Structural Performance and Load-Carrying Capacity of Cross Laminated Timber-Concrete Composite Slabs: Influence of Shear Fasteners

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Abstract. This presents an investigation of the structural performance and load-carrying capacity of cross-laminated timber (CLT)-concrete composite slabs, with a focus on the influence of different shear fasteners. As sustainable construction practices, timber-concrete composite systems offer a promising solution by combining the compressive strength of concrete with the tensile capacity of timber. Despite the growing use of CLT in multi-storey construction, limited research exists on its composite behaviour with concrete, particularly regarding shear connections. This study evaluates two types of shear fasteners, CTC and KOP screws, through medium-scale four-point bending tests on five layered CLT-concrete slabs. Experimental results, including load-deflection behaviour and failure scenarios, are compared with theoretical predictions based on the γ-method from Eurocode 5 and the shear analogy method. Findings show that slabs with CTC screws demonstrate higher load capacity but more conservative theoretical predictions, while KOP screw systems exhibit closer alignment between theoretical and experimental prediction. The degree of composite action is also evaluated, highlighting partial composite behaviour and the importance of fastener orientation and stiffness. These results underscore the need for improved design guidelines and further testing to refine predictive models for CLT-concrete composite structures.

Keywords: CLT-concrete composite slabs, shear fasteners, load testing, structural response

1 Introduction

Environmental impact is an increasing concern in structural design and is often considered in construction industry. Reinforced concrete, though widely used, poses environmental challenges due to limited raw materials, recycling issues, and high CO_2 emissions. In contrast, timber is a sustainable and renewable material, but its application in multi-storey buildings has been limited due to concerns about strength, vibration, and resistance to extreme conditions.

Timber-concrete composite (TCC) structures combine the benefits of both materials and recently started use widely in construction industry to overcome above mentioned issues. In TCC systems, timber and concrete are connected, typically with concrete on top in compression and timber below in tension, to act compositely and enhance structural performance [1]. Mechanical fasteners are used to connect the two elements and ensure composite action.

To date, most research on TCC structures has focused on traditional timber beams or columns with concrete slabs. Cross-laminated timber (CLT), a relatively recent innovation, offers high strength and stiffness and is increasingly used in structural applications [2]. However, limited research exists on CLT-concrete composite floor systems, particularly regarding their performance and design. Additionally, no standard guidelines currently exist, though some manufacturers have developed proprietary handbooks [2,3].

Eurocode 5 [4] provides guidelines for the theoretical prediction of 3-layer elements. Therefore, the application of these guidelines is limited to elements with no more than three layers. To extend their applicability, simplifications and modifications to the existing formulas have been made to predict the load-bearing capacity and maximum deflection. One simplified approach is to neglect all transverse layers, while another method involves modifying the cross-section and accounting for the shear deformation of both the transverse and longitudinal layers [3].

Timber is an anisotropic material, meaning its strength properties vary depending on the grain direction. This anisotropy influences the structural behaviour under loading conditions [5]. Additionally, flaws and other defects can reduce the load capacity and potentially cause premature structural failure.

The performance of shear fasteners, which join the two materials together, is crucial for composite structures [2,3]. While the goal is for the composite structure to behave as a single unit, in practice it often behaves as a partially composite system. Generalised guidelines for selecting optimal shear fasteners are lacking due to limited research in this area, and the performance of various types of shear fasteners has not been sufficiently compared. These research gaps form the primary motivation for this study.

To address these gaps to some extent, the main objective of this thesis is to investigate the load-bearing capacity and structural response of 5-layer CLT-concrete composite slabs using two different types of shear fasteners through medium-scale laboratory testing. As a secondary objective, the study evaluates the validity of the modified Eurocode formulas for theoretical predictions of such 5-layer composite slabs. The paper begins with material specifications and test sample preparation. This is followed by a detailed discussion of the laboratory testing program, including methods and results. Theoretical predictions of the structural behaviour of the tested samples are then presented. Finally, a comprehensive discussion and comparison of the experimental and theoretical results is provided.

2 Materials and Test Sample Preparation

This section begins with information on the materials used for the CLT–concrete composite slabs, followed by the specifications and preparation of the test slabs.

2.1 Cross-laminated timber

The CLT was a ready-to-use five-layer element, bonded with Melamine Urea Formaldehyde (MUF) adhesive [6]. In the cross section, layers 1, 3, and 5 consist of longitudinal lamellae, while layers 2 and 4 are transverse. The slabs, approved by SINTEF, were supplied by Splitkon [6].

The dimensions of CLT slabs are 2100 mm in length, 600 mm in width, and 120 mm in height. The outermost and middle lamellae are oriented parallel to the grain, while the second and fourth lamellae are perpendicular. This pattern is reversed in the longitudinal direction. The thickness of each outermost lamella is 30 mm, and the middle lamella is 20 mm. The outer lamellae are of strength class T22, while the inner three are class T15. The corresponding material properties were taken from Table 2 of Splitkon [6].

2.2 Concrete and quality check

The concrete used in this thesis is self-compacting concrete (SCC) with a strength class of B35. SCC was selected for its ease of use in large constructions where vibration for consolidation is challenging. It flows under its own weight, allowing compaction without external vibration. The material properties for B35 concrete were taken from Eurocode 2 [7].

To assess concrete quality, 12 cubes and 6 cylinders were tested at various intervals after casting. Since all 13 TCC slabs couldn't be tested in one day, cube and cylinder tests were distributed, in day 28: 3 cubes, 2 cylinders; in day 34: 3 cubes; in day 38: 3 cubes, 2 cylinders and in day 40: 3 cubes, 2 cylinders. The concrete cubes (100×100×100 mm) were tested for compressive strength according to NS-EN 206:2013. Cylinders (150 mm diameter, 300 mm length) were prepared with smooth ends and tested following NS-EN 12390-13:2013. Results were based on average compressive strengths of corresponding cube tests. Splitting test was performed in accordance with NS-EN 12390-6:2001. The observed average cube compressive strength values are 55.53, 57.49, 56.59 and 58.67 MPa respectively in 28, 34, 38 and 40 days. The corresponding values for cylinder strengths are 43.61, 45.99, 45.27 and 46.93 MPa respectively. Average values of the modulus of elasticity of the concrete are 33.2, 39.89 and 33 GPa for 28, 38 and 40 days respectively. Average values of the splitting tensile test strength of the concrete are 2.85, 3.29 and 3.27 MPa for 28, 38 and 40 days respectively.

2.3 Shear fasteners

Shear fasteners were selected based on availability, cost, and installation time. The study also compared two types of dowel screws and their orientations to assess their effect on the CLT-concrete composite slab. In collaboration with Rothoblaas, a leading provider of construction solutions, the CTC and KOP screws (see Fig.1) were chosen from their catalogue for laboratory testing.

Fig.1. (a) CTC screw, (b) KOP screw

CTC Screws

The CTC shear fastener is self-drilling, quick to install, and minimally invasive, making it ideal for TCC structures [8]. CTC screws selected for this case were arranged in crossed pairs at 45° and 45°/135°, as shown in the Fig. 2 below. This configuration allows one screw to resist tensile forces while the opposing screw acts as a stiffener [9]. The screw specifications are: head diameter 7 mm, length 160 mm, effective length 110 mm, and characteristic tensile strength 29 MPa [8]. A reinforcement mesh (150×150 mm, 5 mm diameter) was also installed.

The slip modulus for CTC screw (K_{ser}) in serviceability limit state was determined as 23100 N/mm and value for ultimate limit state was determined as 15400 N/mm [4]. The spacing of CTC screws was based on the minimum requirements from the Rothoblaas catalogue [8]. The selected spacings are: 150 mm between shear fasteners longitudinally, 150 mm from screws to longitudinal ends, 120 mm to side edges, and 20 mm between fasteners transverse. The screw arrangement is schematically shown in Fig.2.

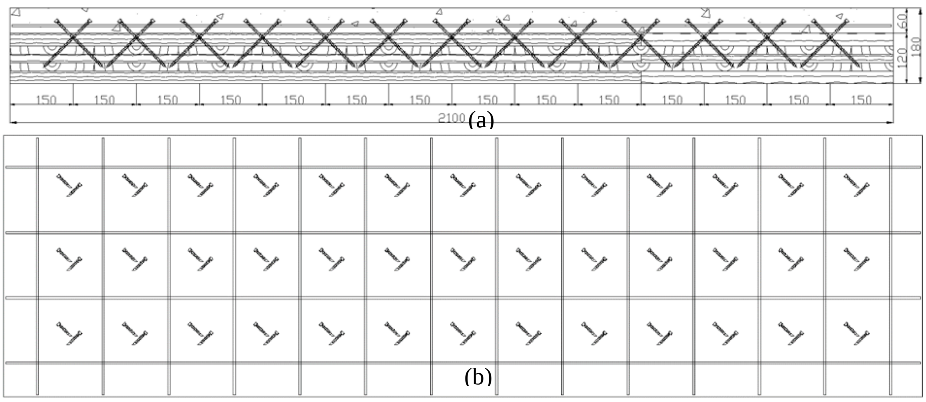


Fig.2. CLT-concrete composite slab with CTC screws: (a) longitudinal cross-section, (b) top view of CTC screws and reinforcement mesh

KOP Screws

The KOP screws (Figure 1) were arranged in parallel pairs at a 45° angle, opposite to the standard design, to study the effect of fastener orientation. The slip modulus for

KOP screw (K_{ser}) in serviceability limit state was determined as 12433 N/mm and value for ultimate limit state was determined as 8288 N/mm [4]. The spacing is based on the minimum requirements from Eurocode 5 [4]. The selected spacings are: 100 mm between shear fasteners longitudinally, 150 mm from screws to the ends, 60 mm to side edges, and 60 mm between fasteners transversely. The screw arrangement is schematically shown in Fig. 3

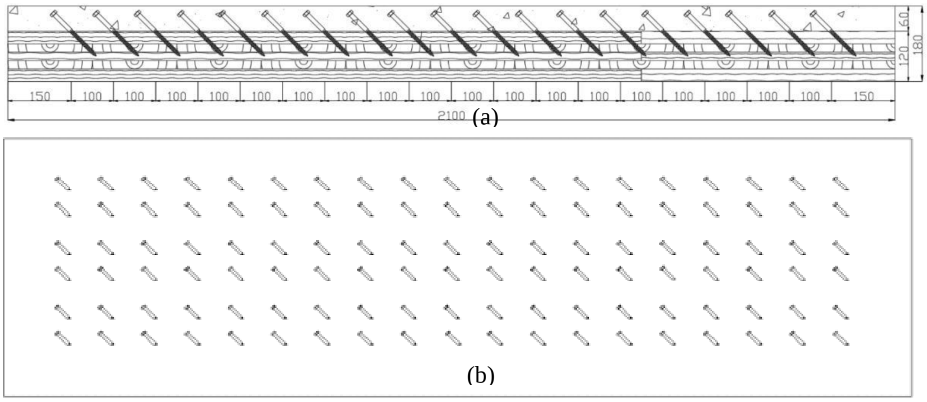


Fig.3. CLT-concrete composite slab with KOP screws: (a) longitudinal cross-section, (b). top view of KOP screws

2.4 Assembling shear fasteners

Two types of shear fasteners, CTC and KOP screws, were installed with slightly different methods. White chalk was hard to see on the wood, so cardboard templates were made for each screw type, with correct spacing between rows and screw pairs.

Using the templates ensured consistent spacing. The two templates differed in row and pair spacing, based on the minimum distances specified in Eurocode 5 [4]. The effective screw length embedded in the timber and covered by concrete was also determined according to Eurocode 5 [4].

CTC Screws -Slab type A

The CTC screw has a diameter of 7 mm and a length of 160 mm. This screw type is self-tapping screw, which means, it can be screwed onto the timber slab without predrilling holes. The pairs of the CTC screws were arranged crossed parallel. In addition, a steel reinforcing mesh with the size of 150 x150 mm and diameter of 5 mm, was used to increase the strength in concrete as shown in Fig. 4 (a).

KOP Screws -Slab type B

The KOP screw has a 10 mm diameter and a length of 140 mm. As with the CTC screws, each location was marked before installation. Since KOP screws are not self-tapping, 6 mm pilot holes were predrilled. A stop collar was used to prevent drilling deeper than the screw length. The CLT slab with assembled KOP screws is shown in Fig. 4(b).

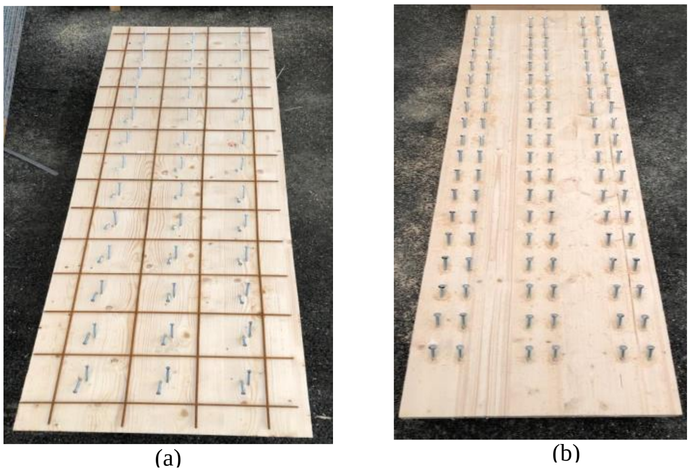


Fig.4. (a) Slab type A: CTC screws with reinforcement mesh, (b) Slab type B: KOP Screws

2.5 Formwork and casting of concrete

Plywood with a thickness of 16 mm was used for the concrete formwork. This thickness was sufficient to resist the lateral pressure from pouring the 60 mm high concrete slab. After installing the formwork and shear fasteners, concrete was poured onto the top of the CLT slabs. Although self-compacting, the concrete was compacted using a poke rod and hammering the formwork sides to remove air pockets. Without this, surface voids or honeycombing could occur, potentially reducing slab strength. Six samples from each type of slabs are casted (i.e. in total 12 test samples) and casted slabs are shown in Fig. 5.

2.6 Curing and demolding

Curing is essential to ensure the quality of concrete properties. An impermeable plastic cover was used to prevent the concrete from drying out. A total of twelve cubes and six cylinders were made to verify that the concrete used in the CLT-concrete slabs met the strength requirements of Eurocode 2 [7]. The samples were initially covered with plastic for 24 hours, then placed in water tanks for the remaining 27 days of curing. After the CLT-concrete slabs had cured for 4 days, the formwork was removed and the covered in plastic again.

Fig. 5. Finished casted CLT-concrete slabs

3 Laboratory Testing

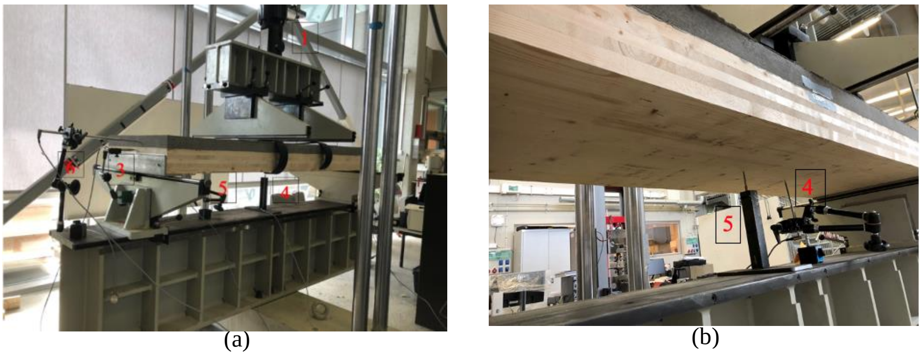
The load test setup, relevant guidelines, and obtained results are presented in detail in this section. A four-point bending test was conducted on all slab samples, including both CTC and KOP screw types (i.e. Type A and Type B slabs).

3.1 Test set up

A universal bending machine was customized to perform a four-point bending test, as shown in Fig. 6. The test setup, load rate, and duration followed NS-ISO 6891:1991 *Timber structures — Joints made with mechanical fasteners* [10]. Two L-shaped stainless-steel profiles were installed on the short sides of the CLT–concrete composite slab to enhance bearing capacity at the supports and prevent timber crushing during testing.

In addition to measuring the ultimate failure load, deflection was recorded at mid-span and beneath one of the applied loads. Transverse displacement on both sides of the slab was also measured using five Linear Variable Differential Transformers (LVDTs): two on the concrete surface and one on the timber

To observe any relative movement between elements, a linear measuring tape was attached to each slab. These measuring tapes were placed near both supports and at midspan; one on the timber side and one on the concrete side.



(a) (b)

Fig. 6. Test setup (a) Side view showing the load cell and vertical and horizontal displacement transducers; (b) Bottom view showing the downward displacement transducers

3.2 Four point bending test

There are no specific standards for testing TCC elements in the laboratory; instead, tests follow NS-ISO 6891:1991 *Timber structures – Joints made with mechanical fasteners* [10]. According to this standard, loading begins with one cycle, followed by continuous loading until failure. The estimated failure load, F_{est} , is calculated using the γ-method and the shear analogy method.

Fig. 7 illustrates the loading process. Load is applied at a constant rate until reaching $0.4 \cdot F_{est}$ (point 04), held for 30 seconds, then reduced to $0.1 \cdot F_{est}$ (point 11) and held again for 30 seconds. From point 21, loading resumes at a constant rate until failure. The load rate, assumed to reach failure in 10 minutes, is set at 0.2 kN/s.

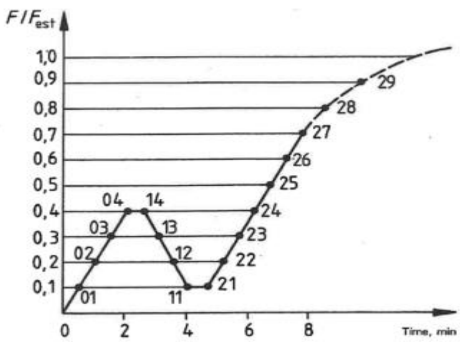


Fig. 7. Loading procedure [10]

3.3 Test results: bending stiffness and load carrying capacity

The load versus vertical displacement was measured and plotted for both types of slabs (Slab A with CTC screws and Slab B with KOP screws), as shown in Figs. 8 and 9.

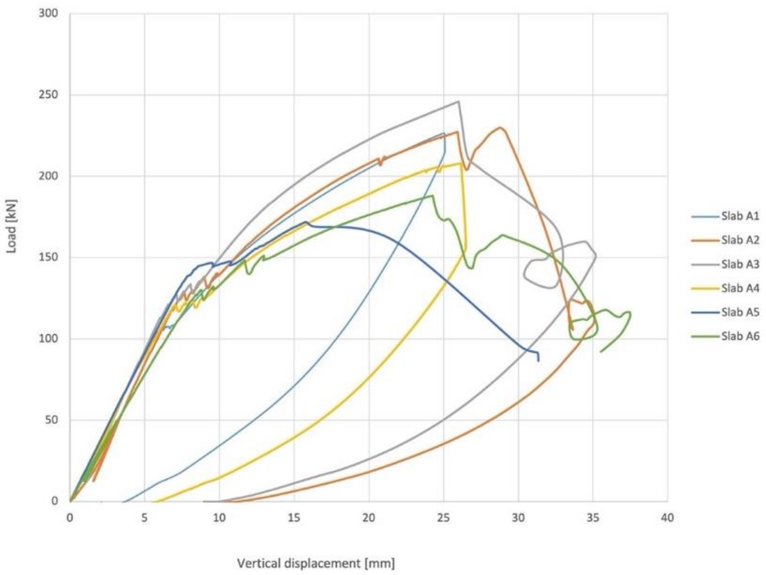


Fig. 8. Load-deflection response for Slab A1-A6

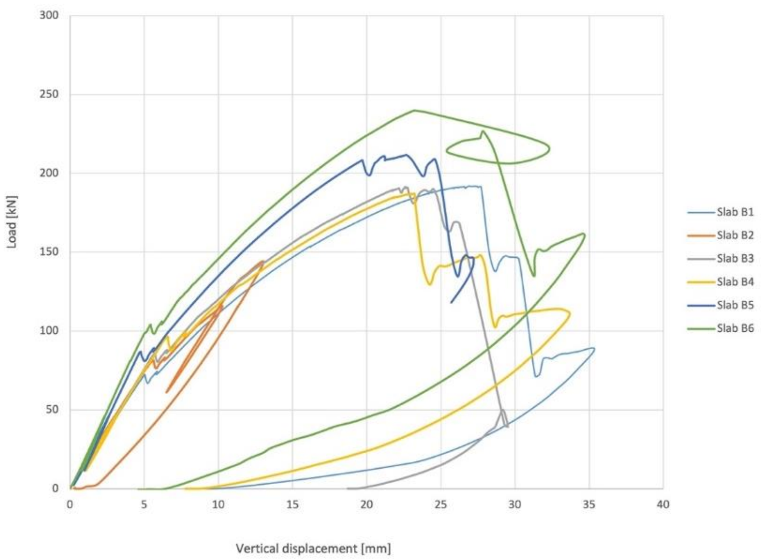


Fig. 9. Load-deflection response for Slab B1-B6

From Figs. 8 and 9, the load-displacement behavior of the slabs shows an initial linear response up to the first load drop, typically caused by premature failure or inter-layer slip. Beyond this point, the behavior becomes nonlinear until reaching the peak load, where final collapse or fracture occurs. The measured load capacities and corresponding maximum displacements are presented in Table 1, which list load values at each failure drop along with the midspan vertical deflections.

Table 1. Load capacity and maximum displacement of slabs of type A: CTC screws and slab type B: KOP screws

Slab	Load capacity (kN)				Maximum displacement (mm)			
	1st drop	2rd drop	3rd drop	Max	1st drop	2rd drop	3rd drop	Max
A1	107.16	-	-	226.60	6.16	-	-	25.03
A2	128.30	138.25	210.85	229.75	7.67	8.99	20.65	28.80
A3	124.25	133.62	-	245.96	6.86	8.07	-	26.01
A4	120.73	124.37	-	207.96	6.99	8.24	-	26.15
A5	114.69	-	-	171.63	8.59	-	-	15.86
A6	130.17	148.41	-	188.12	8.80	11.70	-	24.28
B1	72.40	-	-	191.88	5.04	-	-	26.91
B2	82.29	-	-	144.19	5.58	-	-	13.03
B3	85.96	-	-	191.43	5.73	-	-	22.61
B4	96.49	-	-	181.12	6.59	-	-	23.20
B5	86.88	-	-	211.78	4.76	-	-	22.69
B6	104.08	-	-	239.94	5.43	-	-	23.20

3.4 Test results: slip in the interface and failure

Fig. 10 shows the separation of the concrete and timber elements at the ultimate load. It also illustrates that one element moves in one direction while the other moves in the opposite direction. Fig. 10(a) and Fig. 10(b) demonstrate the movement of Slab A4 at the edge (i.e., near the support where shear is maximum) and at midspan (i.e., where bending is maximum), respectively.

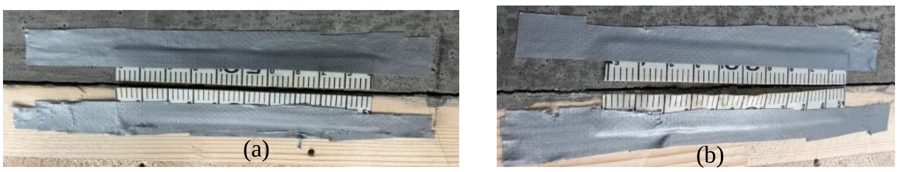


Fig. 10. Slip movement between timber and concrete interface for Slab A4: (a) at the edge, (b) at the mid-span

4 Theoretical Prediction of Load Capacity and Displacement

There is no standardized method for theoretically predicting TCC behavior. In Europe, various approaches exist, some theoretical, others analytical, often adapting CLT mechanical properties. Experimental methods face limitations due to numerous project-specific variables, making them less generalizable and more costly. In contrast, analytical methods use known material properties, offering more generalized, cost-effective predictions of strength and stiffness [11].

CLT–concrete floor systems can be analyzed using a combination of the shear analogy method and the γ-method (effective stiffness method). The shear analogy accounts for rolling shear in transverse CLT layers, as described in the US CLT Handbook [2,12]. The γ-method, from Eurocode 5 Annex B [4], provides a practical means of calculating the effective bending stiffness of composite sections, incorporating connection efficiency.

4.1 γ −method

The γ-method, also known as the mechanically jointed beams theory, is an analytical approach adapted for TCC structures and presented in Eurocode 5 (Annex B of [4]). Its main limitation is applicability only to TCC systems with two or at most three layers. The method estimates the effective bending stiffness based on the degree of composite action, assuming shear fasteners are uniformly distributed along the length [3].

The effective bending stiffness EI_{eff} of the CLT–concrete composite slabs was calculated using Eqs. (1) and (2).

$$EI_{eff} = \sum_{i=1}^{n}(EI)_i + \gamma_i E_i A_i a_i^2 \quad (1)$$

$$\gamma_i = \left(1 + \pi^2 \frac{E_i A_i s_i}{k_i L^2}\right)^{-1} \quad (2)$$

where, $(EI)_i$and A_i represent the bending stiffness and cross-sectional area of the concrete (i=1) and CLT (i=2), respectively, as determined using the shear analogy method. k_i denotes the slip modulus of the connectors, s_i is the spacing between connectors, and a_i is the distance from the centroidal axis of the composite section to the centroidal axis of each individual component of the member as shown in below Eqs. (3) and (4).

$$a_{i=1} = \frac{E_2 A_2 (h_c + h_{clt})}{2(\gamma_1 E_1 A_1 + \gamma_2 E_2 A_2)} \quad (3)$$

$$a_{i=2} = \frac{\gamma_1 E_1 A_1 (h_c + h_{clt})}{2(\gamma_1 E_1 A_1 + \gamma_2 E_2 A_2)} \quad (4)$$

where h_c and h_{clt} are the thickness of the concrete and CLT timber sections.

4.2 Shear analogy method

The shear analogy method is a theoretical approach used to analyze TCC systems, applicable only to face-glued CLT elements (i.e. not to nailed or doweled products). It imposes no restrictions on the type of shear fastener or number of CLT layers. This accounts for shear deformation in both longitudinal and transverse layers [11]. Validated through FP Innovations testing, this method offers precise predictions by considering varying moduli of elasticity within layers and including transverse shear effects [11]. The total response of the CLT-concrete composite is obtained by superimposing the bending and shear stresses of each beam [11].

4.3 Short-term verification

Short-term verification refers to the early stage of loading, where loads are applied instantaneously without considering creep effects. In this study, only the γ-method and the shear analogy method are discussed [13].

The verification is based on the modulus of elasticity for concrete and timber, and includes the slip modulus of the shear fastener. Since the load-slip relationship of the fastener is typically non-linear, it must be considered in design. The slip modulus differs for ultimate limit state (ULS) and serviceability limit state (SLS), denoted as k_u and k_{ser}, respectively, and depends on the applicable standard.

If pull-out test data are available, values for k_u and k_{ser} should be selected according to EN 26891:1991 [19]. For SLS, k_{ser} is taken as the secant stiffness at 40% of the load-carrying capacity of fastners ($k_{0.4}$); for ULS, k_u is taken at 60% ($k_{0.6}$). If no test data are available, values should follow the timber-to-timber connection formulas in Eurocode 5 [4]. For SLS, k_{ser} is twice the calculated slip modulus and for ULS, k_u is 2/3 of k_{ser} [4]. The theoretically calculated load capacities and maximum vertical displacements at failure are presented in Tables 2 and 3, respectively.

4.4 Long-term verification

Long-term behavior of TCC systems is challenging to assess, as effects like creep and shrinkage develop gradually under sustained loads. These time-dependent deformations alter internal forces and stiffness, which affects load distribution in statically indeterminate systems. Creep, especially in longer spans, can lead to increased deformation in components with higher creep coefficients, shifting loads toward stiffer elements and increasing their bending moments while reducing normal forces.

Shrinkage, particularly in concrete, can further impact internal stresses, often increasing stresses in timber due to differential softening. These effects must be considered in design.

Currently, no official standards exist for long-term TCC design. In practice, Eurocode 2 (for concrete) and Eurocode 5 (for timber) recommend the effective modulus method, using creep factors derived from load-duration studies. Long-term effects are estimated by combining the effective modulus values of timber, concrete, and shear connectors with mean elastic moduli [9, 14]. The theoretically calculated load capacities and maximum vertical displacements at failure are presented in Tables 2 and 3, respectively.

4.5 Alternative theoretical prediction

An additional theoretical predictions were carried out following the same procedure described in the subsections above, but with a change in the maximum moment, based on the failure location. Instead of using the moment capacity due to failure of concrete layer at the top of the concrete element, the moments capacities due to failure of top layer of CLT timber section (M3) and bottom layer (M4) of the CLT-timber were calculated respectively. Furthermore, laboratory tests for concrete verification indicated that the concrete had significantly higher strength. Two additional theoretical predictions were performed using the values from [7] for concrete strength class B45, and the overall average value of the concrete strength obtained from the compressive strength tests, with the partial safety factor set to one. The theoretically calculated load capacities and maximum vertical displacements at failure are presented in Tables 2 and 3, respectively.

Table 2. Theoretical load capacities of CLT-concrete composite slabs

Type of theoretical approach	Short-term load capacity (kN)		Long-term load capacity (kN)	
	Slab A-with CTC screws	Slab B-with KOP screws	Slab A-with CTC screws	Slab B-with KOP screws
Conventional approach (failure of concrete & use design parameters/values)	75.68	82.96	117.65	115.52
Failure of top of CLT-timber (M3)	136.52	133.90	188.88	116.04
Failure of bottom of CLT-timber (M4)	177.93	166.44	153.93	143.62
Conventional approach by using B45 concrete strength	94.35	91.99	120.07	117.23
Conventional approach by using average concrete strength	136.51	133.90	118.88	116.03

4.6 Results of theoretical predictions

The theoretical calculations are carried out using the theories and methods discussed in the previous subsections, combining the shear analogy and γ-method. The load capacities and maximum displacements for all 12 slabs are calculated and presented in Tables 2 and 3, respectively. Detailed calculations are provided in the relevant dissertation [15].

Table 3. Theoretical maximum vertical deflection of CLT-concrete composite slabs

Type of theoretical approach	Short-term disp (mm)		Long-term disp (mm)	
	Slab A-with CTC screws	Slab B-with KOP screws	Slab A-with CTC screws	Slab B-with KOP screws
Conventional approach (failure of concrete & use design parameters/values)	5.61	5.73	17.91	18.51
Failure of top of CLT-timber (M3)	9.86	10.13	18.34	18.82
Failure of bottom of CLT-timber (M4)	14.36	13.82	26.33	25.41
Conventional approach by using B45 concrete strength	6.86	26.33	18.33	18.81
Conventional approach by using average concrete strength	9.85	25.41	18.34	18.82

5 Discussion and Comparison of the Results

Due to variations in finger joints, knots, and other defects, no timber element and thus no CLT panel are identical. Typical failure modes are shown in the first subsection, followed by a discussion of the resulting limitations. The remaining sections compare and discuss theoretical predictions with laboratory results.

5.1 Observed failure scenarios

During the four-point bending test, cracking sounds were heard from the initial load drop until the peak load was reached, followed by a distinct fracture noise. All figures in this chapter were captured after the maximum load was exceeded.

Fig. 11, taken two seconds apart, illustrate the rapid failure of Slab A6. A similar failure rate was observed across all test specimens.

(a) (b)

Fig. 11. (a) Two seconds before failure of Slab A6, (b) On set of failure of the Slab A6

Failure patterns varied across specimens. In some slabs, visible cracks appeared in the timber at midspan or along the edges, while in others, especially on the underside, no cracks were visible, regardless of fastener type. In some cases, failure was evident at timber defects such as knots or finger joints, particularly when the two were adjacent. Most tests also showed concrete cracking aligned with the applied load. Fig. 12 show typical failure near a knot and finger joint.

Fig. 12. (a) Finger joint and knot failure in the timber, (b) Failure in just finger joints and knot separately

Many slabs also exhibited longitudinal timber cracks at midspan (Fig. 13 (a)). In some cases, cracks began in the concrete under the load point and extended into the timber, as seen in Fig. 13 (b).

Fig. 13. (a) Cracks in timber towards to longitudinal direction, (b) Cracks in both timber and concrete

Post-test inspections were conducted to assess the role of shear fasteners in the failures. Fig. 14 (a) shows the CTC fastener's position after testing. Fig. 14 (b) shows the KOP screw embedded in both timber and concrete with no sign of displacement of both types of screws. This indicates that the screws may remained stable during loading.

Fig. 14. Stability of the screws after four point bending test: (a) Slab A with CTC screws, (b) Slab B with KOP screws

5.2 Limitations

This section outlines key limitations of the test program and analytical load capacity calculations. First, three of the twelve slabs were shorter about 16 mm than intended. To ensure fair testing, these were distributed across slab types: two to Type A and one to Type B. To compensate for the reduced length, 16 mm plywood was added to each short end before installing the steel L-profiles.

Post-testing, it was found that five slabs (A6, B1–B4) had incorrect lamellae orientations. In a properly oriented CLT slab, outer layers (1 and 5) are thicker and have higher strength (T22), while inner layers (2–4) are thinner and of lower strength (T15). In the affected slabs, transverse layers were mistakenly positioned longitudinally, altering both stiffness and load capacity. This likely contributed to the lower test results of A6 compared to A1–A4, and B1–B4 compared to B5–B6 (see Figures 8 & 9 and Table 1 & 2).

During casting, it was discovered that the concrete mix unexpectedly contained plastic fibres not specified in the order or mix design. Nevertheless, the average cube and cylinder strengths (see section 2.2) were used in the theoretical calculations (section 4.2). Moisture content of the CLT was not measured before or after casting. Tracking this could have provided insights into water absorption from the concrete.

Defining failure loads during testing was also challenging. Type A slabs (with CTC fasteners and mesh) often exhibited one or more sudden load drops before final failure. Since the ultimate failure was abrupt and destructive, the first noticeable load drop was used as the failure load. Variability in timber properties (e.g., knots) further complicated interpretation.

Lastly, theoretical predictions used partial safety factors for timber and concrete, which influence the outcomes. Long-term deflection and load capacity predictions also include effects of creep and shrinkage. However, lab tests were conducted only 28–40 days post-casting, making direct comparison difficult. More detailed discussion is available in the related dissertation [15].

5.3 Comparison of the experimental results

From the graphical and tabulated presentation of the test results in Section 3.3, it appears that the shear fastener used in slabs of Type A (slabs with CTC screws) is the one that can withstand the highest applied loading. Additionally, the orientation of the shear fastener seems to have a significant influence on the composite action, load-carrying capacity, and maximum deflection.

5.4 Comparison of theoretical predictions and experimental results

Fig. 15 compares the conservative experimental load capacities with theoretical predictions for both slab types. In Fig. 15(a), the short-term predictions for slab type A with CTC screws, using the shear analogy and γ-method (dark blue dots), are highly conservative, as they deviate significantly from the reference line. The theoretical capacities calculated based on the additional approach discussed in Section 4.2, which utilizes observed material properties and/or a more realistic failure location corresponding to the maximum moment, show better agreement with the experimental results than the conventional short-term predictions. Please note that the load capacities determined based on failure due to bending moment stress at the top of the timber (M3), and those predicted using the average concrete compressive strength, yield identical values. As a result, the grey M3 dots are not visible in the Fig.15.

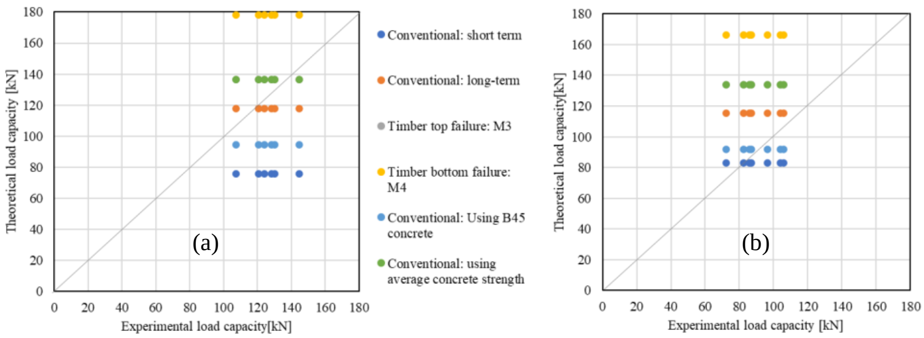


Fig. 15. Comparison of experimental load capacities with theoretical predictions for: (a) Slab A with CTC screws, (b) Slab B with KOP screws

The Fig. 15 (b) presents similar results for type B slabs with KOP screws. The same observation regarding M3 and average compressive strength applies. For this type of slabs with KOP shear fastener type, theoretical predictions align more closely with the reference line, indicating lower conservative outcomes, except for a few test elements.

5.5 Efficiency of composite behaviour of the CLT-concrete composite slabs

The connection between timber and concrete is crucial for achieving a high degree of composite action in TCC (Timber-Concrete Composite) systems. One way to evaluate this is by calculating the composite efficiency, which compares theoretical and measured midspan deflections as shown in Eq. (5) [13].

$$\text{Degree of compoiste action} = \text{Efficiency} = \frac{D_N - D_I}{D_N - D_C} \tag{5}$$

where, D_N theoretical deflection for no composite action, D_C theoretical deflection for full composite action and D_I measured deflection from laboratory tests.

Efficiency ranges from 0% (no composite action) to 100% (fully composite action). In reality, some slip occurs at the interface due to deformable mechanical fasteners, leading to "partial composite action". As load increases, this slip grows, shifting the neutral axis from a shared position to separate axes in timber and concrete. Although full composite behaviour is ideal, slight slippage can help redistribute shear stresses more evenly along the fasteners [13].

The goal is to achieve near 100% efficiency, where timber, concrete, and fasteners act as one unit. Table 4 presents efficiency values calculated from theoretical and experimental deflections. Slabs of Type A exhibit the highest efficiency but still fall short of full composite behaviour. Type B slabs show minimal interaction, indicating little to no composite action.

Table 4. Degree of composite behaviour of the CLT-concrete slabs for tested samples/slabs

Slab	Deflection for no composite D_N (mm)	Deflection for full composite D_C (mm)	Deflection measured in lab test D_I (mm)	Efficiency (%)
A1	5.547	5.612	6.160	9.616
A2	5.547	5.612	7.673	33.367
A3	5.547	5.612	6.859	20.586
A4	5.547	5.612	7.000	22.765
A5	5.547	5.612	8.586	47.693
A6	5.547	5.612	8.803	51.102
B1	6.354	5.725	5.037	2.094
B2	6.354	5.725	5.579	1.233
B3	6.354	5.725	5.730	0.993
B4	6.354	5.725	6.591	-0.3767
B5	6.354	5.725	4.760	2.535
B6	6.354	5.725	5.436	1.466

6 Conclusions

This study examined the structural behaviour and load-carrying capacity of CLT-concrete composite slabs using two types of shear fasteners: CTC and KOP screws. Four-point bending test results were compared with theoretical predictions based on the γ-method from Eurocode 5 and a modified approach combining the γ-method with the shear analogy method, which accounts for shear deformation in multi-layered elements. Laboratory testing followed the NS-ISO 6891:1991 standard for mechanically fastened timber joints. The comparison of results and investigation of the failure behaviour of the composite slabs led to the following concluding remarks.

- The load-displacement response of both slab types showed an initial linear phase up to the first load drop, likely due to interlayer slip or premature failure, followed by nonlinear behaviour until failure.

- Theoretical predictions aligned with experimental results for slabs with KOP screws (type B) but were conservative for slabs with CTC screws (type A).
- Test results indicated that slab type A could withstand significantly higher loads than predicted, while type B showed close agreement between theoretical prediction and experiment observations.
- Due to few limitations affecting both theoretical and experimental results, further research is needed before drawing definitive conclusions about the performance of CTC and KOP screws in CLT-concrete slabs. Currently, no official design standard exists for such CLT-concrete systems.

To address current limitations, additional testing is recommended using the same five-layer CLT, concrete strength, and fastener types. Enhanced instrumentation (e.g., embedded strain gauges in the timber-concrete interlayer and fasteners, and appropriate gauges to measure slip) should be used to better capture slip behaviour. Future studies could also explore variations in fastener types, spacing, and installation efficiency in terms of cost and time.

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