

INNOVATIVE CONNECTION SOLUTIONS FOR TCC FLOOR SYSTEMS: MECHANICAL AND ENVIRONMENTAL ASSESSMENT

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ABSTRACT: The need to reduce carbon emissions in the construction sector has highlighted timber as a viable substitute for carbon-intensive materials such as concrete. Cross-laminated timber (CLT), as a load-bearing element, has gained popularity in recent years due to its favorable structural characteristics and environmental benefits. The use of CLT in timber-concrete-composite (TCC) floor systems has been increasingly explored, but current building codes and standards have not been adapted accordingly. This limits design options, simultaneously fostering opportunities for innovation. In this paper, a new type of shear connector, designed to transfer forces between prefabricated CLT and concrete components in a TCC floor system, is experimentally investigated. The connector is part of a dry-dry system, in which both concrete and timber elements are prefabricated and assembled without wet processes, allowing rapid installation and potential disassembly. To evaluate environmental performance, a functionally equivalent hollow core slab (HCS) is designated as a reference for comparison. The relevant assessment is conducted using the life cycle assessment (LCA), where the manufacturing and end-of-life (EoL) stages are considered. The results reveal promising mechanical performance of the new connection solution for TCC, potential carbon benefits, and viable deconstructability and reusability.

KEYWORDS: timber, CLT, TCC, dry-dry system, carbon emissions

1 – INTRODUCTION

The construction industry is facing increasing pressure to adopt sustainable materials and innovative building methods to reduce its environmental impact. Timber has emerged as a key material in this transition because of its renewable nature, its high structural efficiency, and its carbon storage potential. Cross-laminated timber (CLT), which is used for floors, walls, and roof systems in multistory buildings, has gained significant attention in recent years. In addition, the combination of timber with other materials, such as concrete, in timber-concrete composite (TCC) systems, has proven to be a viable strategy for enhancing structural performance while maintaining sustainability.

In hybrid construction, TCC systems where the CLT is utilized have gained more attention in recent years. These systems take advantage of the complementary properties of timber and concrete, offering benefits such as increased span lengths and improved acoustic performance. A critical determinant of their success is the performance of shear connectors, which are essential to facilitate effective load transfer between the two materials and to ensure reliable composite action [1].

Previous studies (e.g. [2–4]) have explored the design and performance of prefabricated timber-concrete composite floors, and highlighted the need for efficient connection systems to support modular construction and design for deconstruction (DfD). As the construction sector shifts toward circularity, DfD has gained increasing attention as

¹HAMK Tech research unit, Häme University of Applied Sciences, Finland, cristina.dachin@hamk.fi ²HAMK Tech research unit, Häme University of Applied Sciences, Finland, yishu.niu@hamk.fi a framework to allow reuse and adaptability of structural components, especially in systems where different materials are integrated. However, the effectiveness of these systems is highly dependent on the efficiency of their connections, which influence both the mechanical behavior and the long-term durability [5, 6].

A key advantage of the system investigated in this study is the *dry-dry* assembly method, in which both concrete and timber components are prefabricated and connected using mechanical fasteners, thus avoiding the use of wet materials or adhesives. This contrasts with conventional dry-wet systems - where the timber element is prefabricated and the concrete is cast on-site and wet-wet systems, such as fully cast-in-place reinforced concrete slabs, where both components are assembled using on-site casting or wet processes. By eliminating casting and curing on site, the dry-dry method avoids weather-related delays, reduces the risk of concrete shrinkage, and allows immediate load application, thereby accelerating the construction process and improving reliability [7, 8]. In addition, simultaneous site preparation and component production optimize project timelines and reduce labor demands [9].

This study investigates a novel connection solution for the CLT-concrete composite slab (CCCS) system. The proposed connector, referred to in this paper as the V connector, is designed for easy installation and provides reliable mechanical performance. It also supports the prefabrication of floor elements in factory settings. The off-site manufacturing improves quality control, shortens construction timelines, reduces on-site labor, and minimizes waste and disruption on the building site. Together, these advantages contribute to sustainable construction practices. More details on the geometry, materials, and connector installation process are provided in Section 4.2. The connection system also aligns with the principles of DfD, enabling the disassembly and reuse of structural components without damage, supporting the circular economy, and extending material's life cycle [2, 5].

The objectives of this research are to analyze (i) the mechanical performance of the new connection solution, focusing on the load-bearing capacity and the slip modulus, and (ii) the environmental performance of the testing slab through the life cycle assessment (LCA), comparing it to that of a conventional hollow core slab (HCS) alternative. In addition, disassembly and reusability are discussed.

2 – METHODOLOGY

The methodology applied in this study consists of a review of relevant literature, experimental testing and analysis, and LCA.

2.1 COMPARATIVE BASIS AND TEST SET-UP

A literature review was conducted to support the planning and contextualization of the experimental study. The review served three main purposes: first, to identify the mechanical properties that are most commonly evaluated for TCC connectors; second, to determine suitable experimental methods to assess these properties; and third, to identify widely used shear connector types for comparison. Previous studies have reported various connector solutions, including notched connectors, screw-based systems, and plate connectors used in prefabricated TCC slabs [2, 10, 11]. These references provided typical performance ranges and design characteristics, which helped in deciding on the test set-up and the type of reference connectors used for comparative evaluation. Among the test methods available, the push-out setup was chosen due to its practicality, repeatability, and wide use in the evaluation of early phase connectors [4]. Based on the literature, three alternative connector types were selected for additional testing to determine whether the newly proposed V connector performs competitively in this context.

2.2 SMALL-SCALE EXPERIMENTS

Small-scale tests were used to investigate the mechanical performance of the proposed connection system. This method is widely adopted to assess the shear behavior and load-slip response of timber–concrete composite connections. Among various small-scale testing techniques, such as beam shear, single or double shear, and asymmetric fourpoint bending, the push-out test is often favored for its simplicity, repeatability, and consistency with standard evaluation procedures [4]. The standardized setup also allows for direct comparison between different connector types and geometries, supporting informed decision-making in both product development and research.

The tests were carried out according to EN 26891 [12], EN 408 [13], and EN 1995-1-1 [14], in order to determine key mechanical properties of the connector, including slip modulus, shear capacity, and failure modes. These characteristics are essential for assessing the effectiveness of connection systems in prefabricated composite floors and for enabling comparisons across different types of connectors. Furthermore, push-out tests require relatively limited material and equipment, making them accessible and cost-efficient while still producing meaningful structural insights. These advantages make the method particularly suitable for evaluating prefabricated and modular connection systems such as the analyzed CCCS, where consistent mechanical performance and reliability are vital for broader implementation.

The method enables a clear understanding of how shear forces are transferred at the timber–concrete interface, making it especially useful in the initial development and validation of new connection systems, where design optimization and proof of concept are essential.

2.3 ASSESSMENT OF ENVIRONMENTAL PERFORMANCE

The environmental performance of the slab was assessed using the LCA methodology. It is a systematic methodology for evaluating the environmental impacts of products, processes, or systems throughout their entire life cycle, from raw material extraction to disposal. In the construction sector, LCA has been applied in both products and projects (e.g. [15–18]). There is a series of standards that guides the LCA calculation, where the assessment procedure is described and the impact categories are listed.

LCA-related standards have been published since 2006, such as ISO 14040 [19] and ISO 14044 [20]. These standards define four stages of LCA, starting from the definition of the objective and scope, through the analysis of the inventory and the impact assessment, to the final step in the interpretation phase. There are relevant standards specifically designated for construction works, such as EN 15804+A2 [21] and EN 15978 [22]. Regarding the LCA implementation, inventory data(base) are needed, consisting of both generic data and specific data. Specific data may be provided by the manufacturer or published as an Environmental Product Declaration (EPD). The EPD is based on the LCA methodology and complies with ISO 14025 [23], serves as a standardized document that provides transparent and comparable information on the environmental impact of a product. In Europe, the building life cycle stages are defined by these standards, including the product stage (modules A1-3), the construction stage (modules A4-5), the use stage (module B) and the end-of-life stage (EoL) (module C). Supplementary information beyond the life cycle (module D), accounting for relevant benefits and loads due to e.g., reuse and recycling potentials, is included. In addition, for timber products, carbon sequestration and relevant calculations are defined in EN 16449 [24]. Different impact assessment methods (e.g., Level(s) [25] and EN 15804+A2 [21]) are available for LCA studies in the construction sector. These methods evaluate the environmental impacts of a product or process based on various impact categories, such as global warming potential and resource depletion. Among these impact categories, the most common one is global warming potential (GWP), quantified in terms of CO₂-equivalents (abbreviated as CO₂-eq. hereafter), following the IPCC [26].

3 – EXPERIMENT AND ASSESSMENT

This section describes the materials, test configuration, specimen preparation, and testing procedure used to evaluate the mechanical performance of the proposed V connector. The relevant results are compared with those of other commonly used TCC connector types. The experimental program consisted of two separate series. The Main Test Series uses the proposed V connector. The Comparative Test Series uses three alternative connector types to benchmark the performance of the investigated connector. The chapter also includes the LCA of the CCCS system. For environmental comparison, a functionally equivalent HCS was selected as the reference.

3.1 SPECIMEN CONFIGURATION

All samples used in the experimental program consisted of CLT and concrete components connected by a single shear connector positioned at the center. The same material specifications and dimensions were maintained in both the Main Test Series (using the proposed V connector) and the Comparative Test Series (using alternative connectors) to ensure consistency and comparability.

The CLT panels had a total thickness of 140 mm and were made up of five layers, the outer layers oriented perpendicular to the applied load direction. The panels were made of spruce, with a characteristic density of 473.5 kg/m³ and an average moisture content of 9% at the time of the testing. Across all tested samples, the timber density ranged from 468.06 kg/m³ to 478.31 kg/m³. Each panel had a width of 360 mm and a length of 590 mm.

The concrete slabs with a 20 MPa strength target were cast with one shear connector previously installed, following EN 206 [27] standard. The concrete slabs had a width of 360 mm, a length of 590 mm, and a thickness of 80 mm, with a consistent weight of approximately 32.5 kg. The concrete age at the time of the test ranged from 31 to 35 days. No surface treatment was applied at the timber-concrete interface.

All specimens in both series were prepared using the same casting and curing conditions and tested under identical indoor environmental conditions to minimize variability due to external factors.

3.2 CONNECTOR AND SAMPLE PREPARATION

The Main Test Series focused on the V connector, developed specifically for CCCS systems. The V connector consists of a plastic casing that is first fixed to the concrete formwork before casting. During casting, the concrete fully encases the plastic housing. After a 28-day curing period, the pre-cast slab is removed from the formwork and placed on the CLT panel, with an offset of 100 mm in the longitudinal direction. The mechanical connection is completed by inserting screws through the plastic casing and into the timber. This method eliminates the need for adhesives or wet processes, enabling fast and reversible assembly. There is no direct contact between the screws and the concrete. A simplified conceptual sketch of the V connector is shown in Figure 1. As the product is still under development, detailed geometric information is not disclosed. The figure





Figure 1: Conceptual sketch of the novel connector - V connector in this paper

is intended to illustrate the basic working principle of the connector and its role in forming a reversible screw-based shear connection between the prefabricated concrete and CLT components.

The same sample preparation method was applied to the Comparative Test Series, which included three alternative connector types: dovetail notches, screw-based systems, and plate connectors installed parallel and perpendicular to the timber grain. Each type of connector was installed according to the manufacturer's guidelines or design standards. All specimens featured a single centrally placed connector between the CLT and concrete components. The assembly steps were carefully controlled to ensure proper alignment and uniform contact pressure at the interface, preventing premature failure due to installation inaccuracies. All tests were carried out indoors with room temperatures of 18.9 °C to 19.6 °C and relative humidity levels between 28.2% and 33.1%.

3.3 TEST SET-UP

The mechanical performance of the proposed connection was assessed using push-out tests. These were carried out according to standardized protocols to evaluate the slip modulus and shear capacity of the connector. Figure 2 illustrates the experimental setup used to evaluate the mechanical performance of the connection. The setup includes the arrangement of the test specimens, the loading mechanism, and the displacement measurement devices. It was designed to ensure consistent loading conditions representative of real-world applications and complies with the European standards EN 26891 [12] and EN 408 [13]. For all testing samples, the shear load was applied perpendicularly to the CLT until failure occurred, using a hydraulic test machine with a precision of 1% in the load range of 0-250 kN and a sample interval of 0.33 s. The load distribution was achieved by an intermediate steel plate placed on top of the CLT part. The displacement was recorded using three linear Voltage Displacement Transducers (LVTD), one connected to the load cell, and two mounted on each side of the sample to measure the relative slip between the concrete slab and the CLT element. The data acquisition system captured the load and slip at a sampling rate of 3 Hz

This set-up of experiments was used consistently for



Figure 2: Experimental setup for push-out tests

both the Main Test Series using the V connector and the Comparative Test Series evaluating alternative connector types. All specimens were tested under the same conditions to ensure a valid comparison of mechanical performance between connector configurations.

3.4 TEST PROCEDURE

As part of the Main Test Series, a set of ten push-out tests was performed to evaluate the shear performance and the interface behavior of the connection system. The first test, performed on a single sample, was used to estimate the maximum failure load F_{est} and establish the loading protocol. Based on this protocol, the remaining nine samples were tested to evaluate the load-slip behavior, the stiffness of the connection, and the failure modes. The samples were labeled as follows: taking V2-01 as an example, "V2" represents the connector with two screws, and 01 specifies the sequential number of the testing sample. It should be noted that the V2-02 sample was specifically used to estimate the Fest, which was further used to define the loading procedure for the remaining tests. The loading was applied in a controlled sequence according to EN 26891 [12], starting with a preload phase up to 40% of $F_{\rm est}$, followed by a reduction to 10% of F_{est} . Subsequently, continuous loading was applied at a constant rate until failure. The test slabs were disassembled after the tests, to explore the viability of disassembly and reuse.

The Comparative Test Series was conducted using alternative connector types: dovetail notches, screw-based systems, and plate connectors. These tests, although outside the primary scope of this study, were performed under consistent conditions and were used to contextualize the performance of the V connector. Each type of reference connector was tested in sets of five samples under the same testing conditions and using the same procedure. Although the limited number of samples per connector does not provide a lot of statistical data, they offer a useful indication of relative performance. The results of this comparison are discussed in Section 4.1.

3.5 ENVIRONMENTAL PERFORMANCE

A functionally equivalent concrete slab was selected for comparison, i.e. typical prefabricated HCS, under the same load combination and service class. The chosen HCS, designated as GP20 by the local manufacturer (relevant EPD available [28]), has a thickness of 200 mm and a standard width of 1200 mm. It is a prefabricated element, typically produced using C50/60 concrete. The applied load is assumed to be 5 kN/m² (with a maximum of 4 m span). Both slabs (the tested CCCS and HCS) are designed with a service life of 50 years, no maintenance is associated, that is, the environmental impact induced during the use stage is zero. Two EoL scenarios are assumed for the tested CCCS: (a) reuse - CLT being reused and concrete being recycled; (b) common practice - CLT being incinerated for energy and concrete being recycled. The EoL for HCS follows the claim in EPD [28], that is, recycled. Screws and plastic casing are assumed to be reused.

The environmental performance of the two cases (CCCS and HCS) was assessed. The focused environmental impact indicator is the GWP, presented by per m² of the slab during the 50-year service life. The life cycle stages evaluated include the manufacturing and EoL stages: modules A1-3 and C1-4, as defined in the standards [21, 22]. Loads and benefits beyond the system - module D is also presented, where different EoL scenarios are considered. The level(s) method [25] is adopted as the assessment method for the GWP calculation. Generic data are used when there is no available EPD for the material. For the reference slab, HCS, the GWP values of the EPD [28] are used.

4 - RESULTS AND DISCUSSION

The obtained results from the CCCS experiments include, e.g. force-displacement curves, slip modulus, and failure modes. The relevant environmental impacts are presented for the tested CCCS and the HCS, in terms of the GWP indicator. The potential for deconstructability and reuse is also discussed.



Figure 3: Load-Slip representation for V connectors.

4.1 MECHANICAL PERFORMANCE

The push-out tests confirmed that the V connector provides promising mechanical performance for CCCS systems. The slip modulus values ranged from approximately 8.9 to 17.3 kN/mm, while the maximum load, $F_{\rm max}$, varied between 21.76 kN and 46.38 kN, depending on the specimen and the failure mode. The complete test results are summarized in Table 1. Most specimens failed in the concrete layer, typically by internal cracking or crushing near the connector, indicating that the connector itself maintained structural integrity under shear loading. In some cases, failures were attributed to broken screws or installation issues, especially where concrete had entered and compromised the plastic casing.

Sample	$F_{\rm max}$ [kN]	K_s [kN/mm]	Failure Mode
V2-01	38.13	14.34	Concrete
V2-02*	46.38	Fest	Screw
V2-03	36.57	10.60	Concrete
V2-04	40.20	10.43	Concrete
V2-05	21.76	12.90	Screw
V2-06	45.51	8.91	Concrete
V2-07	42.55	16.12	Concrete
V2-08	41.47	14.96	Concrete
V2-09	43.33	14.09	Concrete
V2-10	43 97	1735	Screw

Table 1: Results from the push-out tests.

* The sample was used for obtaining the force at failure F_{est}

The load-slip behavior of the V connector samples is illustrated in Figure 3. It can be seen that all the plots follow a similar pattern, with only minor variations caused by the material inconsistencies. The applied force generally increases gradually with slip, reaching peak loads between 35–46 kN. It can be seen that the maximum recorded slip remained below 7 mm for all specimens. Samples such as V2-01 and V2-07 showed behavior consistent with concrete-related failures, while V2-05 and V2-10 exhibited responses potentially linked to screw failure.

To better understand the performance of the V connector, its results were benchmarked against those of the Comparative Test Series. The mechanical performance of these connectors was assessed in terms of their mean maximum load, F_{max} and the slip modulus, K_s . As shown in Table 2 and illustrated in Figure 4, the V connector performed competitively, with a mean shear resistance of 40.27 kN. Although



Figure 4: Average force-slip curves for different connector types based on small-scale push-out tests.

the dovetail notch and screw-based systems showed slightly higher average loads, the proposed connector maintained a balanced combination of strength and construction benefits. In terms of slip modulus K_s , the V connector achieved a value of 13.82 kN/mm, which, although slightly lower than some of the alternatives, still provides an effective composite action. In particular, the plate connector installed parallel to the grain had the highest slip modulus but lower strength, indicating that stiffness alone does not guarantee superior overall performance.

It is important to note that, due to the limited number of samples (five per connector type), the results should be interpreted as indicative rather than definitive. The purpose of this comparison is not to classify the connectors, but to demonstrate that the V connector provides a valid and mechanically sound option within the broader context of TCC systems.

Table 2: Comparison of the mechanical performance when using different connectors

-		Mean F_{max}	Mean K_s
	Connector Type	[kN]	[kN/mm]
	V connector (this study)	40.27	13.82
	Dovetail (DT)	47.51	17.31
	Plate connector //	27.89	18.75
	Plate connector \perp	20.34	17.61
	Screws (2S)	45.55	14.68

4.2 ENVIRONMENTAL PERFORMANCE

The assessed GWPs of both tested CCCS and reference HCS are listed and compared, as shown in Table 3.

Table 3: GWP-total values of compared cases (in kg CO_2 -eq./m²).

	Modules	Modules	Module
	A1-3	A-C	D
CCCS – Reuse	-86.53	25.97	-14.72
CCCS – Common case*	-86.53	27.31	-5.83
HCS**	21.27	24.41	-2.43

*: EoL scenario: timber being incinerated, concrete being recycled. **: EoL scenario specified in the EPD [28].

It can be seen that, when comparing the GWP throughout the life cycle (modules A-C), the prefabricated HCS has a lower GWP (about 6-10% less), compared to the tested CCCS. However, when considering the GWP from the manufacturing stage (i.e. modules A1-3), the tested CCCS exhibits much better performance, as the carbon is sequestrated in the slab at this stage, indicated by negative values of the GWP. Moreover, when comparing the net benefits after reaching the EoL, i.e. module D, the tested CCCS has a higher GWP than the HCS, regardless of the EoL scenario. Especially when the tested CCCS is under the reuse scenario, it could save approximately 6 times CO₂-eq. compared to the HCS. In addition, from the cradle-to-cradle perspective, which entails the combination of the two values from Modules A-C and D, CCCS demonstrates superior performance in terms of GWP.

4.3 REUSABILITY

The CCCS was disassembled after testing, to explore the potential of disassembly and relevant reusability. An example of the disassembled slab is shown in Figure 5. The



Figure 5: The disassembled CCCS testing sample.

disassembly process is rapid and straightforward and does not require specialized equipment, but rather an electric hand drill. The elements separated from the disassembly remain intact, thereby enhancing the potential for reuse. The connecting parts - screws and plastic casing - remained intact after disassembly, demonstrating high potential for reuse as well.

Regarding the disassembly and reusability of CCCS and HCS in practice, the comparison of the relevant potential is described in Table 4. It is obvious that CCCS has a higher potential for reuse, either as an intact element or as separate elements. This also reflects the benefit of DfD. However, further studies are essential to ensure structural properties and establish guidelines from disassembling to assessment, so disassembled elements can be documented in a similar way to new products.

4.4 CHALLENGES AND DISCUSSION

The experimental results demonstrated promising mechanical performance for the proposed connection system; however, several practical challenges were encountered during testing and assembly. In particular, some issues were observed with the plastic casing. Concrete often entered the inclined screw housing despite sealing attempts, compromising the screw seat and occasionally causing screwrelated failures. Furthermore, the thin walls of the casing around the inclined section lacked adequate strength, resulting in localized cracking during installation. These observations suggest that further refinement of the casing geometry, such as reinforcing critical areas or modifying the sealing strategy, is necessary to enhance the reliability of the connector and ensure repeatable performance under realistic construction conditions.

The study showed the significant potential for disassembly and reusability of the CCCS; however, it should be noted that it was limited to small-scale tests and as an isolated component. In addition, considering the full-scale application, demounting the slab from connected structural elements such as the column and beam needs further discussion. Theoretically, both types (CCCS and HCS) exhibit comparable potential. For example, to separate the hollowcore slab from adjacent components while maintaining its structural integrity, it may be necessary to cut the edges of the slab. This facilitates the adaptability of existing structures to new functional requirements, although minor material losses occur: cutting edges with diamond sawing.

5 – CONCLUSIONS

This study investigated the mechanical and environmental performance of a *dry-dry* system for CCCS, facilitated by a novel connector. The samples were disassembled after testing to explore viability and reusability.

The mechanical performance of the novel connector was explored through small-scale push-out tests. The results obtained demonstrate that the novel connector has reliable mechanical properties under shear loading, with a slip modulus and maximum force values that fall within the range of typical TCC connectors. The mechanical data obtained in this study will serve as a basis for the next phase of research, which aims to validate the proposed connector system under realistic conditions. Further study may include: further refinement of the casing design verified through a new round of small-scale tests, full-scale slab testing to assess the overall structural behavior under service and ultimate loads, and numerical modeling to simulate load transfer, connector interaction, and long-term effects. In terms of deconstructability, guidance and evaluation criteria can be established to analyze disassembly potential, process efficiency, and reusability of separated elements.

Besides the mechanical performance, the environmental performance for the tested CCCS and HCS was assessed through LCA studies. The relevant results indicate that HCS has a lower total GWP value, within the manufacturing and EoL stages. However, when comparing the GWP in the manufacturing stage, CCCS exhibits better performance due to carbon sequestration of the timber. In addition, the CCCS demonstrates higher net benefits beyond its current service life, due to the avoidance of additional CO₂ emissions and the substitution of raw wood materials. Nonetheless, it is rather arbitrary to conclude which type of slab has the lowest environmental impacts. This is due to other factors involved during the lifespan of the structure. such as the life expectancy of the slab and the effect of in-use energy per floor or slab. Further studies may investigate these influencing factors and consequences in terms of both structural and environmental performance.

Table 4: Potential of disassembly and reusability of the slab, after 50-year service life.

	CCCS	HCS
Disassembly	High possibility	N.A.
	Easy and rapid (no special tool required)	
Reusability - as intact element	High possibility	High possibility
	Verification needed (e.g. structural properties)	EPDs claim the lifespan can reach
		100-year (e.g. [28])
	Guideline needed	Regulation available (e.g. [29])
Reusability - as separate elements	High possibility	N.A.
	CLT can be reused directly, demounted concrete slab	
	being recycled or repurposed, other parts like screws	
	being reused or recycled	

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