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INNOVATIVE ADHESIVE BONDING IN TIMBER-CONCRETE-COMPOSITE SYSTEMS: TOWARDS A COMPETITIVE CEILING SYSTEM

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ABSTRACT: The construction industry is facing increased pressure to adopt resource-efficient practices due to escalating global sustainability challenges. This has led to a search for not only innovative and eco-friendly building materials but also designs and processes. One potential approach is the use of adhesive-bonded timber-concrete-composite (TCC) ceiling systems, representing a shift away from conventional construction methods relying on fasteners such as screws and bolts. TCC is presented as a more efficient alternative in terms of structural performance. Despite the recognized potential of the continuous bonding of concrete and timber, a significant knowledge gap remains due to the lack of comprehensive data on the adhesive joint's structural performance. For a full understanding of how these hybrid components perform under load, a systematic investigation is essential to derive reliable data for future design approaches. The presented study includes a series of experimental investigations on full-scale ceiling elements, with different span-lengths, bonding techniques, as well as varying cross sections. Each specimen was subjected to a four-point bending test to evaluate its load-bearing behaviour up to failure. The results indicate that adhesive bonding of timber and concrete enhances bending stiffness, significantly improving the serviceability of ceiling structures. This underlines the clear potential, declaring adhesive-bonded TCC ceiling systems as a competitive option based on the high structural performance. Nevertheless, research is required, particularly regarding the long-term behaviour and its limitations in design. In the interest of climate neutrality, it is also advisable to quantify potential environmental benefits and clearly compare them to alternative systems.

KEYWORDS: Hybrid Building Materials, Composite Structures, Sustainable Construction, Prefabrication Techniques, Economic Efficiency, Structural Glueing

1 – INTRODUCTION

The construction industry is one of the largest contributors to global greenhouse gas emissions, accounting for approximately 37% of total global CO_2 output [1]. As the humanity strives to mitigate climate change and reduce environmental impacts, the construction sector is under increasing pressure to adopt more sustainable and resource-efficient practices. Achieving this goal requires a transformation not only in the materials selection but also in construction methods and building system design. Hybrid constructions, for example, combine the strengths of different materials, and have emerged as a promising solution in this context.

A prominent representation of these hybrid constructions are timber-concrete-composite (TCC) systems. These systems utilise the compressive strength of concrete and the tensile strength of timber, combining the two materials to effectively transfer applied forces. This approach not only improves structural performance, but also optimises material usage, making TCC systems a resource-efficient choice, when directly compared to other conventional construction methods. The concept of bonding timber and concrete with adhesives emerged from the need to develop a technique that enables the connection of fully cured components [2]. This approach enhances manufacturing flexibility, as concrete elements can be prefabricated and stored independently before

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being reliably bonded to timber components. Furthermore, problems caused by shrinkage and early-stage creeping can be reduced compared to methods where the fresh concrete is directly cast onto the wood plates as the bonding happens when the components are already cured. However, a critical aspect influencing the performance of TCC systems is the shear bond between the timber and concrete elements, which ensures the effective transfer of internal forces between the two materials [3].

Historically, mechanical fasteners, such as screws or bolts have been used to provide bonding between timber and concrete, achieving limited performance in terms of stiffness. To overcome these limitations, the use of adhesive bonding in TCC systems represents a significant paradigm shift. Mechanical fasteners rely on discrete connection points, which result in uneven stress distribution along the interface [4]. In contrast to point connections, such as screws or bolts, adhesive bonding establishes a continuous connection between timber and concrete, facilitating uniform stress transfer across the interface, resulting in increased stiffness and strength, with the same geometric boundary conditions of the ceiling element. The need for mechanical fasteners is eliminated, resulting in simpler, faster, potentially more cost-effective construction processes and improved load-bearing behaviour.

Despite the mentioned benefits compared to conventional TCC systems, the application of adhesive bonding remains relatively unexplored. While initial studies have demonstrated its potential, critical knowledge gaps remain, particularly regarding the structural performance, long-term behaviour and design limitations, as well as a lack of manufacturing methods that can be applied to real-world conditions and are economically competitive with other existing bonding methods. Addressing these questions will bridge the gap between fundamental research and practical application, ensuring that future studies contribute directly to the advancement and implementation of adhesive-bonded TCC systems [5].

This study seeks to advance the emerging field by investigating the structural performance of the aforementioned TCC systems through experimental testing. The research focusses on full-scale floor slab elements, assessing their load-bearing behaviour. By providing a comprehensive dataset, to establish a base for future design approaches and contribute to the development of more sustainable and efficient building systems.

2 – MATERIALS AND METHODS

The methodology was designed to ensure reproducibility and reliability, following established standards [6] and incorporating comprehensive documentation of all experimental conditions.

2.1 BONDING TECHNIQUES

Two adhesive application methods were introduced to bond the timber and concrete elements: the "Pocket method" and "Channel method", seen in Figure 1. The Pocket method (as stated in the Patent FIW2938DE [7]) involves placing steel inserts into the concrete formwork to create specific pockets. After curing and demoulding, the pockets are sealed with silicone before the components are aligned to prevent the adhesive from leaking. The adhesive is injected through a designated inlet and exits through a secondary outlet at the opposite end of the pocket, ensuring complete filling while preventing air entrapment. The Channel method, as described in the Patent FIW2891DE [8], requires a channel, as wide as the timber beam, in the concrete surface, which is filled with adhesive after positioning the timber in the channel on spacers. Both methods ensure an uniform adhesive thickness, critical for structural performance [9]. In the Pocket method, the steel inserts define the adhesive layer thickness, whereas in the Channel method, spacers ensure the uniform 2 mm bond line.

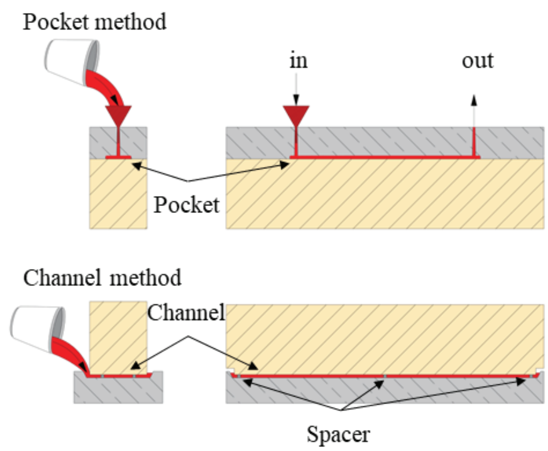

Figure 1. Illustration of the bonding techniques: Pocket method (top), according [7] *and Channel method (bottom) according* [8].

2.2 CONCEPTIONAL DESIGN

In the conceptual design process of the TCC ceiling elements the focus was set on achieving a structurally efficient system while carefully controlling the failure mechanisms to align with the study's objectives. The design process incorporated the principles of hybrid construction, utilizing the tensile strength of timber and the compressive strength of concrete, with the adhesive joint ensuring effective composite action. Within this study three distinct configurations, V1, V2, V3 were investigated, as summarized in Table 1 and Figure 2. Three samples of each configuration were produced and tested. The configurations included both flat and ribbed slabs, bonded using the Pocket or Channel methods, with lengths ranging from 5.55 meters to 5.68 meters and a uniform width of 1.50 meters. Flat slabs were chosen because of their widespread use in Austria, particularly in residential construction. Ribbed slabs, on the other

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Table 1: Overview of specimen geometry and bonding methods for all tested configurations.

Nr.	Tested Specimen	Length [mm]	Width [mm]	Adhesive Surface Area [mm²]	Bonding Method
V1	3	5550	1500	13.44×10^5	Pocket
V2	3	5680	1500	5.76×10^5	Pocket
V3	3	5680	1500	24.99×10^5	Channel

hand, were selected for their material efficiency and sustainability advantages, as the ribbed design allows for a reduction in concrete usage without compromising structural integrity. A schematic visualisation of the cross sections and top view with the zoning of the adhesive bond (in red), of all three configurations is shown in Figure 2. These configurations were dimensioned based on practical requirements identified for a subsequent pilot project [10], in which these elements were incorporated into a real building. The design of the TCC slabs was carried out using the γ-method according to ÖNORM 1995-1 [11], allowing a simplified calculation of such structures. The calculation was based on a flexible composite model, where the composite stiffness c is a key parameter. This bond stiffness c [N/mm²] was determined using Equation (1) [11], which considers the adhesive joint's width b_A [mm] and thickness d_A [mm] as well as the shear modulus G_A [N/mm²] of the adhesive itself.

$$c = \frac{b_A \times G_A}{d_A} \tag{1}$$

The bond factor γ, which describes the degree of bonding between timber and concrete, was calculated based on the calculated bond stiffness c. According to ÖNORM EN 1195-1 [11], the this factor depends on the mechanical properties and geometric parameters of the timber and concrete members.
The structural design of the TCC floor elements was for residential applications, considering load conditions in accordance with ÖNORM EN 1991 [12]. The design accounted for both the ultimate limit state (ULS) and the serviceability limit state (SLS). For the ULS, the elements were assessed for tensile and compressive stress, shear resistance, and connection utilization to ensure the structural safety under the maximum expected loading. The considered loads included the dead load of the floor system, consisting of the timber and concrete layers and the additional dead load of the floor buildup of 2.25 kN/m². In addition, partition walls, treated as permanent loads and imposed live loads typical of residential use of 3 kN/m² were considered in accordance with relevant standards (Eurocode 1). The total design load was 17.46 kN/m for the ribbed ceiling and 19.48 kN/m for the flat ceiling.

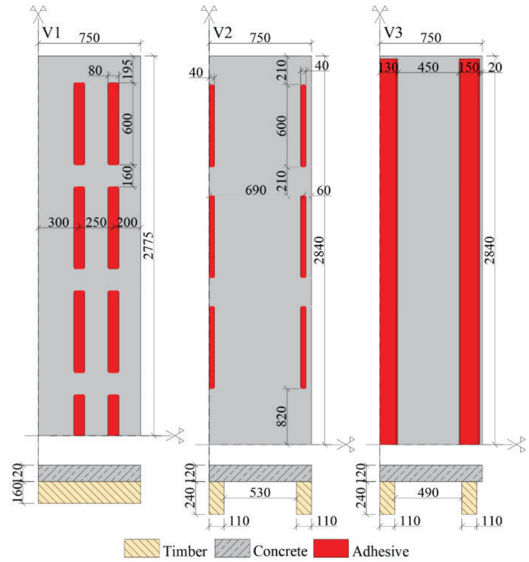

Figure 2. Detailed representation of the specimen geometry, including dimensions of bonded areas (red). All dimensions in mm.

2.3 Materials

The primary materials used in this study were concrete of strength class C40/50, according ÖNORM B 4710-1/2018 [13], timber in the form of glued laminated (GLT) beams with a quality of GL24h and cross laminated timber CLT 160mm 5s with a quality of C24, according ÖNORM EN 14080:2013 [14], and a specially developed 2K epoxy adhesive provided by fischerwerke GmbH & Co. KG. The adhesive was formulated specifically for the project, designed to provide optimal bonding of timber and concrete. The material properties, including mechanical characteristics of the concrete, timber, and adhesive are listed in Table 2. The compressive strength was tested on cubes and cylinders in accordance with ÖNORM EN 12390-3:2019 [15], while the elastic modulus was determined in accordance with ÖNORM EN 12390-13:2013 [16]. It was decided to not conduct additional material tests on the timber elements, as documentation and quality assurance measures were provided by the manufacturer in compliance with ÖNORM EN 14080:2013 [14].

Table 2: Mechanical properties of the materials used in the study, including experimentally determined values and manufacturer-provided data

Material	Specified by the manufacturer	Standard
Concrete C40/50	C 40/50 Consistency Class: B4 Maximum Aggregate Size: 16mm Frost Resistance: F45	ÖNORM EN 206 [18] ÖNORM EN 12620 [19] ÖNORM EN 206 [18] ÖNORM EN 206 [18]
Timber Gl24h	$f_{t,0,k}$ = 19.2 MPa $E_{0,mean}$ = 11500 MPa	ÖNORM EN 14080:2013 [14]
Timber C24	$f_{t,0,k}$ = 14.5 MPa $E_{0,mean}$ = 11000 MPa	ÖNORM EN 14080:2013 [14]
Adhesive	$f_{adh., concrete} \geq$ 2,5 MPa $f_t \geq$ 50 MPa $E \geq$ 3500 MPa	GB 50728-2011 [20]

2.4 Manufactoring and Experimental Setup

Adhesive bonding was performed 21 days after concrete casting, ensuring sufficient curing time [17] for the concrete to reduce a negative impact through shrinkage and creep effects.

One day after bonding, the specimens were transported to the testing facility and tested seven days later. The specimens were stored outdoors, protected from rain using plastic tarpaulins. Environmental conditions, including temperature and humidity during storage and testing, were consistent with those typical of prefabrication facilities. The timber elements had an average moisture content of 12.3% at the time of testing.

The tests were conducted as four-point bending experiments, a widely used method for evaluating the flexural behaviour of structural elements. Loads were applied at the third points of the span, as presented in Figure 3, to create a constant bending moment region between the load introduction points, minimizing shear influence in this section. The loading was applied using a hydraulic system, with a manually controlled valve. It was aimed to apply the load with a constant increase. The force was documented by a load cell, which was integrated in the servo hydraulic cylinder of the testing machine. Each test was designed to last between 25 and 35 minutes, allowing sufficient time to capture detailed deformation and failure mechanisms. The test setup, load application, measurement positions for deflection and slip, as well as the evaluation of deformations were conducted in accordance with the specifications outlined in ÖNORM EN 408:2012 09 01 [6], ensuring compliance with the standard's requirements for bending tests and slip measurements. The measurement setup was designed to capture all critical parameters. Linear Variable Differential Transformers (LVDT) were installed to measure vertical deflection at midspan and load application points, while slip between timber and concrete was monitored at the specimen ends near the supports and at the load application points, as shown in Figure 3. The deformation in the support area was also monitored during the tests. The applied load was continuously recorded using a load cell integrated into the hydraulic cylinder. Each specimen was loaded until failure, and all data were digitally recorded for further analysis.

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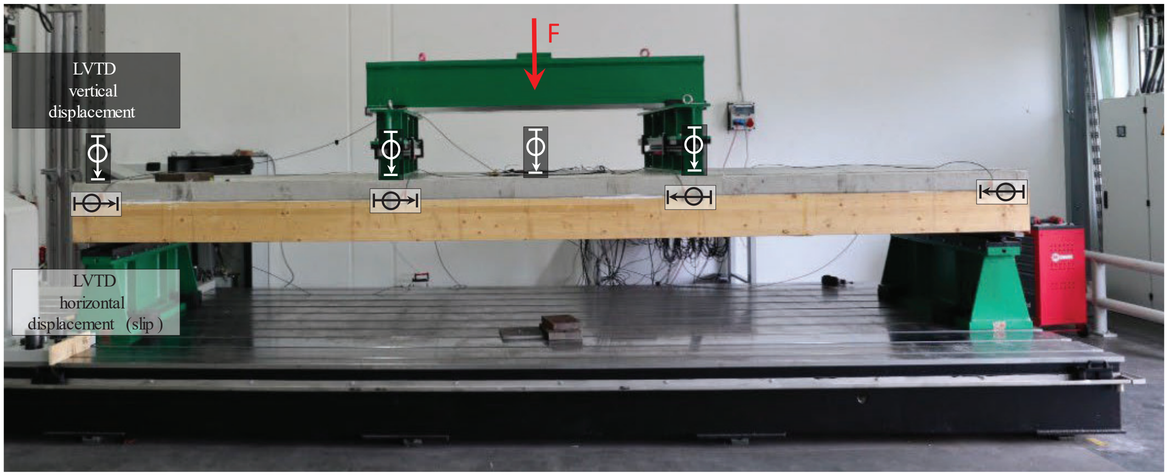

Figure 3. Experimental setup illustrating the location of LDTVs including slip between timber and concrete, vertical displacement at the third points, mid-span, and support

3 – RESULTS AND DISCUSSION

The experimental program included the testing of three different TCC ceiling configurations (V1, V2, and V3), each subjected to four-point bending. Observations during the tests revealed distinct behaviour patterns and failure modes for each configuration. The results are presented in the graphs within Figure 4. The mean ultimate load M_{max}, standard deviations, and failure modes for all three configurations are summarized in Table 3. Dead load of the ceiling itself and the test setup for load distribution (950kg) were not additionally considered within the results.

Table 3: Overview of the results of the experimental investigation.

Nr.	$\bar{M}_{max}$ [kNm]	s [%]	Failure Mode
V1	482.76	9.30	Timber tension zone
V2	401.81	6.37	Timber tension zone
V3	370.29	6.57	Timber tension zone

All samples exhibited linear elastic behaviour up to a certain level. Thereafter, a slight non-linearity was observed though its exact cause could not be clearly identified based on the conducted measurements. However, an increasing relative displacement between the timber and concrete was detected. The change in stiffness within the adhesive joint could potentially contribute significantly to the reduction of the overall bending stiffness as the applied load increases. In all configurations, the failure mechanism was consistently located in the timber tension zone, as dimensioned beforehand. No adhesive debonding or failure at the timber-concrete interface was observed, indicating the effectiveness of the adhesive bonding techniques.

Configuration V1 achieved the highest mean ultimate load, as intended, due to a higher design load resulting from a heavier floor structure within the pilot-project design. Furthermore, higher standard deviation observed in the V1-specimens is likely due to the use of CLT instead of GLT, introducing greater variability in the material properties and, consequently, in the ultimate load. Configurations V2 and V3 showed very similar performance in terms of ultimate load and failure modes. The slightly reduced mean ultimate load observed in V3 can be attributed to the failure of one of the three beams within the specimen in the timber tension zone, where a finger-jointed lamella was located in the mid-span region, experiencing the highest bending moment and therefore leading to early failure of the joint. It can be noted that the reduced adhesive bonding surface of the pocket method did not exhibit any significant negative impact on the experimental test results, in terms of deflection and load capacity.

During the design of the TCC elements, it became apparent that the SLS would not be critical under the given boundary conditions. These included a relatively short span, a 12 cm slab thickness requested by the concrete supplier, and the resulting high overall bending stiffness of the system. For the quasi-permanent load scenario, decisive for the SLS, no combination factor $\psi 2$ was applied, as the assessment focused on short-term deformations, excluding long-term creep effects. Under these conditions, design moments of 48.94 kNm were determined for the flat-slab configuration (V1), and 50.01 kNm for the ribbed slabs (V2 and V3). The limit for deflection was set to L/300, corresponding to 18.5 mm for V1 and 18.9 mm for V2 and V3. At the corresponding SLS load level, the measured mean deflections were 4.02 mm for V1, 3.95 mm for V2, and 4.24 mm for V3—significantly below the respective allowable limits. These results confirm that, within the tested parameter range, the SLS was not decisive due to the relatively short spans and high flexural stiffness of the elements. To further investigate the impact of span length on serviceability performance, the experimentally determined bending stiffness, for the decisive SLS load level, was used under the assumption that the system's bending stiffness remains constant, when increasing the span length. By rearranging the standard single-span deflection formula for uniformly distributed loads such that the resulting deflection δ equals L/300 (Formula 2 and Formula 3), V1 was found to permit a maximum span of 9.23 m, while V2 and V3 could reach 9.52 m before SLS deflection criteria became decisive.

$$EI_{eff} \times \frac{L}{300} = \frac{5}{384} \times q \times L^4 \quad (2)$$

$$L = \sqrt[3]{\frac{32 \times EI_{eff}}{125 \times q}} \quad (3)$$

These findings underscore that serviceability requirements gain significance as span lengths increase. Conversely, for the shorter spans commonly found in residential buildings, the ULS remains the primary design driver.

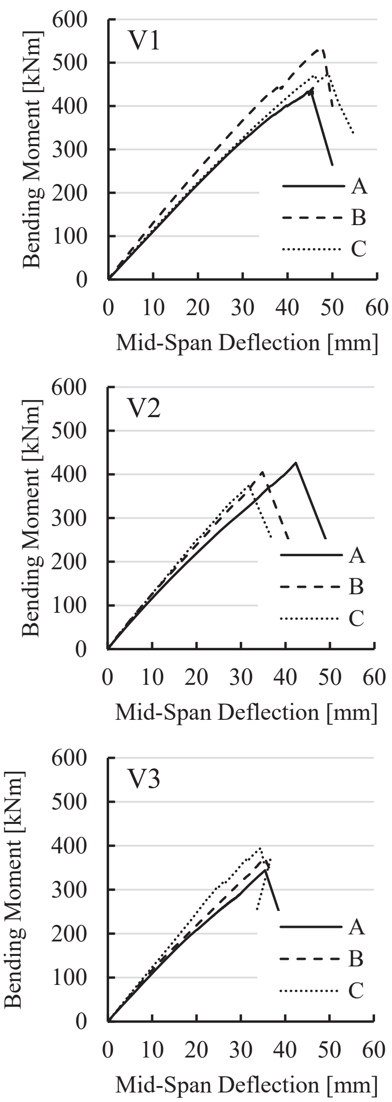

Figure 4. Bending moment versus mid-span deflection curves for all tested specimens across the three configurations

4 – CONCLUSION

The present study investigated the structural performance of three distinct configurations of adhesively bonded TCC ceiling elements through experimental testing under four-point bending. The results provide valuable insights into the load-bearing behaviour and failure mechanisms of this hybrid construction system. All tested configurations demonstrated effective composite action, as evidenced by the absence of adhesive debonding or interface failure. This confirms the reliability of the adhesive bonding methods employed in ensuring shear transfer between the timber and concrete components (at least in a short-term view). In all configurations, failure occurred in the timber tension zone due to the tensile strength of the timber being exceeded. While the SLS remained non-governing under the conditions assessed in this study, these findings highlight its growing importance for larger spans and underscore the need for continued investigation into long-span TCC systems.

The findings highlight the potential of adhesive bonding in TCC systems as a viable alternative to traditional mechanical fasteners. The continuous bond provided by the adhesive not only simplifies the construction process but also provides a great stiffness and strength, making these systems highly competitive for residential and commercial applications. Ribbed TCC ceilings offer an advantageous alternative to flat slabs, as their design reduces overall timber consumption relative to systems incorporating CLT panels, thereby enhancing both material efficiency and cost-effectiveness.

This study provides a first data base for future design approaches for adhesive-bonded TCC systems, nevertheless several critical aspects remain to be explored. The durability of the adhesive bond under varying environmental conditions (e.g., moisture, temperature, and aging) and cyclic loading must be thoroughly examined to ensure the system's longevity. Quantitative evaluations of the environmental and economic benefits of TCC systems compared to conventional construction methods are needed to support their broader adoption in sustainable building practices. By addressing the identified knowledge gaps, these systems could play a significant role in advancing sustainable and high-performance building technologies, contributing to the reduction of the construction sector's environmental footprint.

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