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Serviceability Limit States of CLT–Concrete Composite Slabs: Vibrations and Long-Term Deflections

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Abstract

Cross-laminated timber–concrete composite (CCC) slabs are an increasingly adopted flooring solution that combines the structural efficiency of CLT with the compressive strength of a concrete topping. Despite their growing use, experimental data on the serviceability performance of realised CCC systems remain limited. This paper investigates both the vibration behaviour and long-term deflection response of a CCC floor supported by a steel framing system, through in-situ measurements and a large-scale numerical parametric study.

Vibration measurements were conducted on a completed building in Budapest, where the slab was excited by single-person and group walking at controlled frequencies. The measured fundamental natural frequencies ranged from 13.5 Hz to 18 Hz, satisfying the Eurocode 5 minimum requirement of 8 Hz. Damping ratios ranged from 2% to 3%, consistent with values reported in the literature for similar systems.

The parametric study examined the influence of concrete creep, timber creep, concrete shrinkage, and connection efficiency on long-term deflections over a 50-year service life, using a two-layer finite element model with 36,864 simulation runs. Concrete shrinkage was identified as the dominant factor, increasing deflections by up to 29%. The results offer practical guidance for the serviceability design of CLT–concrete composite floors.

Keywords: cross-laminated timber, timber-concrete composite, CLT-concrete composite, shrinkage, composite factor, vibration, damping ratio, in-situ testing.

1 Introduction

The drive towards more sustainable construction is pushing the building industry to adopt alternative construction materials. The use of cross-laminated timber (CLT) has been growing rapidly across Europe, including Hungary [1]. This engineered wood product is composed of layers of timber boards bonded together with alternating grain direction in each layer, thus resulting in panels that are stronger than regular solid timber [2].

CLT has many advantages, such as a high strength-to-weight ratio, a reduced carbon footprint, fast erection times, and prefabrication [3]. However, meeting serviceability limit states: deflections and vibrations, are always the governing factors in designing CLT slabs [4, 5]. To achieve more efficient designs, composite slabs were introduced, in which a concrete topping is added to the CLT, allowing the concrete to work in compression and the CLT in tension. The idea was first proposed after the First and Second World Wars in Europe. Because of a steel shortage, existing timber frames were strengthened by adding a concrete topping connected to the timber with screws. Nowadays, connections between the CLT and the concrete topping are provided in several ways in addition to screws. Notches in the timber or epoxy adhesives painted on the timber are used [6].

The literature offers insights into vibrations in CLT-concrete composite slabs (CCC). Studies suggest that CCC slabs offer better vibration performance than bare CLT. Both Rijal et al.[7] and Thai et al.[8] show that in their research. They performed vibration measurements on timber-concrete composite (TCC) beams with different shear connectors. They conclude that notches in the CLT result in higher damping ratios.

Predicting instantaneous deflections of CCC slabs can be achieved using proposed simplified analytical models, such as the gamma method in Eurocode 5. The method uses a reduction factor (γ) between 0 and 1 to represent the degree of composite action between connected layers. Predicting the composite slab's long-term deflections is more challenging because many factors affect them. Long-term deflections are influenced by concrete creep and shrinkage, timber creep and moisture content, and connection efficiency. Fragiacomo et al.[9] and Yeoh et al.[10] both performed experimental studies on Timber-concrete composites. They both agree that deflections are affected by humidity fluctuations, concrete shrinkage, and connection stiffness.

In this paper, the serviceability limit states, vibrations, and long-term deflections of a CLT slab supported by a steel framing will be discussed. Vibration measurements are taken from a realised building in Budapest, while the long-term effects are investigated through a large-scale parametric numerical study.

2 Methods

2.1 Description of the composite system and the test setup

The investigated floor system consists of CLT–concrete composite slabs supported by a steel framing system. The slabs are composed of spruce CLT panels with a cast-in-place concrete topping, with composite action achieved through notched shear connections and screws installed in the timber panels. The CLT panels, manufactured by KLH, were connected to the steel beams using mechanical fasteners, while reinforcement mesh was placed within the concrete topping. Figure 1 shows a cross-section of the investigated slab.

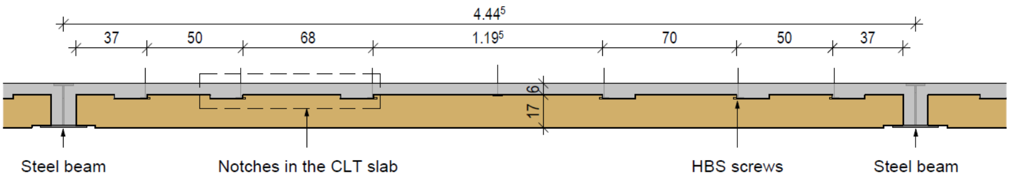

Figure 1: Investigated slab cross-section.

CLT panels had a thickness of 170 mm, a strength grade of C24, and a Young's modulus of 12,000 MPa. The concrete's thickness was 60 mm, and the measured strength grade on site was C16/20, giving a Young's modulus of around 28,600 MPa.

The slab was excited by both a single person and a group of people walking in place at given frequencies measured by a metronome. Acceleration values were recorded by four accelerometers placed on the TCC slab. Figure 2 shows the unfiltered acceleration response. Data were then processed using a MATLAB code written by the authors, which filters the noise with a Butterworth filter and performs a Fast Fourier Transform to estimate the fundamental frequency of the excited slab. Later, the free-decay part of the displacement response, shown in Figure 3, was used to determine the damping ratio using the logarithmic decrement method.

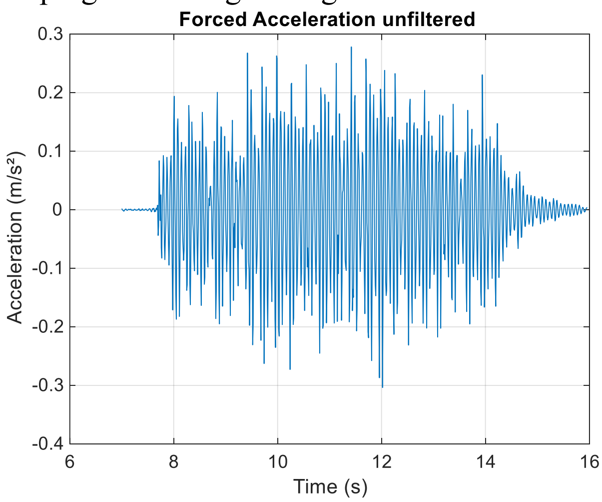

Figure 2: Unfiltered vibration response.

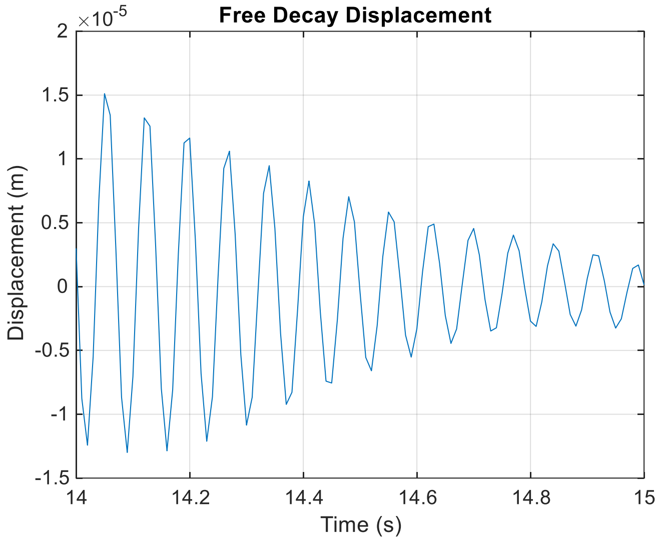

Figure 3: Free decay window.

2.2 Numerical investigations by the use of a parametric study

This study investigates the long-term behaviour of CCC slabs through a parametric analysis focusing on four key variables: concrete creep, timber creep, concrete shrinkage, and connection efficiency. Concrete creep and shrinkage are modelled according to Eurocode 2, while timber creep is represented using the Eurocode 5 deformation factor K_{def}. In addition, a system-level interaction factor (ψ) is used to account for combined creep effects in the composite system.

A two-layer finite element model was developed, in which the CLT and concrete layers were modelled separately using shell elements and coupled through spring-type interface elements representing the shear connectors. The timber was assumed orthotropic, while concrete was modelled as an isotropic linear-elastic material. A large parametric study was conducted considering variations in material time-dependent properties, connection stiffness, slab thicknesses, and environmental conditions. Deflections were evaluated under quasi-permanent loading over a service life of up to 50 years for simply supported configurations. The study was automated using a Grasshopper–AXIS VM workflow, resulting in 36,864 simulation runs.

3 Results and discussion

3.1 Vibrations

The vibration tests showed that measured frequencies of the investigated CCC slab ranged approximately from 13.5 Hz to 18 Hz, with an average of 14 Hz across tests, and slightly different modal responses were observed between single-person and group excitation. Group excitation primarily activates the first mode and produces more consistent frequency results, while single-person excitation shows greater variability due to excitation of multiple modes. However, this fundamental frequency meets the requirements of Eurocode 5, which requires a minimum of 8 Hz.

The measured damping ratios ranged from approximately 2.0% to 2.53%, with group excitation generally yielding higher and more scattered values, likely due to human–structure interaction effects. Overall, the system's damping ratio is 2–3%, consistent with values reported in the literature for similar timber–concrete composite floors, although differences are strongly influenced by connection type, structural configuration, and non-structural elements [11–13]. Figure 4 illustrates the distribution of the measured damping ratios obtained from vibration tests under single-person and group excitation. The individual test results are represented as markers along the horizontal axis, while the associated fitted normal probability density curves are shown as continuous lines.

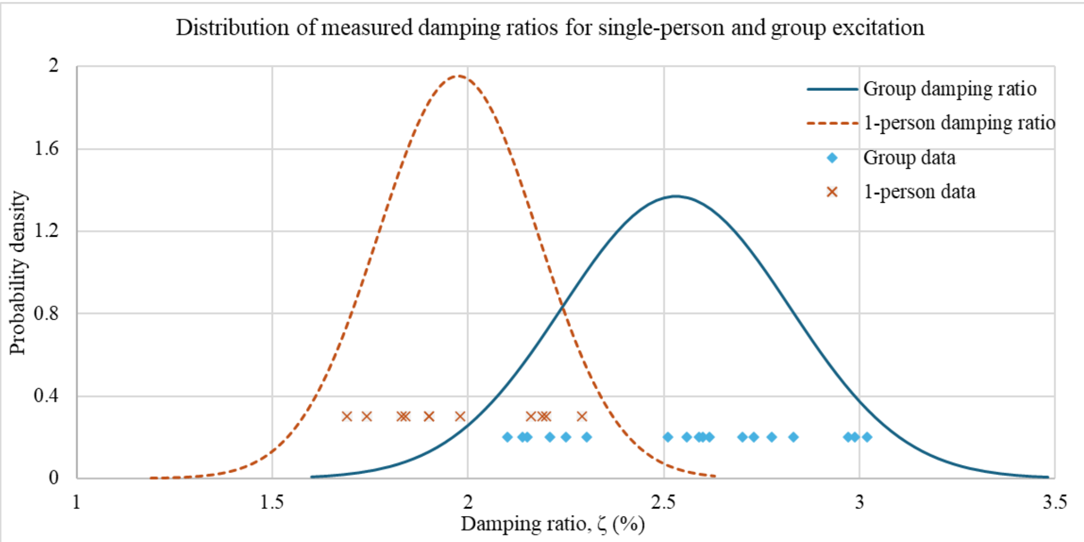

Figure 4: Distribution of measured damping ratios.

3.2 Long-term deflections

The results of the parametric study are presented as midspan deflection in millimetres over time. A representative configuration consisting of 150 mm five-ply CLT and 70 mm concrete topping exhibits deflections that increase rapidly during the first years of loading and then evolve more gradually, approaching a near-linear trend over the long term. This behaviour can be attributed to the dominant influence of concrete creep during the early stages, while timber creep continues to develop after concrete creep has largely stabilised. Figures 5 to 8 illustrate the long-term behaviour of the representative configuration, showing the influence of the investigated parameters: concrete shrinkage, represented by relative humidity (RH); composite factor; concrete creep (Φ); and Timber creep (K_{def}).
The results indicate that:

1- Increased shrinkage leads to increased deflections, consistent with findings reported in the literature [14–16].
2- Lower composite factors lead to larger deflections in the long term.
3- Higher creep coefficients for both concrete and timber increase the long-term deflection response.

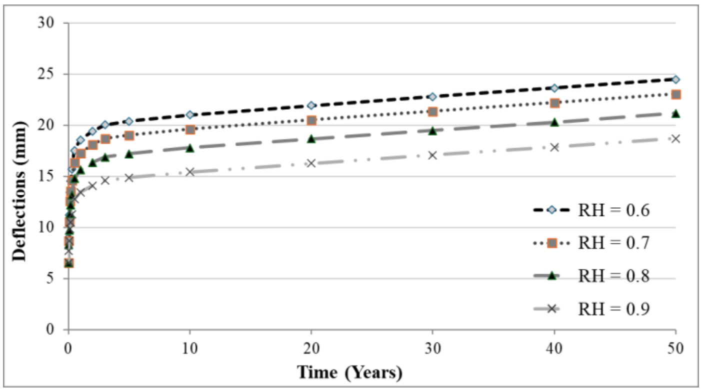

Figure 5: Deflections of 150-5+70mm (Shrinkage)

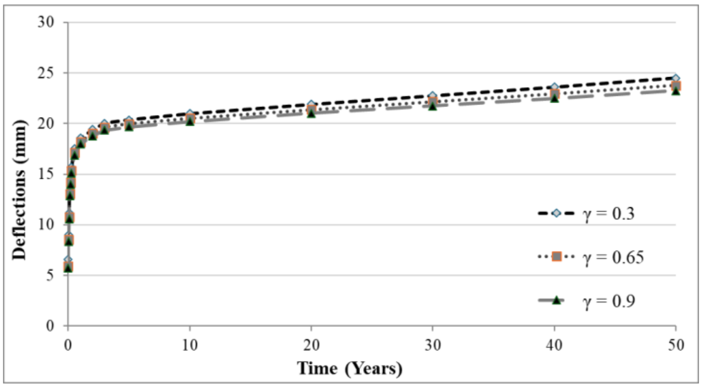

Figure 6: Deflections of 150-5+70mm (γ)

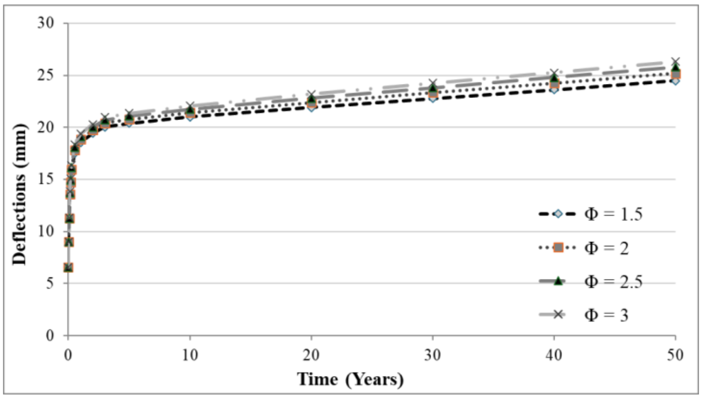

Figure 7: Deflections of 150-5+70mm (φ)

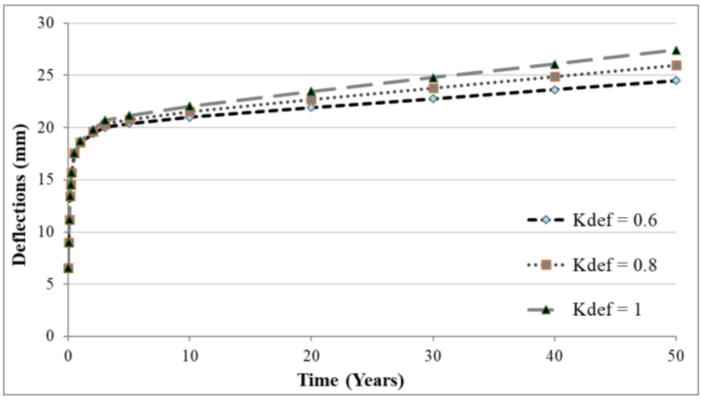

Figure 8: Deflections of 150-5+70mm (K_{def})

To quantify the relative influence of each parameter, all deflection curves were normalised with respect to the minimum-deflection case, as presented in Figures 9–12. The normalised results show that concrete shrinkage can increase total deflections by up to 29% for the investigated configuration, making it the most influential parameter. In comparison, lower connector stiffness increases deflections by approximately 5%, while concrete creep and timber creep increase deflections by up to 7% and 10%, respectively. These findings indicate that concrete shrinkage is the dominant factor governing the long-term deflection behaviour of the composite slabs. The results suggest that geometric and environmental effects associated with shrinkage may be more critical for serviceability design than connector stiffness alone.

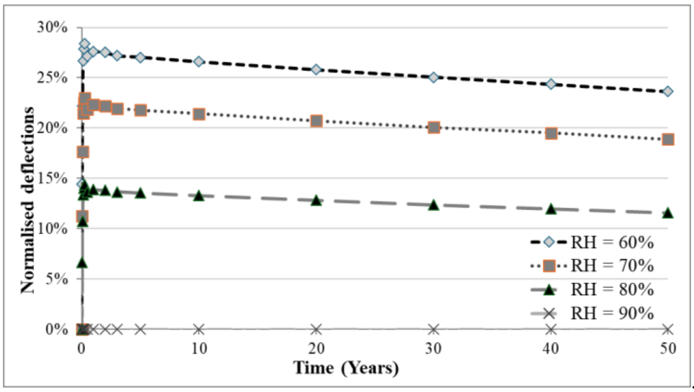

Figure 9: Normalised deflections of 150-5+70mm (Shrinkage)

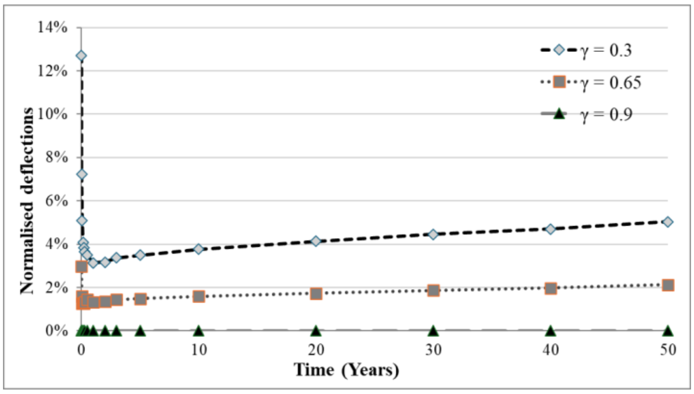

Figure 10: Normalised deflections of 150-5+70mm (γ)

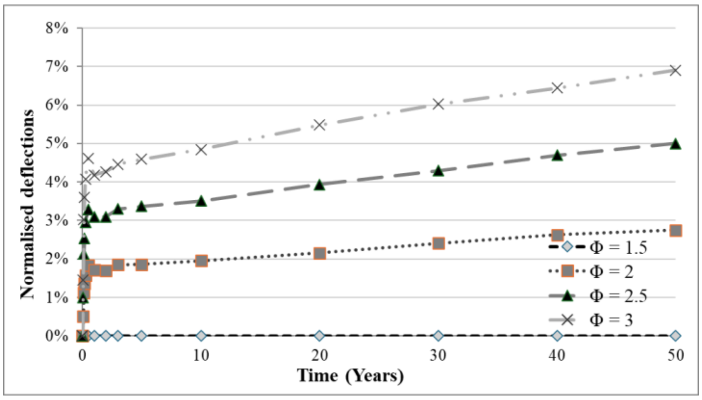

Figure 11: Normalised deflections of 150-5+70mm (φ)

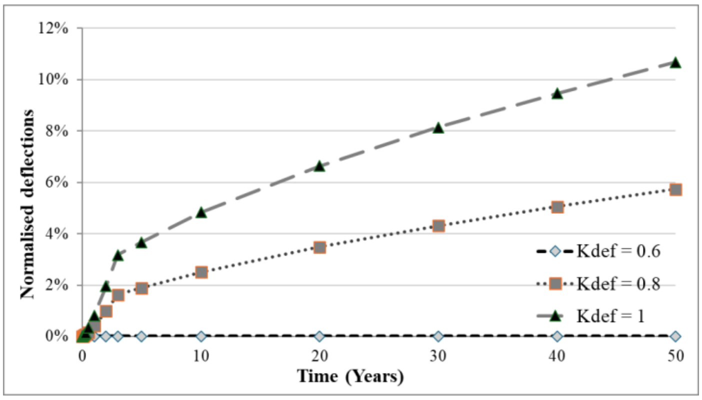

Figure 12: Normalised deflections of 150-5+70mm (K_{def})

4 Conclusions

This study investigated both the long-term behaviour and vibration performance of CLT–concrete composite slabs supported by a steel framing system through numerical parametric analyses and in-situ vibration measurements. The results demonstrated that the investigated floor system satisfies the vibration serviceability requirements of Eurocode 5, with measured fundamental natural frequencies significantly exceeding the minimum recommended limit of 8 Hz. The measured frequencies ranged approximately between 13.5 Hz and 18 Hz under single-person excitation and averaged around 14 Hz during group excitation. Group excitation produced more consistent results, as it primarily activated the first vibration mode, whereas single-person excitation occasionally activated higher modes depending on the excitation frequency.

The measured damping ratios ranged from approximately 2% to 3%, with slightly higher values observed during group excitation due to human–structure interaction effects. Comparison with previously published studies indicates that the damping ratios obtained in this study are within or above the typical range reported for TCC systems. The relatively favourable vibration behaviour may be attributed to the use of notched shear connections combined with screws, which improve composite action and energy dissipation.

The numerical parametric study demonstrated the influence of concrete shrinkage, concrete creep, timber creep, and composite connection efficiency on the long-term deflection behaviour of the composite slabs. Among all investigated parameters, concrete shrinkage was identified as the dominant factor governing long-term deflections, while lower composite efficiency and higher creep coefficients for timber and concrete also contributed to increased deformations over time.
Based on the findings of this study, the use of low-shrinkage concrete mixtures, optimised slab geometries, and proper connection types and stiffnesses is recommended to improve long-term performance. Overall, the results provide valuable experimental and numerical insights into the behaviour of CLT–concrete composite floors and contribute to the limited number of studies that address the serviceability limit-state performance of realised composite timber floor systems.

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