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PRESTRESSING AS A METHOD OF REDUCING THE EFFECT OF CONCRETE SHRINKAGE IN ADHESIVELY BONDED CLT-CONCRETE COMPOSITE PANELS

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ABSTRACT: Gluing timber panels and fresh concrete for shear connection can be considered very effective and almost perfectly rigid, but the effect of concrete shrinkage has a negative effect on the increase in deflection. It is only possible to eliminate these deformations with sufficient cambering, which cannot be achieved with normal support during construction, but only with the help of prestressing. The technical solution of the prestressed adhesively bonded CLT-concrete composite panel consisted of arching the CLT panel in the anchoring device up to the level of 1/100 of the span and subsequent application of glue and fresh concrete. After the concrete hardened and the anchorage was released, prestress was introduced into the composite panel. The measurements confirmed that the chosen value of camber at the level of achieving the design resistance of the CLT panels in bending proved to be adequate to eliminate the deflection due to self-weight and concrete shrinkage and to overcome the negative effect of the fresh concrete gluing. The theoretical parametric analysis revealed that the deflection of the panels is minimally influenced by the timing of anchor removal, and concrete shrinkage cannot be mitigated by delaying anchor removal. The initial camber plays a crucial role in controlling the final deflection of the panels, ensuring structural serviceability.

KEYWORDS: timber, concrete shrinkage, timber-concrete composite, adhesive shear connection

1 – INTRODUCTION

Current architecture and construction demand ecological and sustainable solutions, and timber meets these requirements. As a result, timber structures are becoming increasingly prominent in high-rise and large-span constructions. Timber offers several advantages, including relatively high strength and stiffness in relation to its weight, making it ideal for prefabrication, transportation, and assembly. It is also easy and inexpensive to process, environmentally friendly, and aesthetically pleasing. Moreover, it is readily available and offers numerous other benefits. However, there are some drawbacks to consider. The low weight of timber can result in undesirable vibrational and acoustic properties, and its relatively low modulus of elasticity can lead to significant deformations.

These disadvantages, however, can be mitigated by combining timber with a concrete slab in timber-concrete composite (TCC) structures. This approach provides significantly higher stiffness, both in bending and in the horizontal direction, thereby reducing vibrations. The increased mass improves stability against overturning and tilting while enhancing acoustic properties. The thinner structure also contributes to cost-effectiveness, while the combination offers greater thermal mass and fire resistance. The prefabrication of TCC panels in a single manufacturing facility can eliminate wet processes and the time required for concrete curing, while also ensuring the quality of the produced components.

The combination of mass timber panels, with a concrete layer can effectively replace reinforced concrete panels, particularly in the case of cross-laminated timber, which is load-bearing in both span directions. Architectural studies for buildings do not necessarily have to predetermine the use of either timber or reinforced concrete. The decision can be made at a later stage of the design process.

2 – BACKGROUND

The shear connection of mass timber panels with a concrete layer can be achieved through various methods: mechanical connectors, grooves, bonded perforated steel strips, rods, or

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adhesives [1-4]. Previous research has explored several types of panels with different types of shear connections, such as screws [5], grooves [6], and adhesive bonding of wet concrete and timber [7]. When comparing the short-term and long-term behaviour of various types of composite elements, it has been found that mass panels are highly efficient and practical to manufacture, partly due to the minimal formwork required. In terms of shear connection methods, adhesively bonded joints have proven to be more practical for concreting mass panels. The results have shown that it is possible to achieve rigid shear connection, leading to greater resistance and bending stiffness of the composite panels. An additional advantage of the bonded joint is the uniform distribution of shear flow in the interface between timber and concrete.

The research conducted has demonstrated that bonding fresh concrete to timber slabs requires strict technological conditions, making it particularly suitable for prefabrication. Bonding fresh concrete ensures continuous contact between the timber and concrete, especially in the case of timber-based panels, which may not be perfectly flat. It also allows for adhesion to curved surfaces. However, concrete shrinkage becomes fully apparent through the initial deflection of the composite panels and its gradual increase over time [8].

Temporary support during concreting is required to reduce the initial deflection of a timber-concrete composite element. A more effective practice is cambering the composite element, which can eliminate the deflection from self-weight and possibly even part of the deflection due to concrete shrinkage [8]. However, cambering the element with temporary point supports on the construction side is only feasible to the extent that it does not lift the timber beams or panels off the supports. Adequate cambering can be achieved by e.g. bending and fixing the curved shape of the element [9].

This paper highlights the negative effect of concrete shrinkage and, consequently, the drawback of bonding timber and fresh concrete. It describes a prototype of a prestressed timber-concrete composite (TCC) panel to demonstrate a possible method for eliminating deflection due to self-weight and concrete shrinkage, thereby overcoming the negative effect of fresh concrete adhesion. Through parametric analysis, the influence of concrete shrinkage under different boundary conditions is discussed.

3 – PROJECT DESCRIPTION

To overcome the negative effect of concrete shrinkage in TCC mass panels with adhesive shear connection, prestressing (the precambering of the timber part of the panel before concreting) was proposed as a technical solution. Prestressing ensures the curved shape even after the concrete has hardened. It introduces initial compressive stress into the timber fibres, which are subjected to tension from gravity load, potentially eliminating brittle failure of the timber part caused by defects in the wood. To confirm the hypothesis that prestressing eliminates deflection due to concrete shrinkage and simultaneously increases the usability of relatively thin TCC panels, the following partial objectives were set:

- Prepare a prototype of the designed prestressed TCC panels.
- Develop a model reflecting the production phases of the panel and related rheological phenomena.
- Verify the theoretical model through long-term measurements on prepared prototype panel specimens.
- Verify the short-term resistance and camber of the panels one year after concreting.
- Evaluate the impact of prestressing and other acting loads on the behaviour of the panels.

Two specimens of prestressed CLT-concrete composite panels with different geometric parameters (Table 1) were prepared, and their behaviour was monitored for 125 days in two phases: before and after the application of prestressing by the removal of anchorage, fixing the curved shape [10].

Table 1: Geometry of the prototype test specimens

Parameter	**Specimen**	
	PS1	***PS2***
Theoretical span	4 400 mm	5 800 mm
Initial camber	45 mm	50 mm
Time of achors removal	50 days	75 days
Cross-section width	600 mm	600 mm
Concrete layer depth	50 mm	50 mm
CLT slab depth	80 mm	120 mm
CLT layer depths	30/20/30 mm	40/40/40 mm

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Figure 1. Prestressed CLT-concrete composite panel after anchor removal with visible camber.

The conducted experiments demonstrated the feasibility of the proposed technical solution. The developed theoretical model accurately represented the panel behaviour [10] and was used in the parametric analysis of the influence of concrete shrinkage under different boundary conditions discussed in this paper.

4 – EXPERIMENTAL PART

4.1 SPECIMENS

Prestressed CLT-concrete composite panels were produced by introducing a high initial camber in the CLT slab before concreting and shear connecting it with the concrete slab. The chosen camber values were set at approximately 1/100 of the span, which corresponds to achieving the design strength of the CLT panels in bending. Specimen PS1 measured 4.5 m in length, with a 3-layer CLT slab 80 mm deep, an initial camber of 45 mm, and a 50 mm deep concrete layer. Specimen PS2 measured 6 m in length, with a 3-layer CLT slab 120 mm deep, an initial camber of 50 mm, and a 60 mm deep concrete layer; both specimens were 600 mm wide (Tab. 1). The manufacturing process began by cambering the CLT with timber prisms (45 or 50 mm high) placed under the centre, and anchoring the panel ends to the floor. The adhesive Sikadur®32 [11] was applied to the curved CLT, and a concrete layer was cast. Once the concrete hardened, the anchors were removed on days 50 and 75 after concreting panels PS1 and PS2, respectively, inducing prestress in the CLT-concrete composite panels due to the timber's elasticity (Fig. 1). More about the manufacturing process and material used can be found in [10].

4.2 TEST SETUP

Strain gauges were placed in the middle of the panels' span on the top and bottom surface of the CLT before cambering, and on the top of the concrete 7 days after concreting. Linear variable displacement transducers monitored the panel deflection during the anchor removal and following 125 days. About 100 days after concreting, the panels were loaded with two weights at the thirds of the panels' spans, representing a potential service load of 2.0 kN/m^2 (indicating the increase in deflection shown in the graphs in Fig. 3-8 at around 100 days). After the test, the panels were stored without an external load under indoor ambient conditions. One year after concreting, the deflections of the panels were measured, and a 4-point bending test was performed. More about the long-term measurements can be found in [10], and the short-term measurements in [12].

Fragments of concrete with dimensions of 300 × 450 mm and a depth of 50 mm were made to measure the total shrinkage of the concrete using strain gauges and demountable mechanical gauges. In addition, the ambient temperature and relative humidity were recorded.

5 – THEORETICAL ANALYSIS

To evaluate the measured results, a theoretical model was developed. This model took into account the rheological properties of the composite materials, the effect of concrete shrinkage while considering crack formation, and the impact of temperature and humidity variations in the environment.

5.1 LONG-TERM BEHAVIOUR MODEL

The calculation model accounted for the entire process of manufacturing and subsequent monitoring of prestressed panels. It considered various rheological properties of the connected materials in long-term load cases LC1-LC6.

The prestressing of the CLT panel (LC1) was modelled by displacing the central support of the two-span beam by the camber value of the panel. Until the anchorage of the panel was removed by eliminating the central support, the self-weight of the CLT panel (LC2) and the weight of the fresh concrete (LC3) were considered as uniformly distributed loads on the two-span CLT panel.

After the removal of the panel anchorage, the reactions of the central support R1, R2, and R3 from load cases LC1 to LC3 were taken into account as a force load F = R1 + R2 + R3 at the mid-span of the simply supported, now composite, CLT-concrete panel (LC4). Throughout the manufacturing process, the load due to concrete shrinkage (LC6) was considered, both before and after the formation of shrinkage-induced cracks. After the removal of the supports, the conditions before and after crack closure were also taken into account.

Additionally, short-term loads on the panels were modelled without considering creep, including loading at approximately 100 days (LC5), loads from temperature variations (LC7), and environmental humidity changes (LC8).

The effective bending stiffness of the panels over time was calculated separately for each load case, depending on the start and duration of the load application. The calculation model accurately captured the development of strains and deflections over time [10] and proved to be suitable for parametric analysis of various influences. A comparison of measured and theoretical deflection can be seen in Fig. 3 and 4.

5.2 PARAMETRICAL ANALYSIS

The calculation model was used to analyse the influence of certain boundary conditions on the behaviour of the panels, particularly on deflection, which proved to be a crucial indicator in the design of such relatively thin TCC panels [7,8,10].

Concrete Shrinkage

The influence of concrete shrinkage on real specimens under measured environmental conditions was analysed. In the calculation model, the effect of concrete shrinkage was isolated by linearly subtracting the deflection from load case LC6.

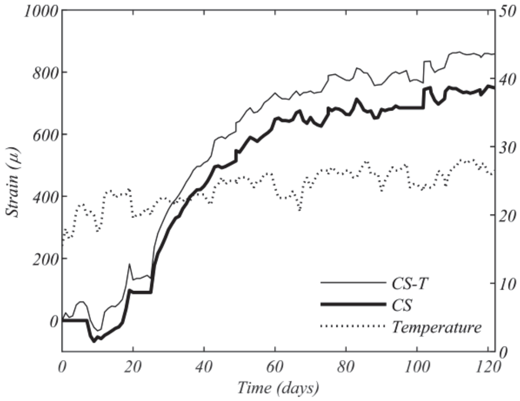

Figure 2. Concrete shrinkage (CS): Strains measured during the test, including temperature deformation. CS-T: Calculated strains excluding temperature effects. T: Ambient temperature.

Different Times of Anchor Removal

The effect of support removal on the deflection of prestressed panels was monitored by varying the initial time of load case LC4 application. However, this analysis was conducted under constant environmental conditions of 20°C and 65% relative humidity, considering the shrinkage behaviour of concrete measured during the experiment without the influence of temperature. The measured strain values due to concrete shrinkage were therefore adjusted by subtracting the strain caused by temperature variations, assuming a thermal expansion coefficient of concrete of 1.10^{-5} 1/°C (Fig. 2).

Different Precamber Values

Under constant environmental conditions of 20°C and 65% relative humidity, and with adapted concrete shrinkage values, influence of the value of precamber was analysed. Within the experiment, the chosen camber values corresponded to achieving the design strength of the CLT panels in bending. In the parametric analysis, lower precamber values were simulated.

6 – RESULTS

6.1 CONCRETE SHRINKAGE

In Fig. 2, the measured values of strain due to concrete shrinkage (*CS*) and the values after subtracting the thermal strain (*CS-T*) are shown. Since the temperature increased over time after concreting, the thermal strain had an opposite value. As a result, the final values of shrinkage strain under constant environmental conditions are higher.

In Figs. 3 and 4, the measured deflections of the panels PS1 and PS2, respectively, are compared with a theoretical model that accounts for actual temperature and humidity conditions as well as concrete shrinkage. The theoretical model accurately captured the behaviour of the panels (compare *test* and *theory* curve). When comparing the *test* and *theory-CS* curves, a significant impact of concrete shrinkage on deflection is evident. The deflections of the panels PS1 and PS2 due to shrinkage reached 19.6 mm and 23.1 mm, respectively. Considering the limit value of deflection for the panels, set at 1/250 of the panel span (17.6 mm and 23.2 mm, respectively), the deflection due to shrinkage is equal to or, in the case of the PS1 panel, exceeds these values. The precambering of such panels is thus necessary.

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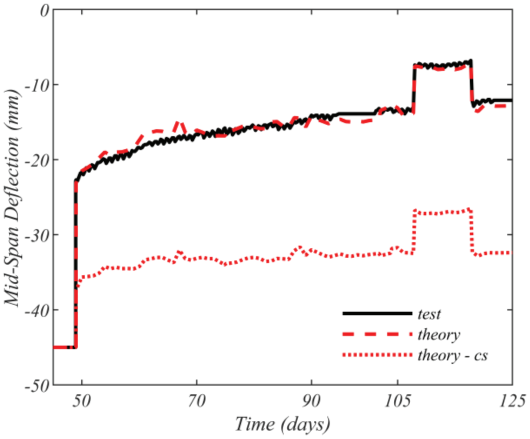

Figure 3. Deflection of the PS1 specimen: Comparison with a theoretical model and the influence of concrete shrinkage.

7.2 TIME OF ANCHORS REMOVAL

In the analysis, the deflection of the panels was calculated using different times for anchor removal t_{AR} under assumed constant environmental conditions (20°C and 65% relative humidity). The results in Figs. 5 and 6 show that the deflection of the panels 125 days after concreting depends little on the timing of the anchor removal.

When comparing the deflections of panel PS1 at 125 days, it can be seen that the difference between a t_{AR} of 10 days and 70 days is 1.9 mm (1/2316 of the span). In the case of panel PS2, the difference between t_{AR} of 10 days and 75 days is 2.8 mm (1/2071 of the span). From a production perspective, the most economical option is a shorter anchoring time for the panels in the manufacturing facility.

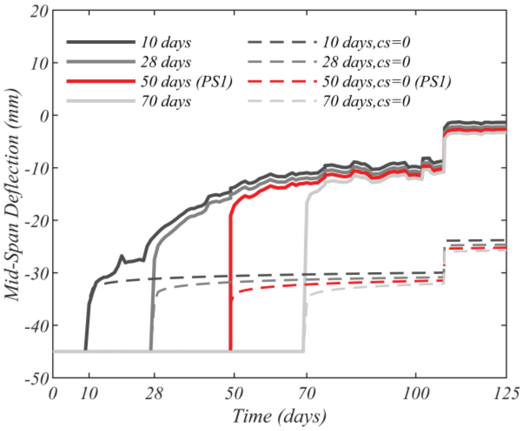

Figure 5. Theoretical deflection of PS1-type panels with different anchor removal times (10 to 70 days after concreting) under stable ambient conditions (20°C, 65% RH) over time. Dashed lines represent deflection without the influence of concrete shrinkage (cs = 0).

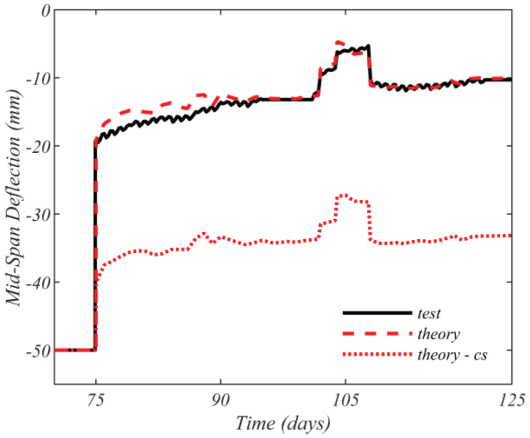

Figure 4. Deflection of the PS2 specimen: Comparison with a theoretical model and the influence of concrete shrinkage.

When comparing 10 days and 28 days, the time typically assumed for concrete to reach its full strength and stiffness, the theoretical difference in the deflection of panels PS1 and PS2 is only 0.9 mm and 1.2 mm, respectively. Therefore, we can conclude that, for the analysed panels, it would theoretically be relatively safe to remove the anchors as early as 10 days; however, a general recommendation is to wait until 28 days after concreting.

In the graphs in Figs. 5 and 6, the deflections without the influence of concrete shrinkage are shown. This deflection is caused by the loading condition, which takes into account the reversible force LC4 and the self-weight LC2. The significant impact of concrete shrinkage is evident, and its effect cannot be eliminated by delaying the removal of the anchors.

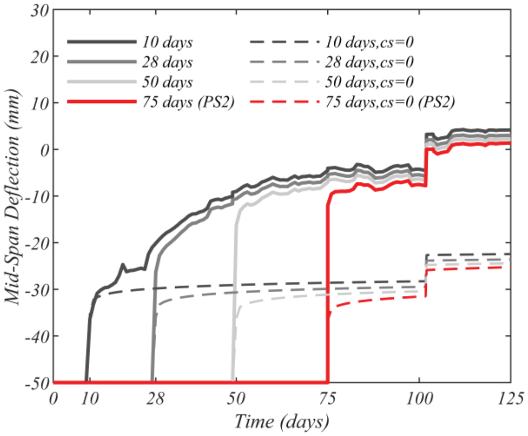

Figure 6. Theoretical deflection of PS2-type panels with different anchor removal times (10 to 75 days after concreting) under stable ambient conditions (20°C, 65% RH) over time. Dashed lines represent deflection without the influence of concrete shrinkage (cs = 0).

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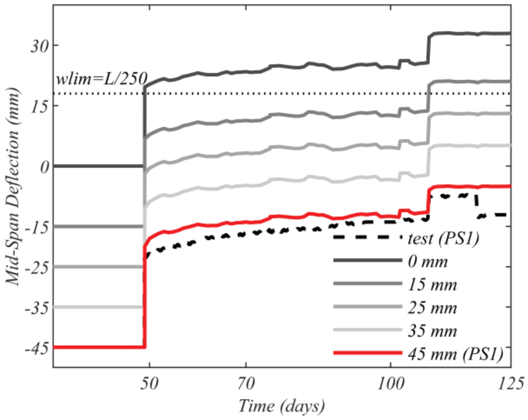

Figure 7. Comparison of the theoretical deflection of PS1-type panels with different precamber values (0 to 45 mm) over time under stable ambient conditions (20°C, 65% RH). Note: Test values correspond to unstable real conditions.

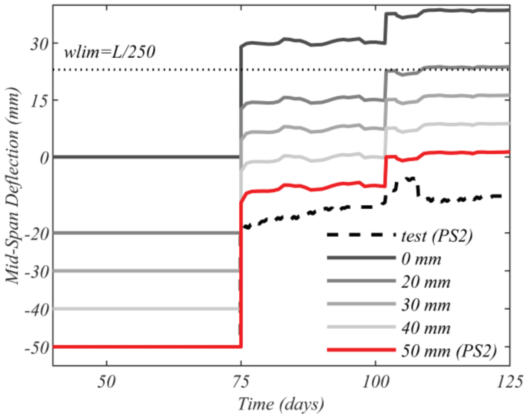

Figure 8. Comparison of the theoretical deflection of PS2-type panels with different precamber values (0 to 45 mm) over time under stable ambient conditions (20°C, 65% RH). Note: Test values correspond to unstable real conditions.

7.3 INFLUENCE OF PRECAMBER VALUE

In the analysis, the deflection of the panels was calculated using different values of initial camber. In Figs. 7 and 8, the measured *test* values are plotted (dashed line). While the calculated values were obtained under assumption of constant environmental conditions (20°C and 65% relative humidity), the measured values (dashed line) and the calculated values (red lines) differ. The visible difference shows the impact of temperature changes and the changes in timber moisture content, which affect the modulus of elasticity of the timber and, consequently, the stiffness of the simulated panels compared to the tested panels.

The graphs in Figs. 7 and 8 show that the value of initial camber has a significant influence on the deflection of the panels. Considering the potential service load of 2.0 kN/m², as indicated by the increase in the graphs around 100 days, a camber of 25 mm for both panels seems to be satisfactory, taking into account the limit value of 1/250 of the panel span.

8 – CONCLUSION

The conducted experiments confirmed the feasibility of the proposed technical solution, demonstrating that significant precambering of the timber part of the panel before concreting can effectively counteract the negative effects of concrete shrinkage in TCC mass panels when fresh concrete is bonded using adhesive.

The developed theoretical model accurately represented the panel behaviour and proved to be a reliable tool for analysing the impact of concrete shrinkage under different boundary conditions. The parametric analysis showed that the deflection of the panels 125 days after concreting was minimally affected by the timing of anchor removal. Furthermore, the results highlighted that concrete shrinkage has a significant impact that cannot be mitigated by delaying anchor removal. The initial camber plays a crucial role in controlling the final deflection of the panels, and a precamber of 25 mm for both panels appears to be an effective solution, ensuring that deflection remains within the acceptable limit.

These findings emphasise the importance of an appropriate initial camber in TCC panels to mitigate the long-term effects of concrete shrinkage, thereby ensuring structural performance and serviceability. Future research should focus on optimising precambering values and techniques to determine the most efficient and practical approach for minimising deflection while considering construction feasibility. Further studies can contribute to improving the reliability, efficiency, and large-scale adoption of prestressed TCC panels in construction projects.

9 – ACKNOWLEDGEMENT

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