall showed higher mechanical properties than edge position. Highest strength and stiffness were found for screwed connections, where the wood-wood connections showed similar results. Connections with acoustic layers exhibited the lowest mechanical properties.

Keywords: Cross-Laminated Timber (CLT), connections, experiments, digital image correlation, slip curve, stiffness, compressive strength, finite element simulation.
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1. Introduction

1.1 Background

Wood is one of the renewable resources, which have a long history as building material used around the world. However, in the last few decades, population increased rapidly worldwide. To fulfil the demand on space for residential use and working place, skyscraper using concrete and steel showed to be the favoured way of building. However, increased environmental awareness and new developments of engineered wood-based products, like cross-laminated timber (CLT), made building with wood again attractive.

In traditional wooden structures, logs were used as beams and columns made of the whole trunk without bark. In this case, higher length and diameter of each log is required, which means the short and thin trunk could not be used in structures. One of the aims of making wood products is to reduce the limitation of size in logs and improve the utilization of timber. In modern wooden structures, wood products such as glued-laminated timber (glulam) boards are glued together to increase the cross-section and finger joints are used to have longer spans.

CLT is a symmetric wood composite, produced by gluing of odd number layers, consisting of wooden boards. Symmetry requires same wood species, grain direction and the thickness in symmetry layers. CLT is made in orthogonal way, which means that it exhibits a 90º angle in fibre direction between adjacent layers.

Wood is an anisotropy material, which means that the modulus of elasticity, strength and Poisson’s ratio are different in the different material directions. Depending on the wood species, the value of modulus of elasticity in grain direction is 10 to 25 times higher than that value perpendicular to the grain. In addition, strength in longitudinal direction could be 2 to 30 times higher than strength in radial and tangential direction [1].

Screws are quite often used for connections and reinforcement purposes in timber structure. Screws are used to carry compressive, tensile and shear forces. In addition, screws minimize the negative effects caused by the defects in wood, such as knots, pitch pockets and seasoning checks [2].

Development of glulam and structural timber in wooden building is mature now. This is proven by availability of regulations in formal standards such as EN 1991-1-1 (Eurocode5) [3]. Designers are able to plan and to build a
wooden construction made of structural timber or glulam. In contrast, regulations for CLT are still under development. The design standard of CLT building is still in the process of establishing.

In early 1990s, Austria and Germany were the first countries that invented and used CLT. After mid-1990s, researchers had completed a series of intensive experiments at Graz University of Technology [4]. In 2014, CLT was the first time incorporated into the European product standard and passed the formal vote of EN 16351[5].

1.2 Problem description

Using the traditional platform building system for CLT-buildings has the drawback of load transfer perpendicular to the grain in the floor element, when transferring loads between wall elements of two storeys. Thus, comparable large deformations are caused by the soft behaviour of wood in compression perpendicular to the grain, which limits the height of buildings made of CLT. In Figure 1, a schematic illustration of such a wall-floor connection is shown, where compression force from the top wall element load the floor element perpendicular to the grain in compression, which
consequently loads the lower wall element via contact forces perpendicular to the grain.

Recently, researchers have done some experiments about compression perpendicular to grain. However, compared to the test setup used herein, steel bars were used to introduce compression forces perpendicular to the grain of CLT elements [6].

In wooden structure, it is quite common to use self-tapping screws for connections, transferring shear or tensile forces, as well as for compressive reinforcement of wood-wood connections. Thus, the situation of screws in the contact area is studied as well

1.3 Aim and purpose

Aim:

The aim of this thesis is to identify the mechanical properties of CLT in case of compressive loading perpendicular to the grain, studying the local deformation behaviour and its effects on stiffness and strength. The experiments will focus on different types of support conditions between walls and floors, to analysis the difference of their mechanical behaviour among different support conditions.

Purpose:

The current design standard for timber structures is missing sufficient regulations of such connections, especially about their deformation behaviour. The purpose of this thesis is to find out how loads are transferred perpendicular to the grain for these different support conditions, and how they take influence on the global mechanical behaviour of the CLT connection. Based on the result, the purpose of this experiment is contributing to a thorough understanding of the forces transferring perpendicular to fibre direction, which can help to set up a standard for engineering design and to improve engineering design models

1.4 Hypothesis and limitations

Hypothesis of different support conditions:
Compression strength of central loading will perform better than eccentric loading. Support condition will influence the load-deformation behaviour of the connection, i.e., stiffness and strength of the connection. Connection with screws will perform better than the other support conditions.

Optical measurement system, based on digital image correlation technique (DIC) gives the displacement during testing. However, surface strains can be calculated by post-processing of displacement data. Some limitations will be caused by the unknown deformation, i.e., strains, and thus stresses at the inside of the connections since DIC gives only access to strains on the specimen surface.

Limitations further include, the moisture content, experimental conditions, like geometry of the test set up, homogeneity of the specimen, sample size etc.

1.5 Reliability, validity and objectivity

In this thesis, experiment and numerical investigation have been used during the process. During the process of experiment, each type of specimen was tested five times, which guaranteed the reliability of the result. Stiffness and strength results are based on regulations given by the current version of the product standard for CLT, which refers the product standard (EN 408) of glulam [7]. All specimens used in this experiment regime were produced by the same company and same species, to reduce variation in experimental results. The moisture content is also an important variable in test on CLT. Thus, all specimens were stored inside a climate room at standard climatic conditions to have the same level of moisture content at the time of testing, to make the result objectively.
2. Literature Review

Since cross-laminated timber (CLT) has been created and used in wooden structures, researchers keep on learning its mechanical behaviour, which helps the designer to satisfy both the safety requirement and its utilization. For glued-laminated timber (glulam), Hoffmeyer [8] concluded that the average compression strength shows no difference between glulam and structural timber. Moreover, researchers did a number of tests in much different density and different gauge length of glulam, the results showed that these variables do not correlate with compression strength. In structural timber and glued-laminated timber, the compression strength is within the range of 2.0 to 4.0 N/mm$^2$ and the mean value of compression strength for both are 2.9 N/mm$^2$, which were tested based on EN1193 [9].

Serrano and Enquist [6] carried out experimental tests about compression strength of CLT perpendicular to grain direction. During their study, different type of loads (line load and surface load), different position of the line load (in the middle of surface and at the edge of surface) and different orientation of line loads (parallel and perpendicular to the surface grain direction) were tested. The conclusion was that the compression strength perpendicular to fibre direction in cross laminated timber is highly influenced by the loading type. CLT performed much better when it is bearing the line load. Moreover, the result showed that line load applied on the edge got lower compression strength, expressed as nominal stress, than that of the line load applied on central position. In addition, the highest compression strength data was collected by CLT tested in the central loading position of line load oriented perpendicular to the surface layer’s grain direction.

Brandner [10] reviewed and studied CLT in compression perpendicular to plane. He focused on the stress dispersion in directions parallel and perpendicular to grain. He studied the influence of (i) contact area, (ii) loading configurations, (iii) support conditions, (iv) lay-up and thickness of the CLT element, and (v) clear edge distances and clear spacing, on stiffness and strength perpendicular to the grain. For the study he considered different load configurations as case (A): uniformly loaded throughout the surface of the prism for calculating basic properties; case (B) & (C): point loads at the end and in the interior parts of on continuously supported beams; case (D) & (E): aligned point loads and point supports at the end and in the interior parts of beams; case (F): load transmission in case of different contact area, case (G) & (H): point loads/supports on beams. According to this study, the main influencing parameters are moisture content, annual ring orientation (compressive stiffness $E_{c,90}$ in radial direction is double of the stiffness in
tangential direction and lowest value is at 45° angle), specimen geometry and load bearing area. In case of uniformly loaded over the entire surface, the influence on specimen depth on basic compressive strength perpendicular to grain is negligible. From this study he suggested a specimen dimension of $L \times w \times d = 150 \times 150 \times 150 \text{ mm}$ but not greater than $L \times w = 300 \times 300 \text{ mm}$. This corresponds to a five-layer CLT element with layer thicknesses of 30 mm and reference lamination width of 150 mm. For the basic properties of CLT, loaded in compression perpendicular to grain at reference moisture content of 12%, the characteristic strength $f_{c,90,12,P,k}$ as 3.0 N/mm² and $E_{c,90,12,P,mean}$ as 400 N/mm² were proposed.

Brandner and Schickhofer [11] analysed tests of CLT compression perpendicular to grain, motivated by the need for the adequate characteristic properties and design procedures. Tests were conducted on point and line loaded conditions with continuously supported CLT elements. The study focused mainly on three factors such as (i) the dependency on the dimension of the contact area $A_c$, (ii) the difference between CLT as floor elements clamped between two columns versus one column on a continuously supported floor, (iii) on the influence of moisture. All findings were based on Ciampitti [12]. All tests were conducted on industrially produced five-layer CLT elements made of Norway spruce with a total thickness of 160 mm where each layer has thickness as 40, 20, 40, 20, 40 mm, respectively (from top to bottom). Tests were done using thick steel plates for loading with area $100 \times 100 \text{ mm}$, $150 \times 150 \text{ mm}$ and $200 \times 200 \text{ mm}$ for point-loads (columns) and $100 \times 400 \text{ mm}$ and $150 \times 400 \text{ mm}$ for line loads (walls). Load was introduced at centre, corner, and edge position, parallel and perpendicular to the grain of top layer. Three sub-samples were conditioned to equilibrium average moisture contents of 8.8%, 12.7% and 15.3%. The conclusion of the tests about moisture content was, that for $f_{c,90}$ and $E_{c,90}$ a correction factor of 4% and 1% per 1% change in moisture content, respectively, can be used. For full surface loaded condition, an increase in strength and stiffness with increase in surface area was found, whereas the opposite was seen in individual loaded condition. The paper confirmed the discussion in the current regulation of EN 408 [7] concerning the shift of tangent E-modulus by 1% strain for calculation of $f_{c,90}$.

Bogensperger et al. [13] conducted a study on properties of CLT panels exposed to compression perpendicular to their plane. Stiffness and strength of cubic CLT was tested in accordance with EN 408 [7]. The mean value of modulus perpendicular to plane and characteristic strength value perpendicular to the plane were evaluated and compared with that of glulam. For the design and verification, they suggested values for $k_{c,90}$, by considering tests for different loading situations like central, longitudinal
edge, crosswise edge and vertex load introduction. Here a CLT specimen with characteristic strength 2.85 N/mm² was chosen for the tests. Based on the conducted tests, a characteristic strength value for CLT with \( f_{c,90,k} = 2.85 \text{ N/mm}^2 \) was proposed. In Table 1, the \( k_{c,90} \) value of 1.9 can be used for central loading and 1.4 for all non-central load positions. In Table 1, the value of \( k_{c,90} \) depend only on geometric parameters like height and load introduction area.

Table 1. \( f_{c,90} \) and \( k_{c,90} \) values of different loading position [13].

<table>
<thead>
<tr>
<th>Loading</th>
<th>No. of tests</th>
<th>( f_{c,90} )</th>
<th>( k_{c,90} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>15</td>
<td>2.85 N/mm²</td>
<td>1.8</td>
</tr>
<tr>
<td>Longitudinal edge</td>
<td>10</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Crosswise edge</td>
<td>10</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Vertex</td>
<td>15</td>
<td></td>
<td>1.4</td>
</tr>
</tbody>
</table>

Van der Put [14] derived a design model for bearing strength perpendicular to the grain for locally loaded timber blocks. He used the equilibrium method of plasticity as theory. The design model is explained in detail in Section 3.5.

Hesen Kathum Hasuni et al. [15] studied experimentally the compressive strength perpendicular to grain in CLT. In addition, theoretical analysis of the problem was done by means of a finite element model using the commercial finite element software (ABAQUS). Specimens with three layered CLT of dimensions 200×200×120 mm and 300×300×120 mm were chosen. The specimens were compressed between stiff steel plates. In total four deformation gauges were placed in each corner and a 5th gauge was used to read the load signal. Furthermore, a contact free deformation measurement system was applied to analyse the deformation. Experiments were done with different orientation of the line load in relation to the fibre direction of the top layer of CLT. One was aligned parallel to the fibre direction of the top CLT plane, and the other perpendicular to it. Test results showed that CLT specimens compressed with line load perpendicular to the surface fibre direction have higher values of compression strength than those with a line load parallel to the surface fibre direction. It was found that CLT
will develop cracks at the layers which were oriented with grain parallel to line load.
3. Theory

Timber is an inhomogeneous, orthotropic material. Thus, mechanical properties depend among others on the material direction, wood species, moisture content and deviation of annual rings. Thus, experiments of each group should be repeated several times, in order to ensure reliability of experimental results.

3.1 Hooke’s law

Hooke’s law is used to explain the relationship between stresses and strains; it means that there is linear relation between stresses and strains.

The constitutive equation reads as:

\[ \sigma_{ij} = C_{ijkl} \varepsilon_{kl}, \]  

(1)

This gives the relationship between the stress tensor \( \sigma_{ij} \) and the strain tensor \( \varepsilon_{kl} \) through the stiffness tensor \( C_{ijkl} \). The inverse of the stiffness tensor is the so-called compliance tensor \( S_{ijkl} \), which gives:

\[ \varepsilon_{ij} = S_{ijkl} \sigma_{kl}. \]  

(2)

In wood mechanics following notation is commonly used,

1. longitudinal direction (l),
2. radial direction (r),
3. tangential direction (t).

Considering orthotropic material behavior and wood mechanics notations, the constitutive equation (Eq. (2)) can be written as:

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\gamma_{12} \\
\gamma_{13} \\
\gamma_{23}
\end{bmatrix} =
\begin{bmatrix}
1/E_l & -\nu_{rl}/E_r & -\nu_{tl}/E_t & 0 & 0 & 0 \\
-\nu_{rl}/E_r & 1/E_r & -\nu_{tr}/E_t & 0 & 0 & 0 \\
-\nu_{tl}/E_t & -\nu_{tr}/E_t & 1/E_l & 0 & 0 & 0 \\
0 & 0 & 0 & 1/G_{lr} & 0 & 0 \\
0 & 0 & 0 & 0 & 1/G_{lt} & 0 \\
0 & 0 & 0 & 0 & 0 & 1/G_{rt}
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{13} \\
\sigma_{23}
\end{bmatrix},
\]

(3)

if the Voigt notation convention for the stresses and strains is used. \( E_i \) is the elastic modulus along axis \( i \). \( G_{ij} \) is the shear modulus in direction \( j \) on the
plane whose normal in direction \( i \). \( \nu_{ij} \) is the Poisson’s ratio that corresponds to a contraction in direction \( j \) when an extension is applied in direction \( i \).

As it can be seen from Eq. (3), that there are six Poisson’s ratio for orthotropic materials, but three of them are linked with the modulus of elasticity. Thus, only three of them are independent.

\[-\nu_{ij} = \varepsilon_{ii} / \varepsilon_{jj}.\]  

(4)

For numerical simulation, transversely isotropic material behavior is assumed. Thus, the same values in radial (\( r \)) and tangential (\( t \)) material direction are used. Consequently, Hooke’s law for transversely isotropic material reduces to

\[
\begin{bmatrix}
\varepsilon_{ll} \\
\varepsilon_{rr} \\
\varepsilon_{tt} \\
\gamma_{lt} \\
\gamma_{rt} \\
\gamma_{rr}
\end{bmatrix}
= 
\begin{bmatrix}
1/E_l & -\nu_{rl}/E_r & -\nu_{rt}/E_r & 0 & 0 & 0 \\
-\nu_{rl}/E_l & 1/E_r & -\nu_{rt}/E_r & 0 & 0 & 0 \\
-\nu_{rt}/E_l & -\nu_{rt}/E_r & 1/E_r & 0 & 0 & 0 \\
0 & 0 & 0 & 1/G_{lr} & 0 & 0 \\
0 & 0 & 0 & 0 & 1/G_{tr} & 0 \\
0 & 0 & 0 & 0 & 0 & 2 + 2\nu_{rr}/E_r
\end{bmatrix}
\begin{bmatrix}
\sigma_{ll} \\
\sigma_{rr} \\
\sigma_{tt} \\
\sigma_{lr} \\
\sigma_{rt} \\
\sigma_{rr}
\end{bmatrix}
\]

(5)

### 3.2 Local stresses and stress dispersion

When the force is applied perpendicular to the fibre direction, see Figure 2, there are angles among the applied compression loading and local material direction of the single layer of annual rings, which causes compression and shear forces in the local material coordinate system.

As per Blass and Sandhaas [16], locally multi-axial stresses will be evoked when an external force is applied at an angle to the grain. This is a reason of the anisotropic behaviour of wood. In Figure 2 it can be seen that the compression force acted at an angle \( \alpha \) to the grain leads to normal stresses parallel and perpendicular to grain (\( \sigma_{\text{parallel}} \) and \( \sigma_{\text{perp}} \) respectively) and shear stress \( \tau \).
Neglecting the contribution of shear stresses, $F_v = \tau = 0$, considering only normal stresses, gives local stresses as result of external loading at an angle to the grain as indicated in Figure 3.

According to trigonometry,

\[
\sin \alpha = \frac{F_{c,90}}{F_{c,\alpha}}, \quad (6)
\]

\[
\cos \alpha = \frac{F_{c,0}}{F_{c,\alpha}}. \quad (7)
\]
So that

\[ F_{c,\alpha} = \frac{F_{c,90}}{\sin \alpha} . \] (8)

\[ F_{c,\alpha} = \frac{F_{c,0}}{\cos \alpha} . \] (9)

Forces from Eq. (8) and (9) can convert into stresses, resulting in

\[ \sigma_{c,0} = \frac{F_{c,0}}{(b \cdot q)} = \frac{F_{c,0} \cdot \cos \alpha}{b \cdot h} , \] (10)

\[ F_{c,0} = \frac{(\sigma_{c,90} \cdot b \cdot h)}{\sin \alpha} , \] (11)

\[ \sigma_{c,\alpha} = \frac{F_{c,\alpha}}{(b \cdot h)} , \] (12)

\[ \sigma_{c,\alpha} = \frac{F_{c,0}}{b \cdot h \cdot \cos \alpha} \] and

\[ \sigma_{c,90} = \frac{F_{c,90}}{b \cdot h \cdot \sin \alpha} . \] (14)

For the assumption of linear interaction between stresses parallel and perpendicular to the grain, while the contribution of shear is neglected, following failure criterion can be used,

\[ \frac{\sigma_{c,0}}{f_{c,0}} + \frac{\sigma_{c,90}}{f_{c,90}} = 1 . \] (15)

Substitute Eq. (10) in Eq. (13):

\[ \sigma_{c,\alpha} = \frac{\sigma_{c,0}}{\cos^2 \alpha} , \] (16)

\[ \sigma_{c,0} = \sigma_{c,\alpha} \cdot \cos^2 \alpha . \] (17)

Putting Eq. (11) in Eq. (14):

\[ \sigma_{c,\alpha} = \frac{\sigma_{c,90}}{\sin^2 \alpha} . \] (18)

\[ \sigma_{c,90} = \sigma_{c,\alpha} \cdot \sin^2 \alpha . \] (19)

Use Eq. (17) and Eq. (19) in Eq. (15), which gives:

\[ \frac{(f_{c,\alpha} \cdot \cos^2 \alpha)}{f_{c,0}} + \frac{(f_{c,\alpha} \cdot \sin^2 \alpha)}{f_{c,90}} = 1 \] (20)

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where \( \sigma_{c, \alpha} = f_{c, \alpha} \).

by solving the above equation, \( f_{c, \alpha} \) can be obtained:

\[
f_{c, \alpha} = \frac{f_{c, 0} - f_{c, 90}}{f_{c, 0, \sin^2 \alpha} + f_{c, 90, \cos^2 \alpha}}.
\]  (21)

The Eq. (21) is called Hankinson equation [17].

\[\text{Figure 4. Stress-grain angle curve of Hankinson formula (similar to Figure D1-5(b) in book “Timber Engineering principles for design” [16]).}\]

Figure 4 shows exemplary the curve of Hankinson curve for compression stress of structural timber (spruce). Hankinson formula can be used to compute the allowable stress in compression of wood loaded at varying angles to grain using Eq. (21).

In longitudinal fibre direction, compression loading will be dispersed parallel to the grain by the wood fibres. This effect is called rope effect. In the case of small strain around 5%, a 45º degree angle for stress dispersion will show up when compression goes perpendicular to the grain. The angle is even larger when specimen is suffering large strains, which is 1:1.5 (56.3º) [4].

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The mechanical behaviour differs with the direction of line load. The strength is higher when the line load is applied perpendicular to the surface grain directions, compared to line load orientation parallel to the surface fibre direction. This is because compression will cause tension in fibre of surface layer, the tensile strength of fibre helps suffering the force and resist the deformation (load distribution effect). On the other hand, when the line load acts parallel to the grain, compressive stresses occur in radial or tangential direction, and additional shear stresses are evoked. Both of them have much lower stiffness and strength compared to the tensile behaviour in fibre direction, see Figure 6 and 7.

Figure 5. Cross-section of timber.

Figure 6. Line load perpendicular to surface grain direction.

Figure 7. Line load parallel to surface grain direction.
3.3 Models to predict the compressive strength perpendicular to the grain

Van der Put [14] found out that the slip curves from experiments can be described by an analytical function with one variable. Therefore, a curve in power law form, with a value of the power of 0.5 was used. As per the theory, the local compression strength perpendicular to the grain may increase due to confined dilatation perpendicular to the loading direction and the increase of strength is proportional to the square root of the length of the plate, \( L \), over the length of the load introduction, \( s \). The compression strength perpendicular to the grain of a locally loaded bearing block increases with a factor \( k_c \). For 1% strain cases the value of \( k_c \) varies from 1.53 to 1.94 (for height of timber element \( h = 200 \) mm) and 1.82 to 2.56 (for \( h = 480 \) mm). In the case of higher strains, \( k_c \) value varies from 1.73 to 2.24 (for \( h = 200 \) mm) and 2.41 to 2.56 (for \( h = 480 \) mm). In local failure mechanism the value of \( k_c \) is 6.23. From Eurocode5 we know that 

\[
\sigma_{c,90,d} \leq k_{c,90} \times f_{c,90,d}
\]

where \( \sigma_{c,90,d} \) is the compressive strength perpendicular to the grain, \( k_{c,90} \) can be find out as the square root of \( L \) over \( s \).

For the bearing strength of a middle section of a beam between two plates of lengths \( L \) and \( s \), \( k_{c,90} \) is calculated as follows [14]

\[
k_{c,90} = 1.1 \sqrt{0.5 + \left(\frac{3H+L}{2s}\right)} \leq 5,
\]

where, 

- \( s \) the length of load introduction,
- \( H \) the height of swell,
- \( L \) the length of plate.

Based on experiments on continuously supported linear members loaded by varying contact area applied at different positions, Madsen [18] derived a model as:

\[
F_{c,90,ult} = C_1 l_c w_c + C_2 l_c + C_3 w_c,
\]

where \( F_{c,90,ult} \) is the ultimate load bearing capacity in compression perpendicular to the grain. \( C_1, C_2 \) and \( C_3 \) are model coefficients. \( C_1 \) is the resistance of timber against uniform compression. \( C_2 \) is the resistance offered by the adjacent unloaded component used for load transfer in direction perpendicular to grain. \( C_3 \) is the resistance offered by the adjacent unloaded component used for load transfer in direction parallel to grain.
Blaß and Görlacher [19] reduced the model of Madsen [18] to:

\[ F_{c,90,ad_t} = C_1 w_c \left( l_c + \frac{c_2}{C_1} \right), \]  

(24)

where \( l_c \) is the contact length and \( w_c \) is the contact width. They suggest to use \( k_{c,90} = 1.00 \) for ULS and \( k_{c,90} > 1.00 \) for SLS design, respectively.

Another stress dispersion model, suggested by Riberholt [20] as:

\[ f_{c,90,LC} = k_{c,90} f_{c,90,p}, \]  

(25)

with \( k_{c,90} = \left( 2.38 - \frac{l_c}{250} \right) \sqrt{(l_{c,ef}/l_c)} \leq 4.00 \) and \( d \leq 2.5 \).

Brandner [10] suggested an equation for the ULS design for CLT as follows:

\[ \sigma_{c,90,d} = \frac{F_{c,90,d}}{A_c} \leq f_{c,90,p,d} k_{c,90}, \]  

(26)

where \( k_{c,90} = \sqrt{\frac{A_{c,ef}}{A_c}} = \sqrt{\frac{l_{c,ef} w_{c,ef}}{l_c w_c}} \leq 5 \), with

- \( \sigma_{c,90,d} \) the design compression stress perpendicular to grain,
- \( F_{c,90,d} \) the design compression load perpendicular to grain,
- \( f_{c,90,p,d} \) the design compression strength perpendicular to the grain.

### 3.4 Digital Image Correlation (DIC), Potentiometers and LVDTs

An optical measurement system, based on digital image correlation (DIC), from the manufacturer GOM GmbH by means of the ARAMIS system is used in the experimental process. DIC system has a stereoscopic sensor, it can focus on a specific pixel in the image plane of each object point. Meanwhile, the image parameter and orientation of the sensors are known, which can be used to calculate the position of each object point in three dimensions. Thus, displacements on material surfaces can be followed during deformation of the specimen caused by external loading. Subsequently, surface strains can be calculated by post-processing [21].

A potentiometer is an electric instrument to measure the EMF (electromotive force) of a given cell, i.e. the internal resistance of a cell. One of the most important applications of potentiometer is measurement of displacement. To measure the displacement of the movable body, it should
connect to the sliding element located in the potentiometer. When the body moves, position of slider also changes as well as the resistance between the fixed point and slider. This results in voltage change of that point. Change in voltage is proportional to the change in displacement of the body. Here in this thesis, there are mainly four potentiometers used to find out deformations of different points [22].

Linear variable differential transformer (LVDT) uses the principle of mutual induction. LVDTs consist of cylindrical iron cores as former which is surrounded by one primary winding in the centre of the former and the two secondary windings at the sides. The number of turns in both the secondary windings are equal, but their direction is opposite to each other. When an external force or displacement, respectively, is applied and the iron core moves to one side, it will induce an EMF difference in those secondary windings. Thus, one non-electrical energy is converting into electrical energy. The main advantage of LVDT is it gives high sensitivity. But the performance of the transducer gets affected by vibrations, temperature and magnetic field, so it should be shielded. In the experiments, there were two LVDTs used for calculating deformation between the floor and wall elements [23].

3.5 Calculation of compression strength and stiffness perpendicular to grain

The nominal compressive strength is calculated by

$$f = \frac{F}{wd}$$

where \( F \) is the total force, and \( wd \) is the contact area.

The compression strength perpendicular to the grain, \( F_{c,90} \) can be calculate by following the procedure given by EN408 [7]. Base on the estimated compression strength, \( F_{c,90,est} \) stress points at 40% and 10% of \( F_{c,90,est} \) are calculated on the load-deformation curve. Consequently, a straight line connecting those two points is drawn. Thereafter, a second straight line parallel to the first one going through the point \((0.01L, 0)\), where \( L \) is the total height of the specimen is determined (see Figure 8). The value of \( F_{c,90,cal} \) will be the compression strength at the intersection of second straight line with the slip curve. The compression strength \( F_{c,90} \) is found if \( F_{c,90,cal} \) is within the range of \( \pm 5\% \) of the \( F_{c,90,est} \). Otherwise the procedure with an updated \( F_{c,90,est} \) value has to be repeated, until the tolerance requirement is fulfilled. The compression strength, \( f_{c,90} \) is expressed as nominal stress and is determined as follows

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\[ f_{c,90} = \frac{F_{c90,est}}{w d}. \]  

(28)

**Figure 8. Schematic Load-deformation curve for calculating \( F_{c,90} \).**

In Figure 8, \( L \) is the thickness of the specimen.

In addition, to the strength definition of EN408, compressive strength was calculated by moving the slope from strength calculation according to EN408 by 0.05\( L \) and 0.1\( L \) as well, to make a comparison.

The stiffness by means of the modulus of elasticity perpendicular to the grain. In this thesis, the stiffness of loading, reloading, the first unloading and the second unloading were calculated. Loading and reloading stiffness were calculated according to the standard (EN 408) [7]

\[ E_{c,90} = \frac{(F_{40}-F_{10})L}{(w_{40}-w_{10})bl}, \]  

(29)

where,

- \( F_{40} \) \( \) 40% of the \( F_{c,90} \)
- \( F_{10} \) 10% of the \( F_{c,90} \)
- \( w_{40} \) displacement corresponding to \( F_{40} \)
- \( w_{10} \) displacement corresponding to \( F_{10} \)
- \( L \) height of the member (here, \( L = 140 \) mm)
- \( bl \) area of contact (here, \( b = 350 \) mm and \( l = 80 \) mm)
The speed of the unloading process was quite fast, which means there were only few points in the data. Thus, the first and the seconding unloading stiffness were calculated by the first point which had a significant force decrease to the next point, using the slope between this first point and 20% force decrease from the first point. The displacement of 20% decrease point is calculated by the displacement of two nearest points using linear interpolation.

3.6 Density calculation

The density of the test specimens is calculated as follows

$$\rho = \frac{m}{V},$$  \hspace{1cm} (30)

where $m$ is the mass in specimens and $V$ is the volume of specimens.
4. Methods

4.1 Experimental test

4.1.1 Loading protocol, load and deformation measurement

The experimental part was completed in the laboratory of Linnaeus University, Växjö. Compression load was applied displacement controlled to the upper edge of wall element through metal plate. The load capacity of this hydraulic testing machine in compression is 300 kN. The load frame of the testing machine provides a free opening width of 1300 mm and a height of 4050 mm.

The loading speed is controlled manually by regulation of the flow of hydraulic oil, by opening and closing a valve. This makes loading with a predefined speed challenging.

In Table 2, it shows the approximated points when the unloading sequence was initiated. The first unloading sequence was applied at half of the estimated elastic connection strength. The second unloading phase was started as a displacement of roughly 13 mm (see Table 2).

<table>
<thead>
<tr>
<th>conditions</th>
<th>Unloading 1 (kN)</th>
<th>Unloading 2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood-wood-ecc</td>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td>Wood-wood-cen</td>
<td>70</td>
<td>8.5</td>
</tr>
<tr>
<td>Acoustic-ecc</td>
<td>65</td>
<td>13</td>
</tr>
<tr>
<td>Acoustic-cen</td>
<td>80</td>
<td>12</td>
</tr>
<tr>
<td>Screws-ecc</td>
<td>65</td>
<td>13</td>
</tr>
<tr>
<td>Screws-cen</td>
<td>75</td>
<td>12</td>
</tr>
</tbody>
</table>

Two steel plates, one from bottom and one from top, provide the loading to test specimen. Accurate positioning of the CLT wall elements on the CLT floor element is of highest importance, in order to avoid geometric
imperfections of the test setup. Based on the relative displacement between top and bottom wall element, in combination with force data from the testing machine, slip curves from connection tests can be determined. From these slip curves connection stiffness and strength can be calculated.

When compression was applied to the specimens, there may have been inclination of the floor element at the beginning or some cracks happened during the tests. Thus, the point of unloading process could be changed during the tests according to the actual situation.

For measuring relative displacements between the top and bottom wall element, LVDT’s and potentiometers were used. In addition, surface deformations, giving access to surface strains were measured by means of a DIC-system (ARAMIS, GOM GmbH).

The load cells of the testing machine directly recorded the reaction forces. The deformation of the wall and floor elements was measured by a non-contact displacement measurement system, based on Digital Image Correlation (DIC). Two digital cameras having 12mpx resolution were used for recording three-dimensional displacement field of the specimen surface. For the clear focussing, after applying a white base coating a fine speckle pattern was sprayed with black on each of the surfaces, i.e. both wall elements and floor element. The field of view for the DIC was chosen to approximately 600×450 mm, which means that the width of each pixel was roughly 0.15 mm. A facet size of 19 px together with a grid spacing of 15 px gave approximately 2.25 mm distance between the measurement points.

![Figure 9. Test setup including DIC measurement system (ARAMIS).](image-url)
For the data of potentiometers and LVDTs, signal one received the data of the recorded reaction force from the load cell and signal two to seven received the data of potentiometers and LVDTs. There were four potentiometers and two LVDTs used during the tests. The measuring length of potentiometers Pot-100-01 and Pot-100-02 are up to 100 mm. Pot-50-05 and Pot-50-06 are up to 50 mm, and the measurement range for LVDT-5 and LVDT-6 are from 0 to 40 mm. Potentiometers and LVDTs were mounted on wall elements and touched the steel plates which were mounted on floor elements or the other wall elements. When compression showed up, the moveable part of potentiometers and LVDTs would be pressed back and the computer would record the data of movement at the same time.

4.1.2 Evaluation methods

Calculation of nominal compression stress and strains

The loading and deformation details obtained from the potentiometers and LVDTs connected in different position of sample and load cell. Using those deformations, it is possible to find out the mean deformation. Contact area of each specimen calculated already. Using the loading and contact area, nominal stress at corresponding time can be calculated as below.

\[ \sigma = \frac{P}{A}, \]  
\[ (31) \]

where \( P \) is the reaction force caused by displacement loading and \( A \) is the contact area.

When dividing the value of displacement with actual depth (here it was 140 mm) the compressive strain can be calculated. Using strain and nominal stress, slip curves of each experimental set-up can be created.

\[ \varepsilon = \frac{\Delta l}{L}, \]  
\[ (32) \]

where \( \Delta l \) is the relative deformation between upper and lower wall-element, and \( L \) is the initial thickness of the floor element.

The stress-strain curve can be used to find out the structural load ability of materials. The linear portion in a stress-strain curve shows the elastic region. Stress-strain curves give access to the stiffness of the connection depending on the loading. Displacements are measured with LVDT’s and potentiometers, respectively. While information on the reaction force, as a consequence of displacement loading, is taken as force of the load cell of the testing machine. By using force data, it is possible to find out stress by
dividing load with the contact area of the specimen (see Eq. (31)). Strain is the ratio of the measured deformation to the height of the floor element (see Eq. (32)).

4.1.3 Test setups

Based on the set up of experimental test, three different support conditions and different loading position between wall and floor elements were considered. The width was 350 mm for all specimens. Additionally, the length of floor element was around 735 mm for eccentric loading, for wood-wood eccentric loading, the length of floor elements was around 370 mm, and there were some cracks. For eccentric loading for acoustic layer and screws, the length of floor elements was around 435 mm.

Figure 10 shows a schematic sketch of the CLT floor element made by C24 structural timber with 5 layers. The thickness was 40 mm for the outer layers, and 20 mm for the inner layers. Depending on different position of contact area, the length of floor element was different.

![Figure 10. Schematic sketch of the floor element.](image)

The wall element (see Figure 11) was 80 mm in thickness and build-up by three layers. CLT elements were provided by Stora Enso and cut to the desired dimension at the laboratory workshop. It was made by 20 mm thickness in outer layers, and 40 mm thickness in the inner layers. The dimension of cross-section area was 80 × 350 mm.

![Figure 11. Schematic sketch of the wall element.](image)
Figure 12 shows the two different loading positions considered in this work, namely eccentric and centric.

For experimental preparation, the dimensions of specimens were measured for determination of the density. Next step was sanding process, using P120 sanding paper. After sanding, white spray paint was used to cover the whole camera facing surfaces. Then using black spray was created the so-called speckle pattern, consisting of random points above the white layer. ARAMIS system can record the movement of these black random points, which gives access to surface displacements, and thus to surface strains.

When the floor element and wall elements were mounted, it was made sure that the central line of two wall elements and steel plates were on the same line to avoid initial geometric imperfections.

Different support conditions and different loading positions are explained in the following.
**Wood-wood contact**

**Wood-wood contact - eccentric loaded (Series A)**

Wood-wood connection is one of the support conditions. Wall element and floor element get in touch directly without the help of any gluing material or screws as shown in Figure 13.

In this support condition, an LVDT was mounted on the left side of top wall element and the other one was on the right side of bottom wall element. Meanwhile, four potentiometers were mounted on both sides of bottom and top wall elements which will touch the steel plate mounted on the back side of floor element.

![Figure 13. Position of LVDTs and potentiometers (wood-wood, eccentric).](image)

**Wood-wood contact - centric loaded (Series B)**

For centric loading, the position of LVDT and potential meters were the same as for eccentric loading of wood-wood contact, but the steel plate for LVDT on the top wall element moves from the side of floor element to the top surface of floor element as in Figure 14.
Acoustic layer contact

Connection with acoustic layers, eccentric loaded (Series C)

Acoustic layers were set between wall element and floor element without gluing. In this case, from the front view, two potentiometers were mounted on the left side of top wall element and touch the steel plate on the bottom wall element. Two LVDTs were mounted on the right side of each wall element which touches the steel plate that was mounted on the surfaces of floor element. When it goes to the back side, two potentiometers were mounted together on the back surface of top wall element and touch the steel plate mounting on the bottom wall element as in Figure 15.

Figure 14. Position of LVDTs and potentiometers (wood-wood, centric).

Figure 15. Position of LVDTs and potentiometers (acoustic layer, eccentric).
**Connection with acoustic layers, centric loaded (Series D)**

Figure 16 shows the position of screws, LVDTs and potentiometers. On the front side, two LVDTs on the lower position mounting on each side of bottom wall element. Meanwhile, two potentiometers were mounted on each side of top wall element. On the back side, the rest of two potentiometers were mounted on the top wall element and touching the steel plate mounting on the bottom wall element.

![Figure 16. Position of LVDTs and potentiometers (acoustic layer, centric).](image)

**Screws contact**

The position of potentiometers and LVDTs in support condition with screws is the same as that in acoustic layer condition.

**Connection with screws, eccentric loaded (Series E)**

Screws put through floor element perpendicular to the grain, one end at the top surface of wall element and one end at the bottom wall element as in Figure 17.
Connection with screws, centric loaded (Series F)

Figure 18 shows the position of potentiometers and LVDTs in screws centric condition.

When combining all support conditions, six groups were tested.

Screws and acoustic layer used were supplied by the company named Rothoblaas. Dimension of fully-threaded VGS screws were 9 mm in outer diameter, and 320 mm in length. The inner diameter of the screws amounted to 5.9 mm. Meanwhile, the diameter of the head is 15 mm. The value of the modulus of elasticity and Poisson’s ratio are not mentioned in the data file.

Acoustic layer was 100 mm in width with mechanical properties, 19 N/mm$^2$ for the modulus of elasticity and 6.5 N/mm$^2$ for the shear modulus.
In this experimental test, every set-up was tested five times each and thus, in total 30 tests were conducted.

Table 3. Details of groups/setups.

<table>
<thead>
<tr>
<th>Series</th>
<th>Width of wall (mm)</th>
<th>Length of wall (mm)</th>
<th>Length of floor (mm)</th>
<th>Support condition (number)</th>
<th>Loading type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>80</td>
<td>350</td>
<td>365</td>
<td>Wood-wood</td>
<td>Eccentric</td>
</tr>
<tr>
<td>B</td>
<td>80</td>
<td>350</td>
<td>735</td>
<td>Wood-wood</td>
<td>Centric</td>
</tr>
<tr>
<td>C</td>
<td>80</td>
<td>350</td>
<td>488</td>
<td>Acoustic layer</td>
<td>Eccentric</td>
</tr>
<tr>
<td>D</td>
<td>80</td>
<td>350</td>
<td>735</td>
<td>Acoustic layer</td>
<td>Centric</td>
</tr>
<tr>
<td>E</td>
<td>80</td>
<td>350</td>
<td>488</td>
<td>Screws (2)</td>
<td>Eccentric</td>
</tr>
<tr>
<td>F</td>
<td>80</td>
<td>350</td>
<td>735</td>
<td>Screws (2 or 3)</td>
<td>Centric</td>
</tr>
</tbody>
</table>

4.2 FEM modeling

Commercial software ABAQUS CAE 2017 was used for studying the load-deformation behavior perpendicular to the grain of CLT, for the different experimental connection setups.

First, the parts of the model were created, including two steel plates; two wall elements and one floor element. In the modeling, the length of floor element was assumed to be equal to 750 mm for both, centric and eccentric loading.

An orthotropic material model was used, which was applied to each partition, considering the fibre orientation, using engineering constants of linear elastic material. Values are given in Table 4.
Table 4: Values of the elastic constants of C24.

<table>
<thead>
<tr>
<th>Property notation</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_L$ ($E_1$)</td>
<td>11500</td>
<td>N/mm$^2$</td>
</tr>
<tr>
<td>$E_R$ ($E_2$)</td>
<td>300</td>
<td>N/mm$^2$</td>
</tr>
<tr>
<td>$E_T$ ($E_3$)</td>
<td>300</td>
<td>N/mm$^2$</td>
</tr>
<tr>
<td>$G_{LR}$ ($G_{12}$)</td>
<td>650</td>
<td>N/mm$^2$</td>
</tr>
<tr>
<td>$G_{LT}$ ($G_{13}$)</td>
<td>650</td>
<td>N/mm$^2$</td>
</tr>
<tr>
<td>$G_{RT}$ ($G_{23}$)</td>
<td>60</td>
<td>N/mm$^2$</td>
</tr>
<tr>
<td>$\nu_{LR}$ ($\gamma_{12}$)</td>
<td>0.00849</td>
<td></td>
</tr>
<tr>
<td>$\nu_{LT}$ ($\gamma_{13}$)</td>
<td>0.00849</td>
<td></td>
</tr>
<tr>
<td>$\nu_{RT}$ ($\gamma_{23}$)</td>
<td>0.538</td>
<td></td>
</tr>
</tbody>
</table>

The values in Table 4 were taken from: Bader et al.: “Numerical modeling of the load distribution in multiple fastener joints” [24]. And herein the values of article took it from EN 14080:2013 [25].

Figure 19. FEM model (wood-wood centric connection).
In the part of steel plate, linear elastic, isotropic material behavior with 210000 N/mm² for Young’s Modulus and 0.3 for Poisson’s Ratio was used.

In reality, the grain of timber may have curves and an angle to the longitudinal axis. Furthermore, radial face may have divergent. In the modeling process, the model assumed idealized conditions. Transversal isotropic material was assumed for the single layers of the CLT, which means the same mechanical properties were used for radial and tangential direction.

For wood-wood contact, surface-to-surface contact is used as definition of the connection among each element. In both contact of wood-wood and steel-wood, hard contact of normal behavior is used. Friction coefficient was assumed to be 0.4 and 0.3 for wood-wood and steel-wood contact, respectively. In addition, a small sliding and hard contact was set to restrict the movement between contact surfaces. Small sliding means the rotation and relative sliding between contact surface.

For support condition with acoustic layer, the length of acoustic layer was 80 mm, width was 350 mm and thickness 6 mm. For the mechanical properties of screws the same material behavior i.e., a Young’s Modulus of 210000 N/mm² and Poisson’s Ratio of 0.3, as for the steel plate was chosen. Meanwhile, the friction coefficient between wood and acoustic layer was assumed to be 0.3. Hard contact between wood and acoustic layer was applied.

![Figure 20. FEM model (eccentric connection with acoustic layers).](image)
For support condition with screws, based on the wood-wood contact model, holes in floor element and bottom wall element were created by using the function “create cut”. The length of screws is 320 mm and the inner diameter of screw body is 5.9 mm, which means that the hole should go through the floor element and the depth of the holes on the bottom wall element is 180 mm. Here, *tie constraint* is used as the contact definition between screws and bottom wall element. But no contact properties are defined between the head of the screws and floor element. Moreover, the distance from the center of the holes to the front and back edges is 115 mm, and the distance between two holes is 120 mm. Figure 21 shows the model of screws condition.

![FEM model (eccentric connection with screws).](image)

An initial boundary condition is set on the bottom surface of lower steel plate, which is constrained all directions (X, Y and Z). Then, create step 1, and make a boundary condition for loading on the top surface of upper steel plate which moves 1 mm downward.

The final step is going to job and start calculating and analyzing.
5. Results

The aim of this thesis is to study mechanical properties of CLT connections, causing load transfer perpendicular to the grain for different support conditions. Thus, experiments as well as numerical simulations, by means of finite element modeling (ABAQUS) were carried out.

In this part, the results from both parts of experimental test and finite element modeling are presented. As mentioned before, there are three different support conditions and two loading positions. Thus, combination of those gives, six setups, which are considered in this thesis. For each setup five tests were carried out. The stress-strain graphs for all tests are based on the data from the load cell of the mechanical testing machine, and potentiometers and LVDTs, respectively. Deformation illustrations, by means of surface strain plots were collected from DIC-measurement (ARAMIS), are shown for one representative experiment for each test setup. Finally, experimental results are compared with numerical simulations (ABAQUS).

Before testing, CLT specimens were stored under constant climate conditions (20°C and 65% Relative Humidity) inside a climate room. Prior to testing, every specimen was measured of their dimensions and weight for calculating density.

5.1 Laboratory results

Five specimens were tested of each setup. Stress-strain graphs are shown for each test in Figure 22 to 27. Furthermore, Table 5, 7, 9, 11, 13 and 15 show results from calculation of density ($\rho$), compression strength ($f_{c,90}$) and modulus of elasticity ($E_{c,90}$), including their mean value and standard deviation. In addition, Table 6, 8, 10, 12, 14 and 16 summarize stiffness properties expressed by the loading, reloading stiffness as well as the stiffness at unloading part 1 and 2.
5.1.1 Series A  (wood-wood contact, eccentric)

Table 5 shows the density, compression strength and elastic modulus of each specimen of wood to wood, eccentric condition. In addition, the mean values as well. Elastic Modulus of this table is the value of the first loading process. The mean density of five tests is 469 kg/m³, 3.97 N/mm² for the compression strength and 377 N/mm² for Elastic Modulus.

Figure 22 shows the strain-stress curves of each test based on the measured data from the load cell and potentiometers/LVDTs, respectively. For illustration purposes, unloading-reloading phases are removed from measured data. In this type of connection, maximum load was found to be 174.4 kN (test A5), which is equal to a nominal stress of 6.23 N/mm². This load was reached at a displacement of 20.4 mm. The corresponding strain was 0.0402.

In Table 6 the elastic modulus for loading, reloading and both unloading sequences is shown.

Table 5. Values of the density, compression strength and stiffness acc.to EN 408 of Series A specimens.

<table>
<thead>
<tr>
<th>No.</th>
<th>Density of floor $\rho$ (kg/m³)</th>
<th>Compression strength $f_{c,90}$ (N/mm²)</th>
<th>Modulus of elasticity $E_{c,90}$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>464</td>
<td>3.47</td>
<td>355</td>
</tr>
<tr>
<td>A2</td>
<td>476</td>
<td>3.75</td>
<td>314</td>
</tr>
<tr>
<td>A3</td>
<td>469</td>
<td>3.99</td>
<td>366</td>
</tr>
<tr>
<td>A4</td>
<td>471</td>
<td>4.33</td>
<td>453</td>
</tr>
<tr>
<td>A5</td>
<td>468</td>
<td>4.31</td>
<td>395</td>
</tr>
<tr>
<td>Mean value</td>
<td>469</td>
<td>3.97</td>
<td>377</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>4.39</td>
<td>0.371</td>
<td>51.66</td>
</tr>
</tbody>
</table>
Table 6. Elastic Modulus in different process of each test for Series A.

<table>
<thead>
<tr>
<th>Number</th>
<th>Loading (N/mm²)</th>
<th>Unloading 1 (N/mm²)</th>
<th>Unloading 2 (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>355</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>A2</td>
<td>314</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>A3</td>
<td>366</td>
<td>366</td>
<td>460</td>
</tr>
<tr>
<td>A4</td>
<td>453</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>A5</td>
<td>395</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Mean value</td>
<td>377</td>
<td>366</td>
<td>460</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>51.66</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Figure 22. Stress-strain diagram for Series A.
5.1.2 Series B (wood-wood contact, centric)

Table 7 shows the density, compression strength and elastic modulus of each specimen of wood to wood, centric condition. In addition, the mean values as well. Elastic Modulus of this table is the value of the first loading process. The average density of five tests is 469 kg/m$^3$, 4.73 N/mm$^2$ for the compression strength and 517 N/mm$^2$ for Elastic Modulus.

Figure 23 shows the strain-stress curves of each test based on the measured data from the load cell and potentiometers/LVDTs, respectively. For illustration purposes, unloading-reloading phases are removed from measured data. In this type of connection, maximum load was found to be 238.07 kN (test B3), which is equal to a nominal stress of 8.5 N/mm$^2$. This load was reached at a displacement of 19.6 mm. The corresponding strain was 0.139.

In Table 8 the elastic modulus for loading, reloading and both unloading sequences is shown.

Table 7. Values of the density, compression strength and stiffness acc.to EN 408 of Series B specimens.

<table>
<thead>
<tr>
<th>No.</th>
<th>Density of floor ρ (kg/m$^3$)</th>
<th>Compression strength $f_{c,90}$ (N/mm$^2$)</th>
<th>Modulus of elasticity $E_{c,90}$ (N/mm$^2$)</th>
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</thead>
<tbody>
<tr>
<td>B1</td>
<td>458</td>
<td>4.08</td>
<td>471</td>
</tr>
<tr>
<td>B2</td>
<td>468</td>
<td>4.73</td>
<td>596</td>
</tr>
<tr>
<td>B3</td>
<td>476</td>
<td>4.84</td>
<td>519</td>
</tr>
<tr>
<td>B4</td>
<td>478</td>
<td>5.29</td>
<td>475</td>
</tr>
<tr>
<td>B5</td>
<td>464</td>
<td>4.72</td>
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<td>4.75</td>
<td>508</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>8.32</td>
<td>0.433</td>
<td>53.00</td>
</tr>
</tbody>
</table>
Table 8. Elastic Modulus in different process of each test for Series B.

<table>
<thead>
<tr>
<th>Elastic Modulus Number</th>
<th>Loading  (N/mm$^2$)</th>
<th>Reloading (N/mm$^2$)</th>
<th>Unloading 1 (N/mm$^2$)</th>
<th>Unloading 2 (N/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>471</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>B2</td>
<td>596</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>B3</td>
<td>519</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>B4</td>
<td>475</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>B5</td>
<td>478</td>
<td>522</td>
<td>573</td>
<td>557</td>
</tr>
<tr>
<td>Mean value</td>
<td>508</td>
<td>522</td>
<td>573</td>
<td>557</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>52.97</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
5.1.3 Series C (acoustic layer, eccentric)

Table 8 shows the density, compression strength and elastic modulus of each specimen of acoustic, eccentric condition. In addition, the mean values as well. Elastic Modulus of this table is the value of the first loading process. The average density of five tests is 480 kg/m³, 3.46 N/mm² for the compression strength and 192 N/mm² for Elastic Modulus.

Figure 24 shows the strain-stress curves of each test based on the measured data from the load cell and potentiometers/LVDTs, respectively. For illustration purposes, unloading-reloading phases are removed from measured data. In this type of connection, maximum load was found to be 166.36 kN (test C3), which is equal to a nominal stress of 5.94 N/mm². This load was reached at a displacement of 29.03 mm. The corresponding strain was 0.207.

In Table 10 the elastic modulus for loading, reloading and both unloading sequences is shown.

Table 9. Values of the density, compression strength and stiffness acc.to EN 408 of Series C specimens.

<table>
<thead>
<tr>
<th>No.</th>
<th>Values</th>
<th>Density of floor $\rho$ (kg/m³)</th>
<th>Compression strength $f_{c,90}$ (N/mm²)</th>
<th>Modulus of elasticity $E_{c,90}$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td></td>
<td>450</td>
<td>3.25</td>
<td>154</td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td>484</td>
<td>3.51</td>
<td>200</td>
</tr>
<tr>
<td>C3</td>
<td></td>
<td>487</td>
<td>3.72</td>
<td>207</td>
</tr>
<tr>
<td>C4</td>
<td></td>
<td>487</td>
<td>3.40</td>
<td>178</td>
</tr>
<tr>
<td>C5</td>
<td></td>
<td>490</td>
<td>3.40</td>
<td>219</td>
</tr>
<tr>
<td>Mean value</td>
<td>480</td>
<td>3.46</td>
<td>192</td>
<td></td>
</tr>
<tr>
<td>Std Deviation</td>
<td>16.68</td>
<td>0.172</td>
<td>25.52</td>
<td></td>
</tr>
</tbody>
</table>

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Table 10. Elastic Modulus in different process of each test for Series C.

<table>
<thead>
<tr>
<th>Elastic Modulus Number</th>
<th>Loading (N/mm$^2$)</th>
<th>Reloading (N/mm$^2$)</th>
<th>Unloading 1 (N/mm$^2$)</th>
<th>Unloading 2 (N/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>154</td>
<td>161</td>
<td>192</td>
<td>198</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>221</td>
<td>271</td>
<td>273</td>
</tr>
<tr>
<td>3</td>
<td>207</td>
<td>225</td>
<td>229</td>
<td>257</td>
</tr>
<tr>
<td>4</td>
<td>178</td>
<td>193</td>
<td>264</td>
<td>247</td>
</tr>
<tr>
<td>5</td>
<td>219</td>
<td>230</td>
<td>237</td>
<td>274</td>
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<tr>
<td>Mean value</td>
<td>192</td>
<td>206</td>
<td>239</td>
<td>250</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>25.52</td>
<td>29.02</td>
<td>31.47</td>
<td>31.09</td>
</tr>
</tbody>
</table>

Figure 24. Stress-strain diagram for Series C.
5.1.4 Series D (acoustic layer, centric)

Table 10 shows the density, compression strength and elastic modulus of each specimen of acoustic, centric condition. In addition, the mean values as well. Elastic Modulus of this table is the value of the first loading process. The average density of five tests is 455 kg/m³, 4.15 N/mm² for the compression strength and 269 N/mm² for Elastic Modulus.

Figure 25 shows the strain-stress curves of each test based on the measured data from the load cell and potentiometers/LVDTs, respectively. For illustration purposes, unloading-reloading phases are removed from measured data. In this type of connection, maximum load was found to be 233.63 kN (test D4), which is equal to a nominal stress of 8.34 N/mm². This load was reached at a displacement of 33.04 mm. The corresponding strain was 0.236.

In Table 12 the elastic modulus for loading, reloading and both unloading sequences is shown.

Table 11. Values of the density, compression strength and stiffness acc.to EN 408 of Series D specimens.

<table>
<thead>
<tr>
<th>No.</th>
<th>Values</th>
<th>Density of floor $\rho$ (kg/m³)</th>
<th>Compression strength $f_{c,90}$ (N/mm²)</th>
<th>Modulus of elasticity $E_{c,90}$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>454</td>
<td>4.04</td>
<td>308</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>451</td>
<td>3.98</td>
<td>258</td>
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<tr>
<td>D3</td>
<td>460</td>
<td>4.29</td>
<td>257</td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>444</td>
<td>4.23</td>
<td>261</td>
<td></td>
</tr>
<tr>
<td>D5</td>
<td>466</td>
<td>4.23</td>
<td>262</td>
<td></td>
</tr>
<tr>
<td>Mean value</td>
<td>455</td>
<td>4.15</td>
<td>269</td>
<td></td>
</tr>
<tr>
<td>Std Deviation</td>
<td>8.43</td>
<td>0.134</td>
<td>21.79</td>
<td></td>
</tr>
</tbody>
</table>
Figure 25. Stress-strain diagram for Series D.

Table 12. Elastic Modulus in different process of each test for Series D.

<table>
<thead>
<tr>
<th>Elastic Modulus Number</th>
<th>Loading (N/mm²)</th>
<th>Reloading (N/mm²)</th>
<th>Unloading 1 (N/mm²)</th>
<th>Unloading 2 (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>308</td>
<td>316</td>
<td>368</td>
<td>390</td>
</tr>
<tr>
<td>2</td>
<td>258</td>
<td>283</td>
<td>357</td>
<td>389</td>
</tr>
<tr>
<td>3</td>
<td>257</td>
<td>274</td>
<td>349</td>
<td>372</td>
</tr>
<tr>
<td>4</td>
<td>261</td>
<td>285</td>
<td>338</td>
<td>366</td>
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<tr>
<td>5</td>
<td>262</td>
<td>270</td>
<td>371</td>
<td>409</td>
</tr>
<tr>
<td>Mean value</td>
<td>269</td>
<td>286</td>
<td>357</td>
<td>385</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>21.79</td>
<td>18.09</td>
<td>13.61</td>
<td>16.93</td>
</tr>
</tbody>
</table>
5.1.5 Series E (screws, eccentric)

Table 12 shows the density, compression strength and elastic modulus of each specimen of screw, eccentric condition. In addition, the mean values as well. Elastic Modulus of this table is the value of the first loading process. The average density of five tests is 460 kg/m³, 4.07 N/mm² for the compression strength and 206 N/mm² for Elastic Modulus.

Figure 26 shows the strain-stress curves of each test based on the measured data from the load cell and potentiometers/LVDTs, respectively. For illustration purposes, unloading-reloading phases are removed from measured data. In this type of connection, maximum load was found to be 202.69 kN (test E4), which is equal to a nominal stress of 7.24 N/mm². This load was reached at a displacement of 44.01 mm. The corresponding strain was 0.314.

In Table 14 the elastic modulus for loading, reloading and both unloading sequences is shown.

Table 13. Values of the density, compression strength and stiffness acc.to EN 408 of Series E specimens.

<table>
<thead>
<tr>
<th>No.</th>
<th>Values</th>
<th>Density of floor $\rho$ (kg/m³)</th>
<th>Compression strength $f_{c,90}$ (N/mm²)</th>
<th>Modulus of elasticity $E_{c,90}$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td></td>
<td>468</td>
<td>3.97</td>
<td>223</td>
</tr>
<tr>
<td>E2</td>
<td></td>
<td>468</td>
<td>4.03</td>
<td>141</td>
</tr>
<tr>
<td>E3</td>
<td></td>
<td>454</td>
<td>4.08</td>
<td>166</td>
</tr>
<tr>
<td>E4</td>
<td></td>
<td>464</td>
<td>4.30</td>
<td>263</td>
</tr>
<tr>
<td>E5</td>
<td></td>
<td>458</td>
<td>3.95</td>
<td>239</td>
</tr>
<tr>
<td>Mean value</td>
<td>460</td>
<td>4.07</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>Std Deviation</td>
<td>6.23</td>
<td>0.142</td>
<td>51.20</td>
<td></td>
</tr>
</tbody>
</table>

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Figure 26. Stress-strain diagram for Series E.

Table 14. Elastic Modulus in different process of each test for Series E.

<table>
<thead>
<tr>
<th>Elastic Modulus Number</th>
<th>Loading (N/mm²)</th>
<th>Reloading (N/mm²)</th>
<th>Unloading 1 (N/mm²)</th>
<th>Unloading 2 (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>223</td>
<td>246</td>
<td>290</td>
<td>297</td>
</tr>
<tr>
<td>2</td>
<td>141</td>
<td>178</td>
<td>284</td>
<td>311</td>
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<td>3</td>
<td>166</td>
<td>220</td>
<td>299</td>
<td>319</td>
</tr>
<tr>
<td>4</td>
<td>263</td>
<td>300</td>
<td>368</td>
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<td>5</td>
<td>239</td>
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<td>Mean value</td>
<td>206</td>
<td>243</td>
<td>312</td>
<td>338</td>
</tr>
<tr>
<td>Std Deviation</td>
<td><strong>51.20</strong></td>
<td><strong>47.07</strong></td>
<td><strong>34.05</strong></td>
<td><strong>41.56</strong></td>
</tr>
</tbody>
</table>

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5.1.6 Series F (screws, centric)

Table 14 shows the density, compression strength and elastic modulus of each specimen of screw, centric condition. In addition, the mean values as well. Elastic Modulus of this table is the value of the first loading process. The average density of five tests is 462 kg/m³, 5.21 N/mm² for the compression strength and 372 N/mm² for Elastic Modulus.

Figure 27 shows the strain-stress curves of each test based on the measured data from the load cell and potentiometers/LVDTs, respectively. For illustration purposes, unloading-reloading phases are removed from measured data. In this type of connection, maximum load was found to be 218.75 kN (test F4), which is equal to a nominal stress of 7.81 N/mm². This load was reached at a displacement of 18.40 mm. The corresponding strain was 0.131.

In Table 16 the elastic modulus for loading, reloading and both unloading sequences is shown.

Table 15. Values of the density, compression strength and stiffness acc. to EN 408 of Series F specimens.

<table>
<thead>
<tr>
<th>No.</th>
<th>Density of floor ( \rho ) (kg/m³)</th>
<th>Compression strength ( f_{c,90} ) (N/mm²)</th>
<th>Modulus of elasticity ( E_{c,90} ) (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>452</td>
<td>5.43</td>
<td>200</td>
</tr>
<tr>
<td>F2</td>
<td>444</td>
<td>5.22</td>
<td>463</td>
</tr>
<tr>
<td>F3</td>
<td>459</td>
<td>5.22</td>
<td>424</td>
</tr>
<tr>
<td>F4</td>
<td>470</td>
<td>5.17</td>
<td>398</td>
</tr>
<tr>
<td>F5</td>
<td>475</td>
<td>4.98</td>
<td>376</td>
</tr>
<tr>
<td>Mean value</td>
<td>462</td>
<td>5.21</td>
<td>372</td>
</tr>
<tr>
<td>Std Deviation</td>
<td>12.71</td>
<td>0.116</td>
<td>101.64</td>
</tr>
</tbody>
</table>
Figure 27. Stress-strain diagram for Series F.

Table 16. Elastic Modulus in different process of each test for Series F.

<table>
<thead>
<tr>
<th>Elastic Modulus Number</th>
<th>Loading (N/mm$^2$)</th>
<th>Reloading (N/mm$^2$)</th>
<th>Unloading 1 (N/mm$^2$)</th>
<th>Unloading 2 (N/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>200</td>
<td>250</td>
<td>383</td>
<td>536</td>
</tr>
<tr>
<td>F2</td>
<td>463</td>
<td>510</td>
<td>538</td>
<td>595</td>
</tr>
<tr>
<td>F3</td>
<td>424</td>
<td>453</td>
<td>552</td>
<td>601</td>
</tr>
<tr>
<td>F4</td>
<td>398</td>
<td>447</td>
<td>541</td>
<td>565</td>
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<tr>
<td>F5</td>
<td>376</td>
<td>406</td>
<td>572</td>
<td>564</td>
</tr>
<tr>
<td><strong>Mean value</strong></td>
<td><strong>372</strong></td>
<td><strong>454</strong></td>
<td><strong>551</strong></td>
<td><strong>581</strong></td>
</tr>
<tr>
<td><strong>Std Deviation</strong></td>
<td><strong>101.64</strong></td>
<td><strong>42.88</strong></td>
<td><strong>15.39</strong></td>
<td><strong>19.50</strong></td>
</tr>
</tbody>
</table>

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5.2 DIC results

In this part, surface strain images from DIC-measurements are shown. The most meaningful test from Series A (wood-wood, eccentric) and Series B (wood-wood, centric) have been chosen for illustration purposes (see Figure 28 and 29, respectively). Surface strains, expressed as engineering strains, are shown for a displacement of approximately 3mm, which is equal to a strain of 0.0214 according to Eq. (32).

5.2.1 Series A (wood-wood contact, eccentric)

Strain images output by the A1 specimen

![Strain images output by the A1 specimen](image)

In Figure 28, picture a) ($\varepsilon_{xx}$), red colour shows in the second and fourth layer of floor element, which means there were some strains in x axis happen in those areas. In second and fourth layer of CLT floor element, the fibre direction is perpendicular to the loading. Meanwhile, there were some strains happen in the inner layer of wall elements. The highest strains were

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located in the second and the fourth layer of floor element with around 0.5% (0.005).

In picture b) ($\varepsilon_{yy}$) of Figure 28, compression strains along y axis can be seen in the contact area between floor element and wall elements, inner layers as well. The highest strains show up in the contact area between wall elements and floor element with around 4% (0.04).

Picture c) ($\varepsilon_{xy}$) shows the shear strains in Figure 28 and happen in the inner layers of floor element and the right-side corner of contact area. The highest strains were around 0.008% (0.00008).

### 5.2.2 Series B  (wood-wood contact, centric)

![Figure 29. Surface strains from DIC-measurements of Test B3; a) strains parallel to the grain orientation of the floor deck layer $\varepsilon_{xx}$; b) strains perpendicular to the floor deck layer $\varepsilon_{yy}$; c) shear strains $\varepsilon_{xy}$.](image)

In Figure 29, picture a) ($\varepsilon_{xx}$), red and yellow colour shows in the inner layer of wall elements, which means there were some strains in x axis happen in those areas. Meanwhile, there were some strains happen in the fourth layer of floor elements. The highest strains were located in the inner layer of wall elements with around 1.4% (0.014).
In picture b) ($\varepsilon_{yy}$) of Figure 29, compression strains along y axis can be seen in the outer layer of floor element, inner layers as well. The highest strains show up in the outer layers of floor element with around 5% (0.05).

Picture c) ($\varepsilon_{xy}$) shows the shear strains in Figure 29 and happen in the corner of contact area. The highest strains were around 0.01% (0.0001).

5.3 FEM modelling results

5.3.1 Series A  (wood-wood contact, eccentric)

In Figure 30, picture a) ($S_{11}$), red and yellow colours show in the inner layers of wall elements and the second and the fourth layer of floor element, which illustrate the strains in x axis. The highest strains happen in the second and the fourth layer of floor element.

In picture b) ($S_{22}$) of Figure 30, compression strains show up in the floor element. The highest strains happen in the outer layer and the third layer of floor element.
Picture c) (S12) shows the shear strains in Figure 30, and shear strains happen in the right-side corner of the contact area.

![Stress-strain diagram from FEM modelling for Series A.](image)

Figure 31 shows the stress-strain curve from FEM modelling of Series A. When the loading reached a displacement of equal to 3mm, which was 0.0215 in strain value, the $f_{c,90}$ value was 7.56 N/mm$^2$. $E_{c,90}$ value calculated by this point was 353 N/mm$^2$. 

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5.3.2 Series B (wood-wood contact, eccentric)

Figure 32. Surface strains from FEM modelling of Series B; a) strains parallel to the grain orientation of the floor deck layer $\varepsilon_{x1} (S_{11})$; b) strains perpendicular to the floor deck layer $\varepsilon_{y2} (S_{22})$; c) shear strains $\varepsilon_{xy} (S_{12})$.

In Figure 32, picture a) $(S_{11})$, strains show up in the outer layers of wall elements and the second and the fourth layer of floor element, which illustrate the strains in x axis. The highest strains happen in the second and the fourth layer of floor element.

In picture b) $(S_{22})$ of Figure 32, compression strains show up around the contact area. Meanwhile, the highest strains happen in the edge of contact area in the outer layer of floor element. The second and the fourth layers of floor element had small strains comparing with the other layer of floor element.

Picture c) $(S_{12})$ shows the shear strains in Figure 32, and shear strains happen around the corner of the contact area.
Figure 33 shows the stress-strain curve from FEM modelling of Series B. when the loading reached a displacement of equal to 3mm, which was 0.0215 in strain value, the $f_{c,90}$ value was 10.27 N/mm$^2$. $E_{c,90}$ value calculated by this point was 479 N/mm$^2$. 

Figure 33. Stress-strain diagram from FEM modelling for Series B.
6. Discussion

In the following, mechanical properties, i.e. stiffness and strength of CLT connections are compared between the different setups. Thus, the influence of the position of the wall element on the CLT floor, and the influence of additional acoustic layers and screws are discussed. Furthermore, the influence of different evaluation methods, closely related to the connection displacement are shown.

6.1 $E_{c,90}$ and $f_{c,90}$ values according to EN408

Compression tests perpendicular to the grain were performed by considering three different connections and two different loading conditions in each connection.

![Figure 34. Connection strength ($f_{c,90}$) for all tests.](image)

In Figure 34, the bar chart shows the connection strength $F_{c,90}$ determined according to EN408 (see Section 3.5). A comparable low variance of experimental findings gets obvious from Figure 34, which was less than 15% for all setups. The highest mean connection strength was found for the screwed setup with centric position of the wall element, which amounted to 5.43 N/mm², followed by wood-wood centric connection with a strength value of 5.29 N/mm² (-3%) and acoustic layer setup with 4.29 N/mm² (-21%) with centric positioning. Centric connection showed remarkable higher
connection strength than eccentric connections, which is a reason of the load distribution effect when located in the center of the floor element. In this case, larger areas of the CLT-floor element can be activated, and thus a higher strength can be generated. For eccentric connections, almost the same mean strength for wood-to-wood and screwed connections was found, with slightly higher values for the screwed connection. Eccentric setups including acoustic layers showed a strength being 15% lower than for screwed connections.

When comparing centric and eccentric setups, up to 28% higher strength values were found for the centric position with screws. Less pronounced was the effect for the wood-to-wood setup (+19.6%) and acoustic layer setup (+19.9%). The less pronounced difference between centric and eccentric position for connections with acoustic layers might be explained with the soft interlayer, which does not allow to activate the load distribution effect in centric connections in the same manner as for wood-to-wood connections at this deformation state.

In Figure 35, the bar chart shows the differences between each test in the same series of $E_{c,90}$ values. In case of screw centric connection, first test gave less value compared to other tests. In first test, three screws were used. It was observed that the contact area of wood was small and the distance between each screw was less than the minimum distance required, also
distance between edge and screws. Thus, from the second test onwards two screws were used.

In Table 17, the compression strength of screwed connection is higher than wood-to-wood connection. However, the stiffness of screwed connection is lower than that of wood-to-wood connection. The reason may be that screwed connection destroyed partly the structure of CLT when the screws were mounted. Cracking could easily happen in the weak part of CLT specimens while loading.

Table 17. Mean value of $p$, $F_{c,90}$ and $E_{c,90}$

<table>
<thead>
<tr>
<th>Type</th>
<th>Values</th>
<th>Density of floor $\rho$ (kg/m$^3$)</th>
<th>Compression strength $f_{c,90}$ (N/mm$^2$)</th>
<th>Modulus of elasticity $E_{c,90}$ (N/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>469</td>
<td>3.97</td>
<td>366</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>469</td>
<td>4.75</td>
<td>508</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>480</td>
<td>3.46</td>
<td>192</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>455</td>
<td>4.15</td>
<td>269</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>460</td>
<td>4.07</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>372</td>
<td>5.21</td>
<td>372</td>
<td></td>
</tr>
</tbody>
</table>

While considering the different loading conditions, central loading condition results in higher compressive strength than the eccentric one in all cases. The results are shown in Table 10. From the results it is clear that the modulus for the wood–wood centric connection was 10% higher than for connections with centric screws. It was unexpected and might be explained by following reasons:

1) When the screws were mounted, the head of screws were lower than the surface of floor element. In this case, due to the positioning of screws, it may reduce about 1.5% of contact area. This does however not fully explain the differences of 8.6% stiffness between wood-wood and screwed connections.

2) During first tests of wood-to-wood connections there were only two instead of four potentiometers/LVDTs at disposal. Thus, the accuracy of
displacement measurement, and consequently of the calculated stiffness could be questioned.

3) Testing speed influences the mechanical properties of wood as well. Since the loading speed had to be controlled manually, the loading speed might have varied from test to test, which could have taken influence on the stiffness properties as well.

6.2 Connection strength $f_{c,90}$ values for different deformation states

According to EN408 [7] the strength $f_{c,90}$ is defined by the intersection of the line with a slope of the line calculated by 40% and 10% of $f_{c,90}$, moved by a strain of 1% (1.4 mm). Herein we compare connection strength for larger displacement as well, i.e. at strains of 5% and 10%, which refers to displacements of 7 mm and 14 mm respectively. The results are illustrated in Figure 36 for eccentric and in Figure 37 for centric setups. Some of the tests were stopped in the earlier time and could not reach the point of 10% strains. Thus, the average values are calculated without the values from those tests, which were A2, A4 and B1.

![Figure 36. $f_{c,90}$ values of eccentric conditions in different strains.](image)

For eccentric loading, all setups showed pronounced displacement hardening. This gets obvious from Figure 36 when comparing strength values at a strain of 1%, 5% and 10%. Strength increased by up to 45% between calculation at
1% and 10% strain for the setup with acoustic layers. Wood-Wood and screwed connections showed an increase of 36% and 39%, respectively. The strongest increase for the setup with acoustic layers might be an indicator for a delayed activation of the load distribution effect in connections with acoustic layers. The strength of the screwed connection was always the highest, and the strength of the setup with acoustic layers always the lowest compared with the other setups, independent of the deformation state, i.e. of the strain at which the strength was calculated.

A similar behaviour was seen for centric connection layouts (see Figure 37). However, compared to eccentric layouts, wood-wood connections showed a more pronounced hardening, i.e., an increase of 63% compared to 41% for screwed connection. Thus, wood-wood connection reached a higher strength at a strain of 10% compared to screwed connections. This fact cannot be fully explained mechanically since it was not seen for eccentric connections, which indicates, that possible cracking of the wood matrix due to the inserted screws is unlikely. The screws seem to influence negatively the development of the load distribution effect. Connections with acoustic layers showed a hardening similar to wood-wood connections, i.e. an increase in strength of 61%.

![Figure 37. $F_{c,90}$ values of centric conditions in different strains.](image)

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6.3 Connection stiffness $E_{c,90}$ of different support conditions

In most of the tests, two loading processes were used, which means that the stiffness can be calculated for loading, reloading and unloading sequences. Herein, the connection stiffness of the loading, first reloading and first and second unloading part is presented and discussed. It should be mentioned, that for wood-wood connections only partly unloading reloading cycles were included.

In test F1, the uncertainty is in the size of the tested value. Thus, in Figure 38, the mean value of screw-centric-loading condition is not including test F1, which changed the mean value from 372 to 415 N/mm$^2$.

As mentioned before, wood-wood eccentric and centric condition had only one test of five with unloading process, where for the later only one unloading-reloading cycle was applied. Thus, for these setups no variation interval can be given for the bar plot showing the mean connection stiffness (see Figure 38). For screws and acoustic layer conditions, both centric and eccentric are using mean values in the graph. The black lines here are showing the range of five tests.

Figure 38. $E_{c,90}$ values for all series in different loading process.

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Comparing the values of different loading positions in the same support condition:

The Elastic Modulus was highly related to the position of contact area. In all of the three support conditions, $E_{c,90}$ value for centric one is much higher than that of eccentric with up to 100% difference. This can be explained by the load distribution effect, which is more pronounced in the centric setups. For compression at the centre position of specimens, continuous fibres in the surface on both sides, will resist the deformation, providing resistance. However, for eccentric condition, continuous fibres go only one side, the resistance of fibre is much lower.

Comparing the values of different process in the same support condition:

In Figure 38, in almost every condition, the stiffness of reloading process is up to 18% higher than value of loading process, while the unloading stiffness properties are the highest. The reason may be that, when the force is applied on the wood specimens, compression and deformation would occur. Thus, in the first loading path visco-elastic and plastic deformations are included beside elastic deformations, which causes a lower stiffness as compared to the unloading part, which represents the pure elastic response. As obvious from Figure 38, reloading stiffness was consistently higher than the loading stiffness, since local contact imprecisions are excluded when reloading.

Unloading stiffness turned out to be up to 8% higher for the second unloading sequence than for the first sequence (see Figure 38), except for the wood-wood centric condition. In Wood-wood centric connection, $E_{c,90}$ value for second unloading was less than the first unloading. It also occurred in a few single tests of other conditions. The decrease in stiffness between first and second unloading cycle might be explained by the reason that some cracks already appeared and some parts of the wood were already destroyed at the second unloading cycle. Furthermore, the speed of removing the loading was quite fast, LVDTs and potentiometers could not record a sufficient number of points at the beginning of unloading process. Meanwhile, Elastic Modulus decreased quickly during the unloading process. It is possible that the first unloading stiffness was calculated at the beginning of the process and the first data of the second unloading process missed the highest point. Thus, the stiffness value of the first unloading process is higher than that of the second unloading process.
**Comparing the values in the same process of different conditions:**

In loading, reloading and the first unloading process, the highest stiffness happens in the wood-wood connection and the lowest stiffness happens in the acoustic layer condition while the position of the contact area is the same. However, in the process of the second unloading, centric support condition with screws was stiffer than the other support conditions, which means also higher than in wood-wood connections. Except for this special case, it gets obvious from Figure 38, that connection stiffness shows the same trend between the setups, independent if loading, reloading or unloading stiffness is used. Furthermore, it can be seen from Figure 38, that the variation in the stiffness data is lowest for unloading stiffness.

**6.4 Comparison between DIC-measurements and FEM modelling**

When DIC-measurements and FEM modelling were compared, we can see that the strains in Figure 28 and Figure 30 were not coincide but similar, Figure 29 and Figure 32 as well. Some differences can be caused by the method using in FEM modelling where linear elastic material properties was used, but wood has both elastic and plastic properties. On the other hand, wood is not homogeneous material, there is difference between each specimen.

In this thesis, FEM modelling could be a reference when learning about strains in CLT specimen.

**6.5 comparison of stress-strain curves and $E_{c,90}$ between experimental tests and FEM modelling**

Stress-strain curves from FEM modelling are quite different to that from experimental tests. The curves from FEM modelling are linear and experimental curves are non-linear. However, comparing the $E_{c,90}$ between FEM modelling and experimental tests, in wood-wood eccentric condition, $E_{c,90}$ value is 353 N/mm² from FEM modelling which is 94% of that mean value (377 N/mm²) from experimental tests in the same support condition. In wood-wood eccentric condition, $E_{c,90}$ are 479 N/mm² from FEM modelling and 508 N/mm² from experimental tests (94%). Thus, the stiffness from FEM modelling and experimental tests are quite similar, (the stiffness values from experiments are given in Tables 7, 9,11,13,15 and 17).
7. Conclusion

From this study and previous articles, it is clear that compression strength perpendicular to grain is an important property in timber design. However, research on this topic for CLT was limited up to now. In this thesis, for the first time CLT wall elements were used for load introduction, to simulate real support conditions.

The study was about different connections and loading conditions. Including two loading conditions, i.e. a centric and eccentric position of the wall, and three different connections layouts, i.e., wood-to-wood contact, acoustic interlayers and screws in the contact area.

Experimental findings and numerical results showed a pronounced influence of both, the loading position and connection layout on the stiffness and strength of the connection. Strength and stiffness were found to be up to 32% and 70% higher in centric compared to eccentric position. This can be mainly explained by the load distribution effect, which is more pronounced when loaded at the centric position. In general, connections with screws in the contact area were found to give the highest connection stiffness and strength. Nevertheless, the layout with direct wood-to-wood contact gave similar values, only the layout with acoustic layers in the contact area gave up to 40% lower stiffness, and 20% lower strength.

A remarkable increase of connection strength got visible when evaluating the strength at large displacements. Displacement hardening up to 45% when comparing strength at 1% and 10% strain got visible for evaluation of connection strength at large displacements.

This study highlighted the sensitivity of the connection layout on its strength and stiffness. The latter is of highest importance for the structural analysis of CLT structures, when approaching the field of multi storeys buildings, since it significantly influences the global deformation behaviour of such structures. Thus, a deeper understanding of the mechanical behaviour of such CLT connections is of highest relevance for improvements in the design of future multi-storey CLT buildings.

Stiffness determined by FEM modelling was similar to DIC-measurements. Thus, FEM modelling can be considered as a verification of stiffness and strains to experimental tests.
References


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