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STRUCTURAL PERFORMANCE OF TIMBER-CONCRETE COMPOSITE FLOOR ELEMENTS WITH DECONSTRUCTABLE CONNECTORS AND ITS POTENTIAL FOR REUSE

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ABSTRACT: By incorporating design methods that allow for disassembly, buildings can be deconstructed at the end of their service life, thereby supporting the principles of circular economy and reducing waste. This paper provides a summary of the latest research advances by the research group for Wooden Structures (Aalto University) on the development and mechanical characteristics of a deconstructable connection system for timber-concrete composite (TCC) floors. This includes an overview of the experimental investigations conducted to date, focusing on the performance of the proposed system both at the connection level and at the floor level. At the connection level, the paper highlights the experimental investigations on the static and cyclic shear properties, as well as the ease of deconstruction after being exposed to substantial loads. Additionally, the floor level examination includes an overview of the bending properties, vibration characteristics, and deconstructability after reaching the failure point. A subsequent experiment is also reported here on the flexibility of the deconstructable connector for reuse and the influence of pre-existing concrete cracks on the performance of prefabricated TCC floors. The paper concludes with an outlook on the future of designing for deconstruction of TCC structures, as it not only reduces the environmental impact of construction but also allows for the efficient reuse of valuable resources.

KEYWORDS: Timber-concrete composite, cross-laminated timber, design for disassembly, vibration, four-point bending, cyclic shear test, self-tapping screws

1 INTRODUCTION

Deconstructable timber-concrete composite (TCC) structures combine the advantages of both timber and concrete in such a way that would allow for the structure to be disassembled at the end of its service life. This eases the process of recycling or reuse of the materials, which makes it a more environmental-friendly option compared to conventional forms of TCC structures. Therefore, deconstructable TCC structures are gaining more attention because of their potential to reduce waste and the environmental impact of buildings [1-5]. However, they are relatively new in the field of construction and the connector options for such structures are limited on the market, especially for the cast-in-situ construction method (i.e., the wet-dry system). Accordingly, the current knowledge on certain attributes of deconstructable TCC connectors is quite limited, specifically regarding their mechanical performance such as long-term static or dynamic properties or even their ability to be disassembled and taken apart at the end of their service life.

A number of factors play a major role in determining the efficiency and success of a deconstructable TCC connector. This includes technical requirements, such as the resistant of the connector against loads and environmental exposures factors such as humidity and temperature fluctuations without a considerable decrease in its performance; practicality factors, such as simplicity and easy installation effort, if possible, without additional training for the construction worker and without requiring specialized tools; versatility factors, such as suitability for various construction methods; market success factors, such as cost-effectiveness and viability for the target market in comparison to the regular connectors.

Considering the above factors, a deconstructable TCC system has been recently developed at the research group for Wooden Structures (Aalto University, Finland) using self-tapping screws. In this paper, the research activities related to the development and experimental investigations of the deconstructable TCC system are shortly summarized and discussed. Furthermore, a test report is provided which highlights both the potential of the deconstructable connector for reuse and the importance of preventing concrete cracks in prefabricated deconstructable TCC floors. The paper also highlights the outlook of the topic of design for deconstruction of TCC structures, with emphasis on raising awareness about the benefits of deconstructable connection systems to promote their use in sustainable construction projects.

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2 DECONSTRUCTABLE TCC CONNECTOR

The existing deconstructable TCC connectors in the literature have been made using either screws or bolts [e.g., 3,4,6,7]. In most cases, the mechanical performance of the proposed connectors has been investigated only either for a certain type of construction or for a certain floor type. Therefore, the versatility aspects remain to be demonstrated.

Our project at Aalto University was initiated by evaluating various deconstructable connector prototypes. To be able to disassemble a TCC connection in general, the following two conditions were found to be vital:

1. The connector inside the concrete must be accessible. The connectors in a regular TCC system are normally covered by concrete and cannot be reached.
2. The connector must be removable. Some connectors are not removable even if they can be accessed inside the concrete, e.g., glued-in plates or glued-in steel rods.

Considering these conditions, self-tapping screws were selected as the target connector, as they can be removed if they can be accessed. To enable the accessibility, the upper parts of the screw must be protected from being covered by the concrete. The design and the material type of the protection layer were investigated during the prototyping. One of the early prototypes consisted of a protective layer (or plug) made with polyvinyl chloride (PVC) and a lid and a level adjuster made of silicon rubber. Several versions of this prototype were tested during the preliminary investigations, see the results here [8]. Overall, the connector was easy to use; however, it did not provide sufficient shear properties compared to a regular screw, which was attributed to the design and the material type of the protective layer.

After the pre-investigation, it was decided to use a thin protective layer that mimics the shape of the screw threads. To accomplish this, heat-shrink tubing (HST) was chosen as it is cost-effective and can create a thin layer around the screw threads by shrinking around them when heated. The configuration of the connector is shown in Figure 1.

For cast-in-situ fabrication of TCC floors and prefabrication in the wet-dry system, the connector can be used in the same way as a regular screw, in which the connector is first driven into the timber component, then concrete is poured on top.

For prefabrication in the dry-dry system, the connector is inserted into the base of a formwork before pouring concrete to create the slab. Once the slab has dried, the screw is detached, the slab is then laid on top of the timber member and the screw is reinserted through the connector hole in the slab into the timber.

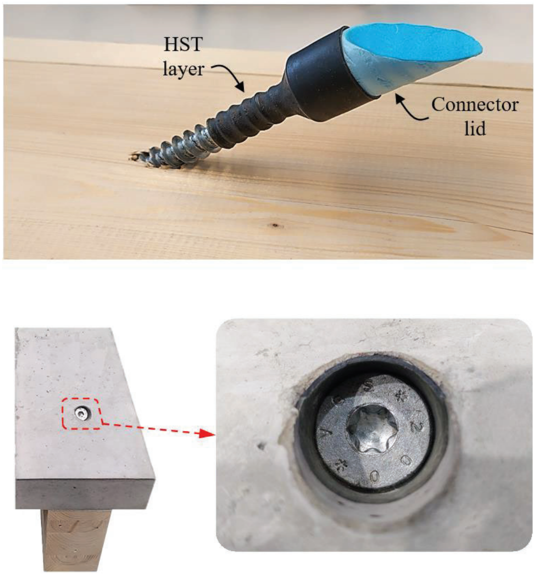

Figure 1: *The deconstructable connector components (top); a glulam-concrete composite connection made with the connector (bottom).*

In both wet-dry and dry-dry construction methods, the TCC system can be deconstructed by removing the screw from the connector hole in the concrete section. Once the screw is removed, the timber component and the concrete slab can then be separated.

3 EXPERIMENTAL INVESTIGATIONS OF THE TCC CONNECTOR

In the following sections a summary of the experimental investigations on the deconstructable TCC connector is presented.

3.1 SHEAR TESTS OF THE CONNECTOR UNDER STATIC LOADS

In an early study [1], the static shear strength and stiffness of the deconstructable connector concept were evaluated on several glulam-concrete composite connections. The focus of the study was on the wet-dry construction system, however, the application in the dry-dry system was also investigated to confirm the versatility of the connector and its potential for use in different types of construction. Other test variables included insertion angle, screw type and diameter, and screw arrangement.

A push-out shear test set-up was used to load the connection specimens (Figure 2). At the end of the tests, some of the tested connections were evaluated for deconstructability by removing the screw from the assembly.

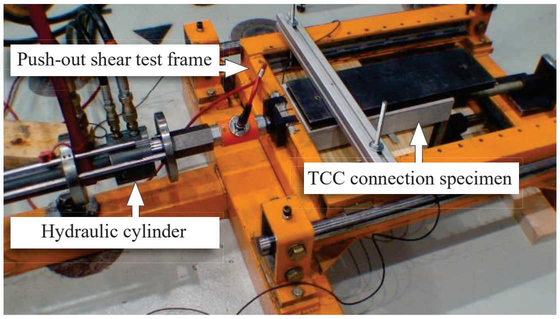

Figure 2: *Example cyclic load-slip curve of a deconstructable connector.*

The strength and stiffness of the deconstructable connections were relatively similar to those of identical connections made with regular self-tapping screws. The difference between the shear properties of the two connector types was the lowest when the connectors were inserted at 30˚ angle. Furthermore, it was demonstrated that the deconstructable connectors with 30˚ insertion angle can still be disassembled even if 15 mm slip is reached at the timber-concrete interface under loading. However, this level of slip prevents the disassembly of the connectors with a larger angle of insertion.

3.2 SHEAR TESTS OF THE CONNECTOR UNDER CYCLIC LOADS

In an ongoing study, the shear properties of the deconstructable connector were evaluated in a CLT-concrete composite system under cyclic loading. One objective was to determine how much the cyclic shear properties of the deconstructable connector might differ from those of a regular screw. Another objective was to evaluate the deconstructability of the connector at the end of cyclic loading.

For the shear tests, the push-out load set-up shown in Figure 2 was used. Several load levels within the serviceability range were applied, where the lower load level represented the dead load on the structure in an office floor and the upper load level represented the combination of the dead load and possible live loads. Each specimen was loaded up to about 130 k load cycles. They were then disassembled, reassembled, and then loaded to failure.

The results of the study showed that the trends in the load-slip behaviour of both types of connections were similar. An example load-slip curve during the cyclic loading of a deconstructable connection can be seen in Figure 3. The deconstructable connections were able to reach the same initial level of shear stiffness as the regular connections, which was likely due to the same CLT-concrete interface characteristics.

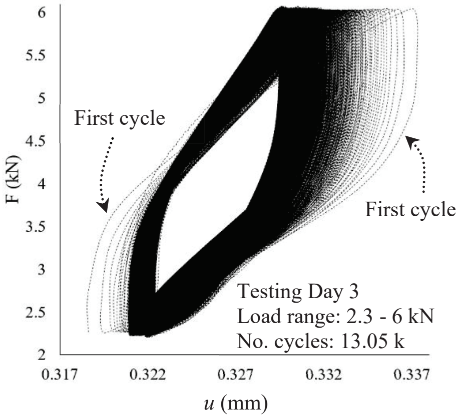

Figure 3: *Example cyclic load-slip curve of a deconstructable connector.*

As the cyclic test progressed, the shear stiffness increased as a result of the wood fibers hardening at the screw contact points but this also led to an increase in accumulated slip. Interestingly, the accumulated slip for the deconstructable connections was found to be lower than that of the regular connections during the cyclic loading.

The disassembly and reassembly processes of the connections were straightforward because no detectible plastic hinge had been formed in the connectors. After the reassembly process, the deconstructable connections retained 70% of their initial shear stiffness and their load-bearing capacity remained comparable to that of the regular connections.

3.3 BENDING TESTS OF A CLT-CONCRETE FLOOR ELEMENT

Following the completion of the test at the connection level, the effectiveness of the deconstructable connector was further evaluated in a CLT-concrete composite floor system, see [2]. To do this, a number of composite CLT-concrete beams, representing a strip of a full-scale floor, were constructed using the new connector. The properties of the beams were experimentally evaluated, including vibration performance, bending properties, interface slip, failure modes, and ease of disassembly. A control group of composite beams made with regular self-tapping screws was also fabricated and tested to provide a point of comparison. During the fabrication of the specimens, concrete was poured in such a way that a 3-mm concrete layer would form above the connector's lid. As a result, the composite beams made with both deconstructable and regular connectors were visually identical (Figure 4).

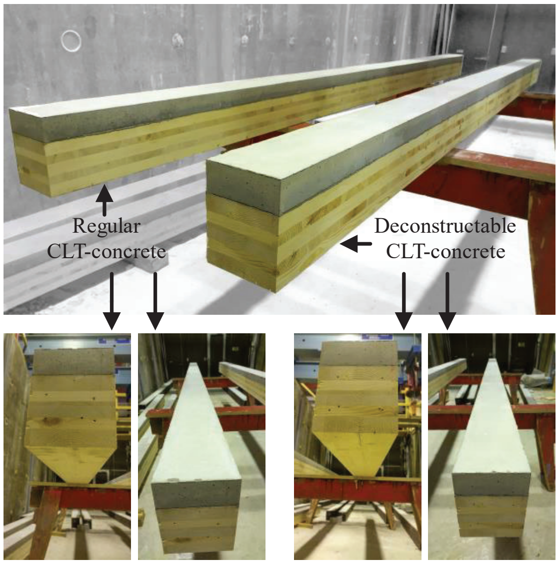

Figure 4: *The visual characteristics of a deconstructable and a regular CLT-concrete composite beam tested in: [2].*

Overall, the study found that the natural frequency, bending strength, and bending stiffness of the deconstructable composite beams were similar to those of the beams made with regular screws. Furthermore, the connectors inserted at a 30˚ angle did not show any detectable signs of plastic deformation, even after undergoing significant deformation under bending load. This indicates that the new connector system is able to maintain its deconstructability even under large loads.

4 DECONSTRUCTABLE CLT-CONCRETE FLOOR MADE WITH REUSED ELEMENTS

After the completion of the tests in the previous study [2], the deconstructable CLT-concrete composite beams were disassembled; one example is shown in Figure 5. A subsequent experiment was then undertaken aiming to connect one of the disassembled concrete slabs, with pre-existing cracks, to a fresh CLT beam using the self-tapping screws that were also disassembled in the previous study. The objectives were to a) evaluate the effect of concrete cracks on the performance of the system and b) demonstrate the ability of the connector for reuse in a disassembly-reassembly process. The composite beam was fabricated using 5-layer CLT with the dimensions of $b \times h \times l = 145 \times 130 \times 4000$ mm^3. The dimensions of the concrete slab were $b \times h \times l = 145 \times 55 \times 4000$ mm^3. The concrete slab contained multiple cracks along the span due to the previous bending tests (as shown in Figure 6).

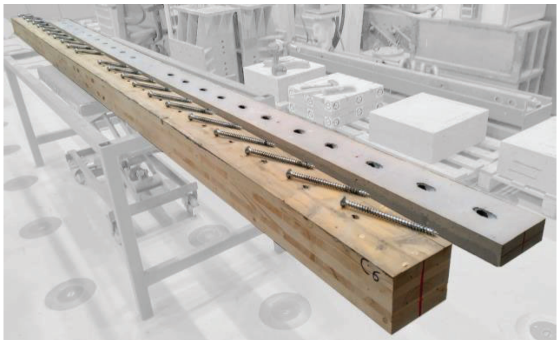

Figure 5: *A CLT-concrete composite beam deconstructed after destructive bending test.*

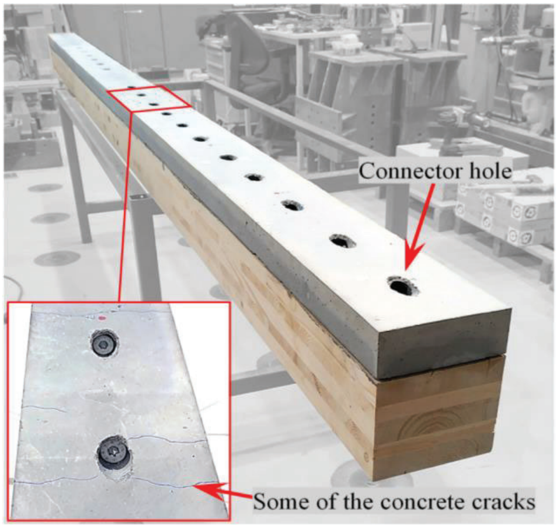

Figure 6: *The composite beam with concrete cracks.*

The first eigenfrequency (f) and the damping ratio (ζ) of the CLT beam prior to the assembly process and those of the composite beam with cracks were measured from several points along the beams using a hammer, an accelerometer, a charge amplifier, and a dynamic signal analyzer. The effective bending stiffness (EI_{eff}) of the CLT beam was measured in the elastic region prior to the assembly process using a four-point bending test set-up in accordance with EN 408 [9]. The bending properties of the composite beam with cracks were also measured using the same test set-up; however, the loading continued until after the failure point was reached.

The vibration characteristics of the pure CLT and the composite beam with cracks are given in Table 1. The results of the vibration test on the composite beam without cracks from the previous study [2] are also presented as a reference. The composite beam without cracks is the same one from which the concrete slab and the screws reused in the new beam were obtained.

***Table 1:** The vibration characteristics and bending performance of the beams.*

Characteristics	CLT	CLT-concrete	
		With cracks	Without cracks
f (Hz)	18.3	18.8	19.8
ζ (%)	2.9	5.6	3.1
EI_{eff} (kN.m^2)	227.6	677.9	898.7
F_{max} (kN)	-	27.6	28.9

The first eigenfrequency (f) of the composite beam with cracks was only 2.7% higher than that of the pure CLT beam and about 5.3% lower than that of the composite beam without cracks (Table 1). Nevertheless, the damping ratio (ζ) was considerably higher for the composite beam with pre-existing cracks. The higher damping ratio is a result of cracks and related gaps in the concrete which can further dissipate the vibration energy.

The load-deflection curves of the composite beams with and without concrete cracks as well as that of the pure CLT beam are illustrated in Figure 7. The maximum load carrying capacity (F_{max}) of the composite beams were relatively similar. However, F_{max} was governed by the finger joint failure in the bottom lamella and, therefore, is not discussed further. The most apparent difference in the load-deflection curves of the two composite beams appeared at the initial stages of the loading. The composite beam without cracks exhibited a nearly linear trend up to F_{max}. The composite beam with cracks, however, initially exhibited a larger deflection up to approximately 15 kN load level. Afterwards, the slope of the load-deflection curves of the composite beams was relatively similar up to the failure point. The composite beam with cracks exhibited a significantly higher bending stiffness than the pure CLT beam. Nevertheless, the bending stiffness was lower than that of the composite beams without cracks.

Overall, this preliminary experiment provided a quantitative comparison between the performance of TCC floor elements with cracked and uncracked concrete slabs. The results tend to indicate that the benefits of the composite system are considerably minimal when cracks exist in the concrete slab. Therefore, it is important to reduce the likelihood of crack development during transportation and assembly of TCC structures, especially when the dry-dry system is used and the concrete slab is prefabricated and transported separately.

Furthermore, this experiment demonstrated the flexibility of the deconstructable connector for disassembly-reassembly process. This can offer some advantages in TCC structures such as e.g., flexibility for repairs or design changes in buildings, in addition to its potential for easing the reuse process of the materials at the end of service life.

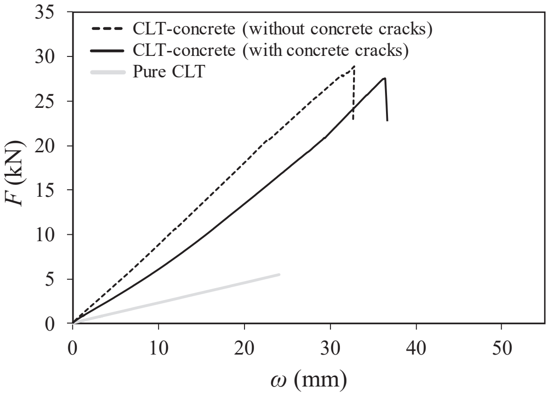

***Figure 7:** Load-deflection curves of the beams.*

5 CONCLUSIONS AND OUTLOOK

Overall, the research works summarized in this paper have demonstrated the performance of the deconstructable TCC connection system, making it a viable alternative for applications where easy disassembly is of interest. This can be important not only for improving the circularity aspects of regular buildings, but also for other applications such as for temporary structures or for future design changes or repairs in buildings.

Although it was demonstrated that deconstructable solutions can be highly effective, to realize their true potential and promote their use, more needs to be done to educate and raise awareness in the field of design for deconstruction. For this, various strategies such as establishing design for deconstruction guidelines as well as providing training programs and other educational resources for designers and builders could be considered. Furthermore, showcasing and providing examples of successful deconstruction projects can help to educate and inspire designers and builders to create sustainable buildings that can be easily taken apart and recycled or repurposed.

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