Derikvand, Mohammad; Fink, Gerhard

Deconstructable connector for TCC floors using self-tapping screws

Published in:
Journal of Building Engineering

DOI:
10.1016/j.jobe.2021.102495

Published: 01/10/2021

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Derikvand, M., & Fink, G. (2021). Deconstructable connector for TCC floors using self-tapping screws. *Journal of Building Engineering*, *42*, Article 102495. https://doi.org/10.1016/j.jobe.2021.102495

Journal of Building Engineering 42 (2021) 102495

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: http://www.elsevier.com/locate/jobe

Deconstructable connector for TCC floors using self-tapping screws

Mohammad Derikvand *, Gerhard Fink

Department of Civil Engineering, Aalto University, Finland

ARTICLE INFO

Keywords:
Timber-concrete composite
Design for disassembly
Prefabrication
Shear properties
Failure analysis

ABSTRACT

Timber-concrete composite (TCC) systems are effective solutions for the construction of new structural floors and the rehabilitation of the existing ones. Nevertheless, the subject of design for disassembly of TCC floors is still an area that requires further research and development. In this paper, the concept of a deconstructable connector using self-tapping screws is presented that is aimed to be used for both prefabrication and cast-in-situ construction of TCC floors. On a total of 61 T-section glulam-concrete composite specimens, the shear properties of the deconstructable connector were evaluated and compared to equivalent permanent connectors. The experimental investigation was performed for single and cross-paired screw arrangements with various insertion angles and two different types of screws. A comprehensive failure analysis was performed and the differences between the developed connector and the permanent ones were described. Overall, the deconstructable connector demonstrated a similar shear behavior to the permanent connectors with only marginally smaller strength and stiffness properties and could therefore be used as an environmentally friendly solution for TCC connections.

1. Introduction

Timber-concrete composite (TCC) solutions have been used for the rehabilitation of existing timber floors and gained in popularity over the past decades as an effective alternative to traditional concrete floors [1,2]. In TCC floors, a relatively thin concrete slab is connected to a timber component using shear connectors. The timber component could be made of either a slab-type engineered wood product or several individual timber beams in a joisted system. The timber component is designed to predominantly resist tension, whereas the concrete slab is placed on top to resist compression. The high compressive strength of concrete combined with the high tensile strength of timber results in a floor system with better structural performance than timber-only floors [2–4]. TCC floors also have a lower self-weight and a lower carbon footprint than traditional concrete floors due to the reduced amount of concrete and reinforcement used in their construction [5].

TCC can be fabricated in either a wet-dry or a dry-dry construction system. In the wet-dry system, the wet concrete is poured on the dry timber component to fabricate the composite structure (e.g., cast-in-situ construction). In the dry-dry system, a prefabricated concrete slab is connected to the timber component. The wet-dry system is usually accompanied with the application of permanent connectors, meaning the timber components and concrete slab cannot be disassembled. This can limit the options for recycling or reusing the materials at the end of service life. Examples of permanent shear connection systems investigated in the previous studies are adhesive connections [6], glued-in steel mesh connections [5], notch connections with or without steel fasteners [7,8], dowel-type connections [9], and connections with non-metallic connectors such as glued-in plywood plates [10]. Depending on the type of connector, a medium to high level of composite action can usually be achieved using the permanent connectors by implementing the right design approaches. However, due to the sustainability issues of permanent connectors, the subject of design for disassembly of TCC floors still requires further research in order to develop and encourage the use of more eco-friendly building solutions.

To address this issue, a few studies attempted to develop deconstructable connectors for TCC floors [11,12]. Deconstructable connectors can aid in the process of dismantling and recycling of the composite floors at the end of service life [11]. The deconstructable connectors developed in the previous studies and those that are commercially available in the market have specifically been designed for prefabricating TCC floors in the dry-dry system. To prefabricate the concrete slab in the dry-dry system, usually some connectors in the form of steel/plastic tubes are placed in a formwork and then fresh concrete is cast [3,13–15]. After it has cured, the concrete slab and the timber components are assembled by driving some screws or bolts into the timber components through the steel/plastic tubes. Zhang et al. [16] created holes in the prefabricated concrete slab through which the

* Corresponding author. Aalto University, PL 11000 (Otakaari 1B) 00076 AALTO, 02150, Espoo, Finland.
E-mail addresses: Mohammad.Derikvand@aalto.fi (M. Derikvand), Gerhard.fink@aalto.fi (G. Fink).

https://doi.org/10.1016/j.jobe.2021.102495
Received 15 December 2020; Received in revised form 15 March 2021; Accepted 4 April 2021
Available online 16 April 2021

connectors could be driven into the timber components. The gaps between the connectors and the hole walls in this system can be filled with a gap-filling epoxy or a non-shrinking concrete. It is also possible to use solid wooden blocks instead of holes or tubes to prefabricate the concrete slab [11,15]. The screw connectors can then be driven through the wooden blocks that are placed inside the concrete.

The goal of this research was to develop TCC floor connectors that can be disassembled at the end of building's life in order to ease the process of recycling or reusing the materials. The concept of a novel deconstructable screw connector was developed that can be used in both wet-dry and dry-dry construction systems. The proposed connector concept consists of a self-tapping screw covered at the upper section using a thin protective layer and a reusable rubber lid. An experimental campaign was carried out to evaluate the shear properties of T-section glulam-concrete composite connections fabricated in 17 different configurations using both the new connector and equivalent permanent connectors. The experimental investigations were performed to evaluate the potential of the deconstructable connector in the wet-dry system by comparing its shear properties with those of the permanent ones. The application in the dry-dry system was also investigated on one specific connector arrangement. The results of the experiments are presented in this paper together with a comprehensive analysis on the failure mechanism and performance of self-tapping screws in glulam-concrete composites when subjected to different production and design scenarios.

2. Deconstructable connector using self-tapping screws

In this research, a deconstructable connector is defined as a shear connector that enables the disassembly of the TCC plate into its three constituent parts: timber component, concrete slab, and shear connector. In the context of TCC floors, this term has often been used to refer to connections that can be disassembled and reassembled as well. However, Khorsandnia et al. [12] demonstrated that reassembling a deconstructed screw connection can lead to reduced stiffness due to the looseness of the screw in the timber section after reassembly. The focus of the here presented research lies on the design for disassembly.

For a deconstructable screw connector that can directly be used in both wet-dry and dry-dry systems, it is necessary to protect the screw head from being covered by the fresh concrete during casting. This way the screw head can be reached for disassembly purposes. The main body of the screw inside the concrete section should also be covered using a protective layer to avoid direct interlocking between the screw and the concrete. Based on this concept, several prototypes were fabricated and tested under push-out shear loads during the preliminary stage of this research [17]. The preliminary test suggested that satisfactory shear properties can be achieved if the thickness of the protective layer is minimized. This resulted in a deconstructable connector that consists of a self-tapping screw covered in the concrete section using a thin protective layer made of heat-shrink tubing (HST) and a reusable lid made of silicon rubber (Fig. 1). An HST was selected as the protective layer because it turned out to be a cost-effective solution that can easily mimic the shape of the screw by shrinking around it during the production of the connector. The HST shrinks radially to about one-third of its original diameter during the production process at 100 °C and becomes extremely rigid after cooling. This results in a thin protective layer of ~ 0.5 mm thick that tightly covers the shank and threads of the screw without any bond formation. In the here presented concept, the HST layer has three main functions:

(i) Protecting the screw:

Prevent the screw from direct contact to the fresh concrete. The lower friction between the inner surface of the HST and the screw, compared to that between the concrete and the screw, makes it easier to twist and remove the screw during the disassembly process.

(ii) Mechanical interlocking:

Sufficient mechanical interlocking between the concrete and the threads of the screw. The thin HST layer that is formed around the screw can mimic the same shapes of the head, the threads, and the shank of the screw after shrinking around them during the production process (Fig. 1). This guaranties the load transfer in the screw head and the threads.

(iii) Plug for the rubber lid:

The HST layer creates a pip-type plug in which the lid could be inserted before casting the concrete. The removeable rubber lid makes it possible to reach the screw head for disassembly purposes after the concrete has cured.

The connector doesn't require any additional elements such as steel or plastic tubes inside the formwork before casting the concrete. Theoretically, the concept is flexible to further modifications as well, such as inclusion of an additional washer in order to increase the screw head contact with the concrete. However, one of the main considerations in this study was the ease of use and accordingly the system was kept simple.

For application in the wet-dry system, the connector is driven into the timber component and the concrete is cast on top (Fig. 2), which is similar to how a permanent connector is used in practice. This represents an advantage especially for cast-in-situ production of TCC floors and

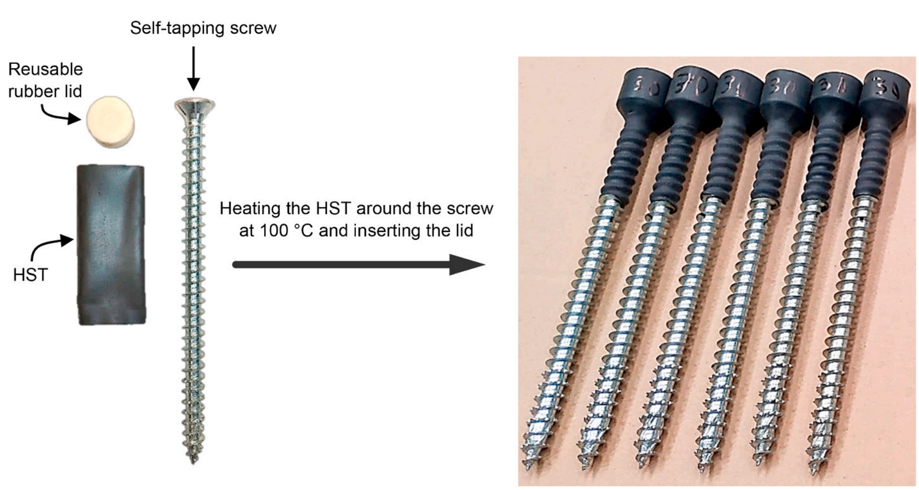

Fig. 1. Deconstructable connector using self-tapping screws: individual components, production process, and final configurations.

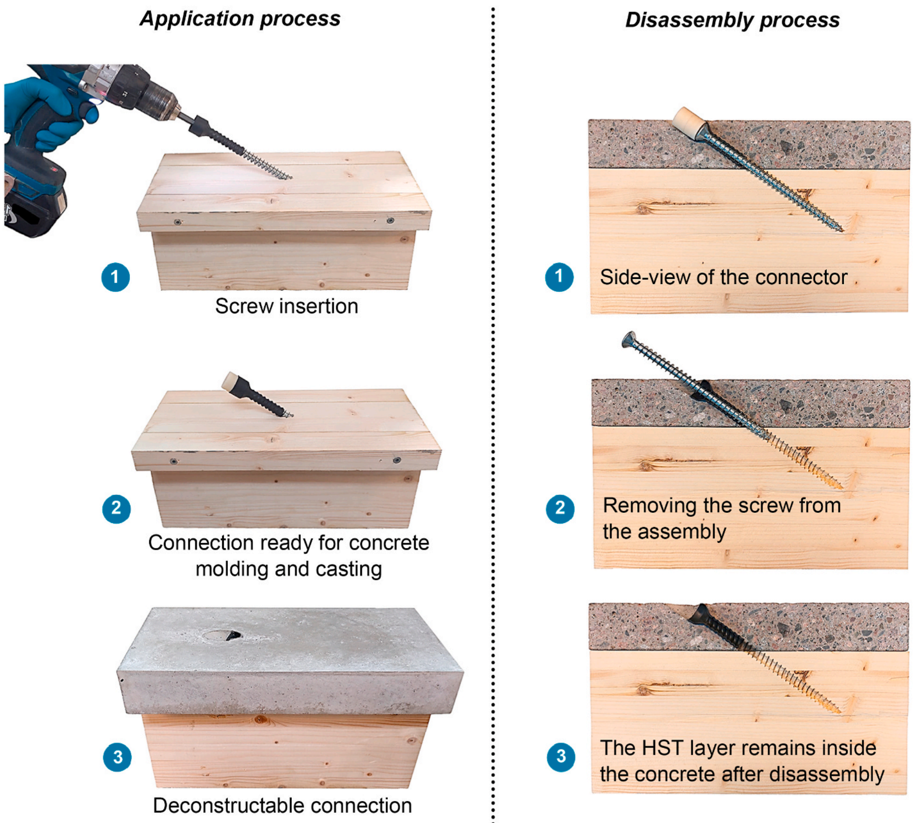

Fig. 2. Application steps and disassembly of the deconstructable connector in the wet-dry system.

gives the connector a high level of versatility to be used for different construction methods. For the disassembly process, the screw could be accessed and removed through the open hole of the connector in the concrete section, which is covered by the rubber lid during casting. The HST layer remains inside the concrete after twisting and removing the screw (Fig. 2). Once the screw is removed, the timber component and the concrete slab can be taken apart.

For application in the dry-dry system, the connector is inserted into the base of the concrete formwork. After the concrete has dried, the screw is removed from the assembly. The concrete slab can then be placed on top of the timber member and the screw is driven into the timber member through the HST hole inside the concrete section (Fig. 3).

3. Materials and methods

3.1. Specimens

Two types of fully threaded self-taping screws were used, namely, VGS11200 and VGS13200. Both screws were 200 mm long and had deep threads. The h_t/d_s ratio was $\sim$ 0.28 in both screws, where h_t is the depth of the threads and d_s is the shank diameter. These screws belonged to the same suite of products produced from galvanized carbon steel as per the manufacturer's technical data sheet [18]. Selected mechanical properties of the screws can be seen in Table 1. The screws are originally designed for applications that require high tensile and sliding strengths, however, it has recently been demonstrated that they can also provide satisfactory stiffness when used as shear connectors in TCC structures [19]. The design of the head, shank, and threads of the two screws were similar, whereas the configurations of the drilling tips and the screw diameters were different (Fig. 4).

17 groups of connections with different configurations were produced and tested: Nine groups with deconstructable connectors and eight groups with permanent connectors (see Table 2). About half of the specimens were produced with single screw and half with cross-paired screws. The permanent connections were identical to the deconstructable connections and served as control specimens to provide a basis for comparison. The dimensions of the connections are illustrated in Fig. 5. The edge and the end distances of the connectors were based on the minimum values recommended by European Technical Approval [20] to avoid cracking of the glulam member and brittle failure of the connections. To evaluate the effect of manufacturing method on the shear properties, a group of deconstructable connections with single screw and insertion angle of $\alpha = 30^\circ$ was produced in both wet-dry and dry-dry systems. The other connections were produced in the wet-dry system. The timber members of the connections were cut from 6-layer glulam beams from Nordic Whitewood (strength class GL30c). A low-shrinkage concrete was selected for producing the connections. The concrete recipe is given in Table 3.

3.2. Preparation of the specimens

To produce the wet-dry specimens, the top surface of the glulam members was covered by a layer of water-proof paint to prevent moisture absorption from the wet concrete, see also Derikvand and Fink [17]. The connectors were then driven into the glulam members through predrilled holes with Ø = 6 mm for the VGS11200 screws and Ø = 7 mm for the VGS13200 screws. A plywood formwork was fixed around the glulam and a steel reinforcement wire mesh (Ø = 10 mm) with the grade of B500A was placed inside the formwork to maintain the integrity of the concrete and minimize crack development. After pouring the concrete into the formwork, the connections were left to cure for four weeks prior to testing.

In the dry-dry system, the glulam member and the concrete slab were prefabricated separately and then connected after the concrete had cured. For this purpose, a formwork was produced consisting of a base

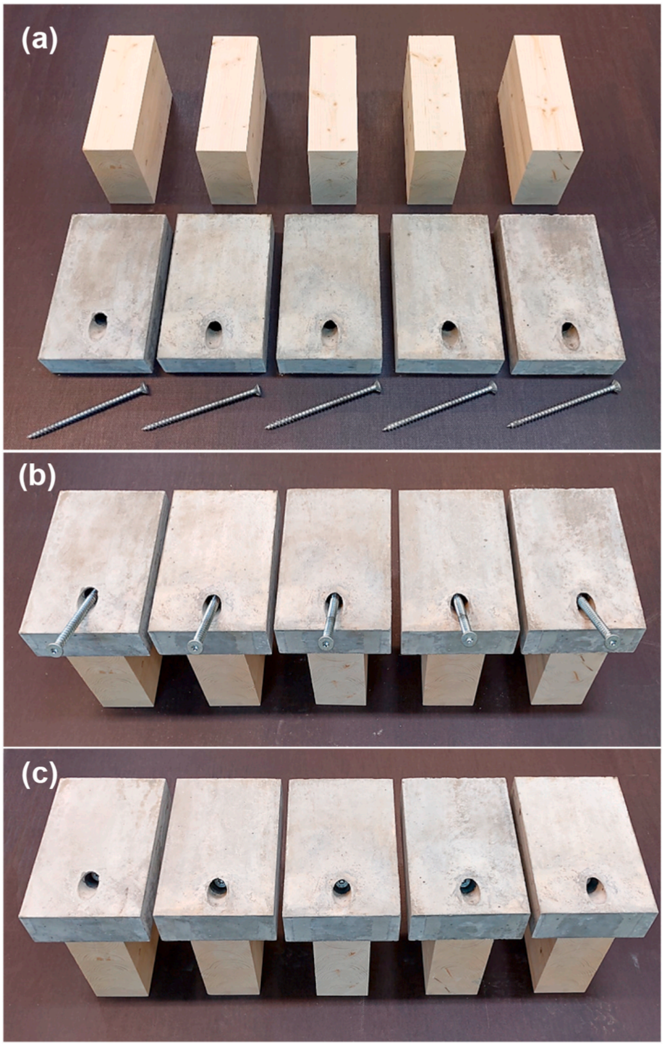

Fig. 3. Prefabricating the connections in the dry-dry system. (a) prefabricated concrete and glulam members; (b) assembling the elements; (c) driving the screws into the glulam through the HST hole.

Table 1
Selected mechanical properties of the screws used [18].

Properties	Screw code	
	VGS11200	VGS13200
$f_{y,k}$ (N/mm^2)	1000	1000
$M_{y,k}$ (kN.mm)	45.9	94.5
$f_{tens,k}$ (kN)	38	53

made of reusable Styrofoam boards around which plywood formworks were fixed. The deconstructable connectors were inserted into the Styrofoam boards and steel reinforcement wire mesh (Ø = 10 mm) was installed. The concrete was then cast. After four weeks, the formwork was opened and the screw was removed from the concrete slab, while the HST layer remained inside the concrete. The slabs were then placed on top of the glulam members and the screws were driven through the HST hole as illustrated in Fig. 3. The connections were assembled using an electric screwdriver with the torque control set at 50 N.m.

3.3. Push-out shear tests

The connections were tested under push-out shear loads using the test frame shown in Fig. 6. The test frame was fixed to a multipurpose strong floor. Two linear variable differential transformers (LVDT) were installed on both sides of the connections to record the slip between the glulam and concrete.

In accordance with EN 26891 [21], the connections were loaded using a load-control protocol up to 70% of the estimated maximum load (F_{est}) followed by a displacement-control protocol up to $u = 15$ mm slip. A cycle of unloading and reloading of the connections was also pursued in the range of 10% to 40% of F_{est}. The F_{est} was held constant in each group and was adjusted only when the mean value of the actual load-carrying capacity (F_{max}) deviated more than 20% from F_{est}.

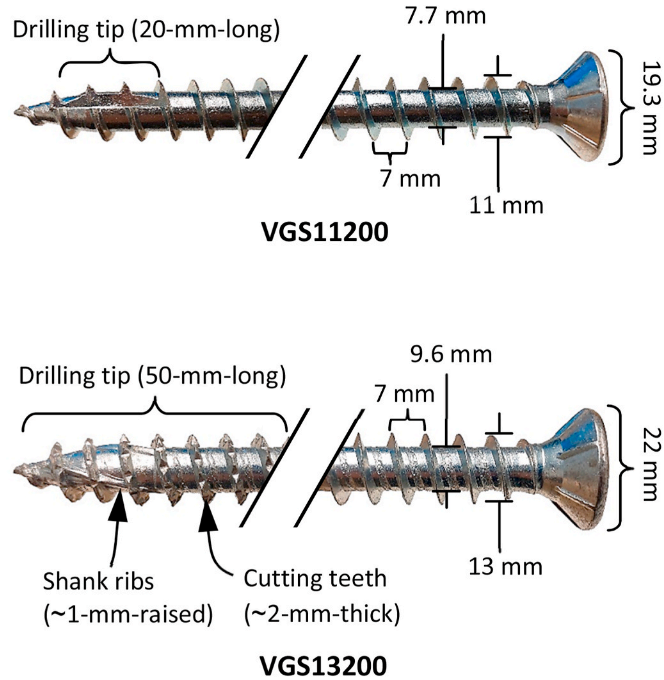

Fig. 4. Configurations of the screws used in the experimental investigation.

3.4. Additional tests

After the shear tests, 61 specimens were cut from the full section of the glulam members of the connections based on the procedures of EN 408 [22] to measure the density (ρ) and moisture content (MC). The MC of the prepared specimens was measured using the oven-dry method described in EN 13183-1 [23].

The 28-day compressive strength and density of the concrete were measured on a total of 21 cubic samples collected from the prepared concrete batches, following the procedures of EN 12390-3 [24]. At least three samples were taken and tested from each batch. The dimensions of the cubic samples were $b \times h \times l = 100 \times 100 \times 100$ mm^3.

4. Results and discussion

4.1. Overview

The load-slip curves were calculated using the average value of the two LVDT measurements on both sides of the specimens, they are illustrated in Fig. 7 and Fig. 8. For all configurations and arrangements of the reference connector, a typical load-slip behavior has been observed. For the connection with cross-paired screws, higher strength and stiffness values were obtained. The insertion angle α substantially influenced the load-slip behavior of the connections, which is in agreement with the findings of Mirdad and Chui [19] on the shear capacity of glulam-concrete connections made with fully threaded self-tapping screws. Moshiri [25] also reported similar results for the

Table 2
Experimental design of the study.

Connector type	Screw arrangement	Screw type	Insertion angle α (°)	Construction system	Symbol	No. of samples	Dimensions ($b \times h \times l$ mm^3)	
							Glulam	Concrete
Deconstructable	Single screw	VGS13200	30	Dry-dry	DS13D30	5	90 × 170 × 300	180 × 65 × 300
				Wet-dry	DS13W30	4	90 × 170 × 300	180 × 65 × 300
			45	Wet-dry	DS13W45	4	90 × 170 × 300	180 × 65 × 300
			60	Wet-dry	DS13W60	4	90 × 170 × 300	180 × 65 × 300
			90	Wet-dry	DS13W90	4	90 × 170 × 300	180 × 65 × 300
	Cross-paired screws	VGS13200	30	Wet-dry	DC13W30	4	105 × 170 × 380	180 × 65 × 380
			45	Wet-dry	DC13W45	4	105 × 170 × 380	180 × 65 × 380
		VGS11200	30	Wet-dry	DC11W30	4	105 × 170 × 380	180 × 65 × 380
			45	Wet-dry	DC11W45	4	105 × 170 × 380	180 × 65 × 380
Permanent	Single screw	VGS13200	30	Wet-dry	PS13W30	3	90 × 170 × 300	180 × 65 × 300
			45	Wet-dry	PS13W45	3	90 × 170 × 300	180 × 65 × 300
			60	Wet-dry	PS13W60	3	90 × 170 × 300	180 × 65 × 300
			90	Wet-dry	PS13W90	3	90 × 170 × 300	180 × 65 × 300
	Cross-paired screws	VGS13200	30	Wet-dry	PC13W30	3	105 × 170 × 380	180 × 65 × 380
			45	Wet-dry	PC13W45	3	105 × 170 × 380	180 × 65 × 380
		VGS11200	30	Wet-dry	PC11W30	3	105 × 170 × 380	180 × 65 × 380
			45	Wet-dry	PC11W45	3	105 × 170 × 380	180 × 65 × 380

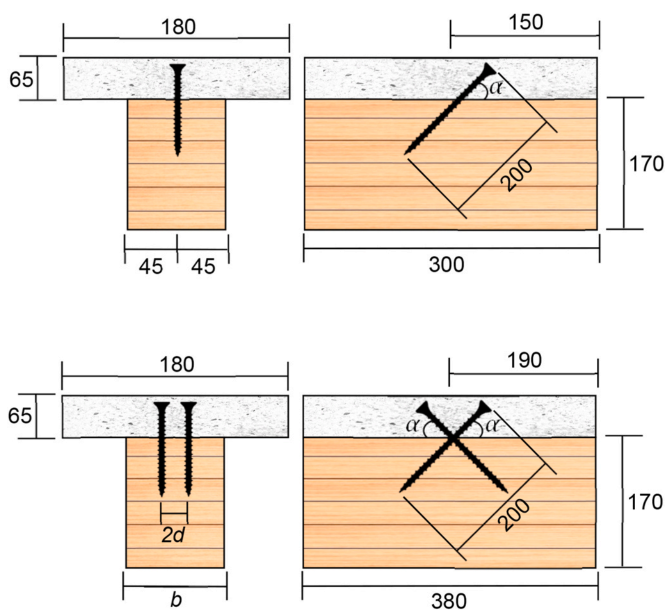

Fig. 5. Configuration and dimensions (mm) of the connections with single and cross-paired screws, with b = 90 mm and 105 mm for VGS11200 and VGS13200 screws, respectively.

Table 3
Concrete recipe used in this study.

Components	Total weight percentage in the mix (%)
Sand[a]	29.5
Aggregates[b]	40.1
Filler	6.1
Cement	17.5
Superplasticizer (SP)	0.2
Water added to the SP	1.3
Water added to the mix	5.3

[a] The maximum size was 2 mm.
[b] The maximum size was 16 mm.

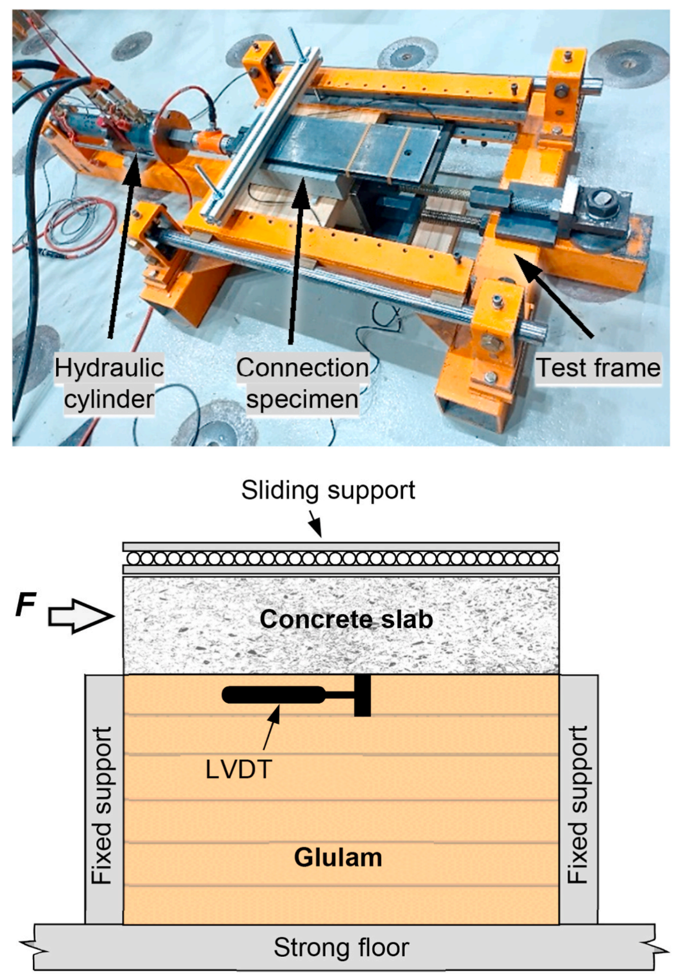

Fig. 6. The push-out load set-up: test frame (top); schematic illustration of the specimen (bottom).

effect of α on the shear capacity of screws in other types of TCC connection systems.

Overall, the load-slip patterns of the deconstructable connections were very similar to those in the permanent connections, although the load-carrying capacity was slightly lower and the slip was higher for the deconstructable ones (see Sections 4.2 and 4.3). As the number of test samples was kept small at 3–5 replicates per group, the randomness of the experimental investigation has to be considered in the interpretation of the results.

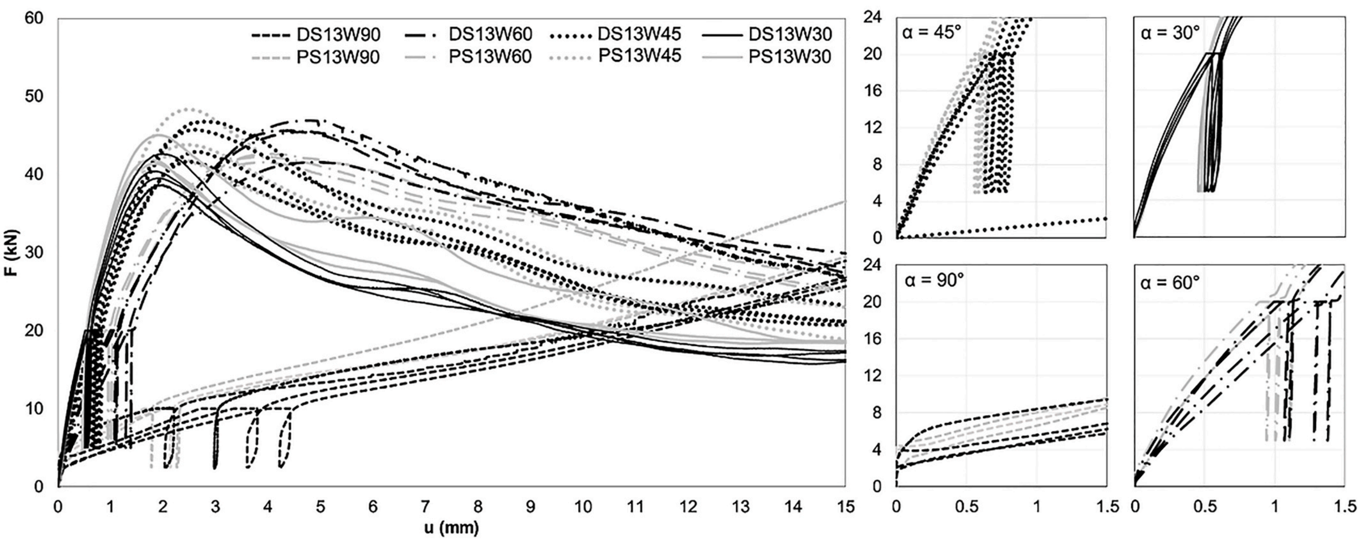

Fig. 7. The load-slip curves of the connections with single screw; whole range (left) and lower range (right).

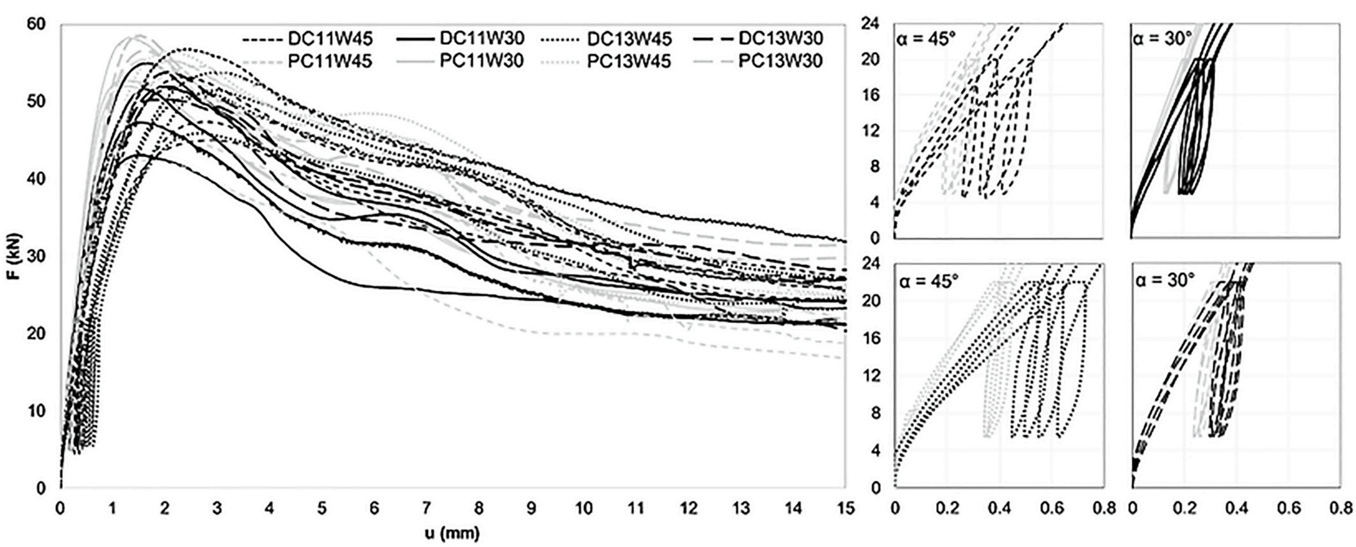

Fig. 8. The load-slip curves of the connections with cross-paired screws; whole range (left) and lower range (right).

4.2. Shear strength

The shear strength of the connections was defined as the maximum force recorded during the test. The results (mean value and coefficient of variation COV) are summarized in Table 4 and Fig. 9. Overall, similar strength properties have been identified for all connector types. In two groups, even a slightly higher shear strength was measured for the deconstructable connector. However, it is clear that the modifications applied on the screws cannot positively affect the shear strength. The observed higher shear strength values result from the randomness of the experimental investigation combined with the low number of test samples.

In order to investigate the effect of the HST and the mechanically-not-covered screw head (due to the rubber lid) on the shear strength reduction, the results were compared with those from the reference tests. In Fig. 10, the shear strength of the individual deconstructable connections relative to the average shear strength of the equivalent permanent connections are shown. In general, the shear strength values of the two connector types are comparable, especially for the connections with inclined screws. On average, the strength reduction was less than 1% for the single inclined screws, 15% for the single vertical screws, and 6% for the cross-paired screws. In addition, also an analysis of variance was performed. For all groups, the difference between the strength of the two connector types was statistically insignificant at 95% confidence level (p-value > 0.05).

A comparison of the different screw types shows that the shear strength is slightly higher for the 13-mm screws. This difference, however, was insignificant (p-value > 0.05). It has to be noted that for the smaller screw significantly larger variations of the load-caring capacity have been observed (see Fig. 9).

4.3. Shear stiffness

The stiffness at serviceability limit state ($K_{0.4}$) was calculated by the secant slip modulus at 0.1 F_{est} to 0.4 F_{est}, taken from the first loading cycle. The average values and the COV of the stiffness are given in Table 4.

As expected, the permanent connectors were stiffer than the deconstructable ones (see Fig. 11). The differences were statistically significant (p-value < 0.05), except for the insertion angles of $\theta = 60°$ and $\theta =$

Table 4
The shear properties and failure modes of the test connections together with the average ρ and MC of the glulam member in each group.

Connector type	Symbol	ρ (kg/m^3)	MC (%)	F_{max} (kN)	$K_{0.4}$ (kN/mm)	Failure mode[b]
Deconstructable	DS13D30	417.9 (2.3)[a]	9.6 (3.1)	41.8 (9.1)	35.0 (22.6)	GC + SP
	DS13W30	418.2 (4.5)	9.9 (1.3)	40.3 (4.2)	32.4 (4.6)	GC + PH + SP
	DS13W45	427.2 (1.6)	9.7 (2.1)	44.3 (5.4)	26.5 (6.4)	GC + PH + SP
	DS13W60	426.9 (4.3)	9.9 (1.0)	44.9 (5.1)	16.0 (12.5)	GC + PH
	DS13W90	413.7 (1.5)	9.9 (2.1)	27.0 (5.2)	2.8 (3.6)	CC + GC + PH
	DC13W30	406.5 (4.7)	10.0 (1.0)	51.9 (2.7)	51.0 (5.7)	CC + GC + PH + SP
	DC13W45	412.1 (6.2)	9.8 (3.1)	50.6 (6.5)	32.1 (11.5)	CC + GC + PH + SP
	DC11W30	423.4 (3.7)	9.8 (1.1)	49.2 (10.6)	63.5 (10.0)	CC + GC + PH + SP
	DC11W45	426.6 (4.2)	9.6 (2.1)	50.6 (10.7)	40.3 (19.9)	CC + GC + PH + SP
Permanent	PS13W30	426.6 (4.5)	9.8 (2.0)	42.8 (4.7)	37.1 (2.4)	GC + PH + SP
	PS13W45	410.0 (2.5)	9.9 (1.0)	44.9 (6.9)	32.6 (3.4)	GC + PH + SP
	PS13W60	430.2 (2.8)	9.7 (3.1)	42.2 (1.4)	18.5 (7.0)	GC + PH
	PS13W90	429.2 (2.7)	9.9 (1.0)	31.6 (13.6)	4.1 (9.8)	CC + GC + PH
	PC13W30	431.2 (1.5)	10.1 (2.0)	56.9 (2.8)	61.7 (3.1)	CC + GC + PH + SP
	PC13W45	428.8 (1.6)	10.1 (2.0)	55.2 (2.5)	45.1 (6.0)	CC + GC + PH + SP
	PC11W30	430.5 (4.0)	9.8 (3.1)	54.3 (6.3)	82.5 (3.5)	CC + GC + PH + SP
	PC11W45	416.9 (3.1)	10.0 (2.0)	48.2 (12.7)	56.1 (8.4)	CC + GC + PH + SP
Average		421.6 (3.7)	9.8 (2.1)			

[a] Numbers in parenthesis are COV values (%).
[b] CC = Concrete cracking, GC = Glulam crushing, PH = Plastic hinge in the screws, SP = Screw pull-out.

90°. However, in the case of the vertical screws, on average, only about 70% of the stiffness of the equivalent permanent connector could be achieved. For the inclined screws, the average stiffness reduction was significantly lower, with about 85% and 80% of the stiffness of the permanent connectors being attained by the single and the cross-paired screws, respectively. Beside the lower stiffness, slightly higher variation (on average COV = 9.3%) was also observed (see Fig. 12), which might result from the reduced surface interaction between the screw and the concrete.

The screw type appeared to have a high influence on the stiffness of both deconstructable and permanent connections, with p-value < 0.05 (see also Fig. 12). The surprising observation was that the 11-mm screws were about 25–30% stiffer than the 13-mm ones. One reason for this phenomenon might be the geometry of the drilling tips of the screws. The threads of the drilling tip in the 13-mm screw has cutting teeth that are noticeably thicker than the threads in the rest of the same screw and has additional spiral shank ribs (see Fig. 4).

4.4. Failure modes

Two connections from each test group were longitudinally cut in half after the push-out tests, the observed failure modes are illustrated in Fig. 13 and Fig. 14.

For single screws, the failure modes of the deconstructable and permanent connections were similar. None of the connections exhibited any brittle failure. Plastic hinges in the screws were observed in all the test groups, although they were hardly detectible in the single screw connections with $\alpha = 30°$. Furthermore, concrete cracking was observed at the glulam-concrete interface of the connections with $\alpha = 90°$. For the connections with $\alpha = 30°$ and $\alpha = 45°$, the screw also slightly pulled out of the glulam member.

For cross-paired arrangement, the failure modes were also similar: plastic hinges were observed in both screws, concrete cracking occurred above the shear-compression screw, and the pull-out of the shear-tension screw occurred in the glulam section. The only notable difference between the failure modes was that the shear-compression screw in the deconstructable connections tends to move upward through its open hole during the test. This upward movement occurred at a relatively high load level $0.8\,F_{max} < F \leq F_{max}$. The reason for this phenomenon was the loss of pull-out resistance of the shear-compression screw inside the concrete section which occurred when the increased load transfer in the connector led to concrete fracture around the screw threads. Principally, this effect is similar in the permanent connections as well. However, unlike the deconstructable connections, the screw head in the permanent connections is also covered by the concrete in addition to the screw threads. Therefore, the upward movement is resisted by both the threads and the head of the screw and this results in a higher pull-out resistance in the concrete section. The crack development above the shear-compression screw was an evidence of its upward movement in both

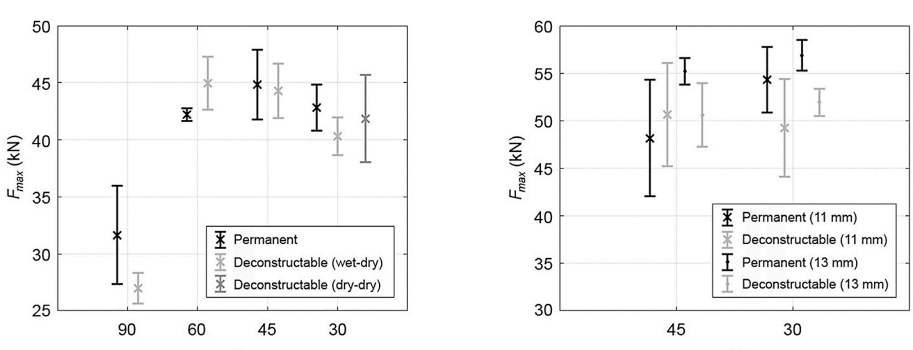

Fig. 9. The influence of insertion angle, construction method, and diameter on the shear strength of single screw (left) and cross-paired screw (right) connections (error bars: ± standard deviation SD).

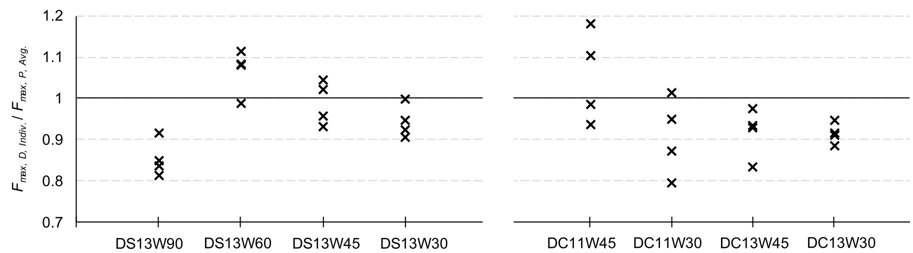

Fig. 10. The shear strength of the individual deconstructable connections ($F_{max,\ D,\ Indiv.}$) relative to the average shear strength of the equivalent permanent connections ($F_{max,\ P,\ Avg.}$) in each test group.

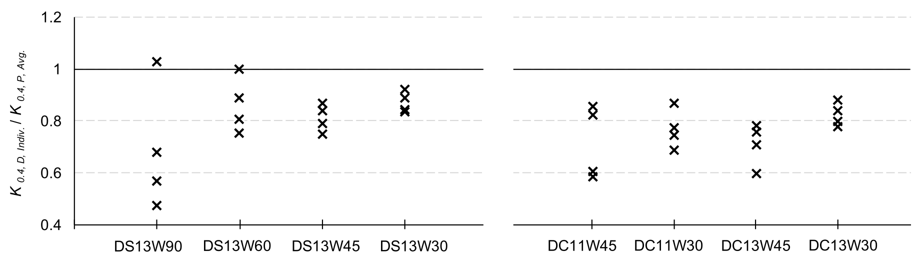

Fig. 11. The stiffness of the individual deconstructable connections ($K_{0.4,\ D,\ Indiv.}$) relative to the average stiffness of the equivalent permanent connections ($K_{0.4,\ P,\ Avg.}$) in each test group.

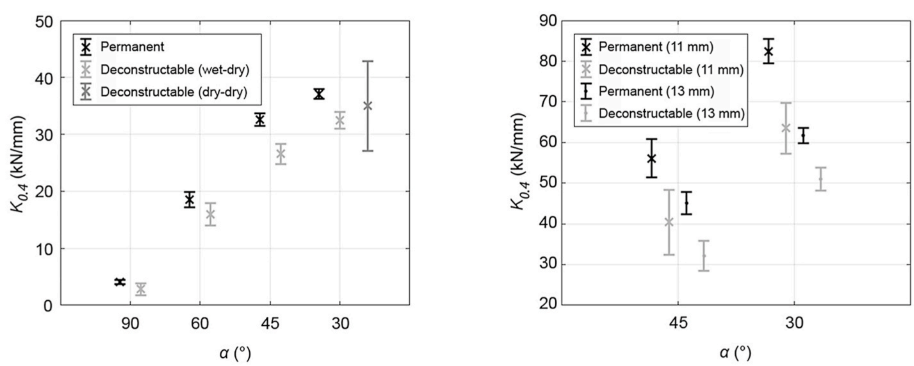

Fig. 12. The influence of insertion angle, construction method, and diameter on the stiffness of single screw (left) and cross-paired screw (right) connections (error bars: ±SD).

permanent and deconstructable connections (Fig. 14).

4.5. Shear properties of the connections in the dry-dry system

The connections prefabricated in the dry-dry system were slightly stiffer and stronger than the identical deconstructable connections fabricated in the wet-dry system (Table 4). However, the difference was statistically insignificant (p-value > 0.05). Furthermore, a significantly larger variation of the shear stiffness was observed by the dry-dry connections (Fig. 15). The differences might be the result of the different initial frictions between the surfaces of the glulam and concrete, which is related to the assembly procedures of the two construction methods. In the wet-dry system, the concrete is poured directly on the timber and accordingly uneven surfaces or small gaps are filled. In contrast, the initial friction in the dry-dry system is affected by the torque force used for inserting the screws (for information on the influence of various parameters on the friction behavior of TCC refer to Ref. [26]). Khorsandnia et al. [12] have also reported high COV values (higher than 60% in several cases) for the stiffness of other types of deconstructable connections tested in their study.

The failure mode of the dry-dry connections was similar to that of the identical wet-dry ones. However, no plastic hinge of any kind was observed in the screw used for these connections.

4.6. Ease of disassembly

The ease of disassembly of the connections was initially evaluated on several preliminary specimens without exposing them to any shear loads. The preliminary specimens included both single and cross-paired screws. These specimens were successfully disassembled using a cordless electric screwdriver. In addition, the possibility of disassembly of the specimens from the here presented test series was also evaluated after 15 mm slip was reached under the push-out load. It was confirmed that the connections without significant screw deformation (e.g. single screw with $\alpha = 30°$) could be still disassembled. As expected, it was no longer possible to disassemble the connections with large deformations. Large deformations, however, are not expected under standard service loads.

Fig. 13. Failure modes of the permanent (left) and deconstructable connections (right) with single screws.

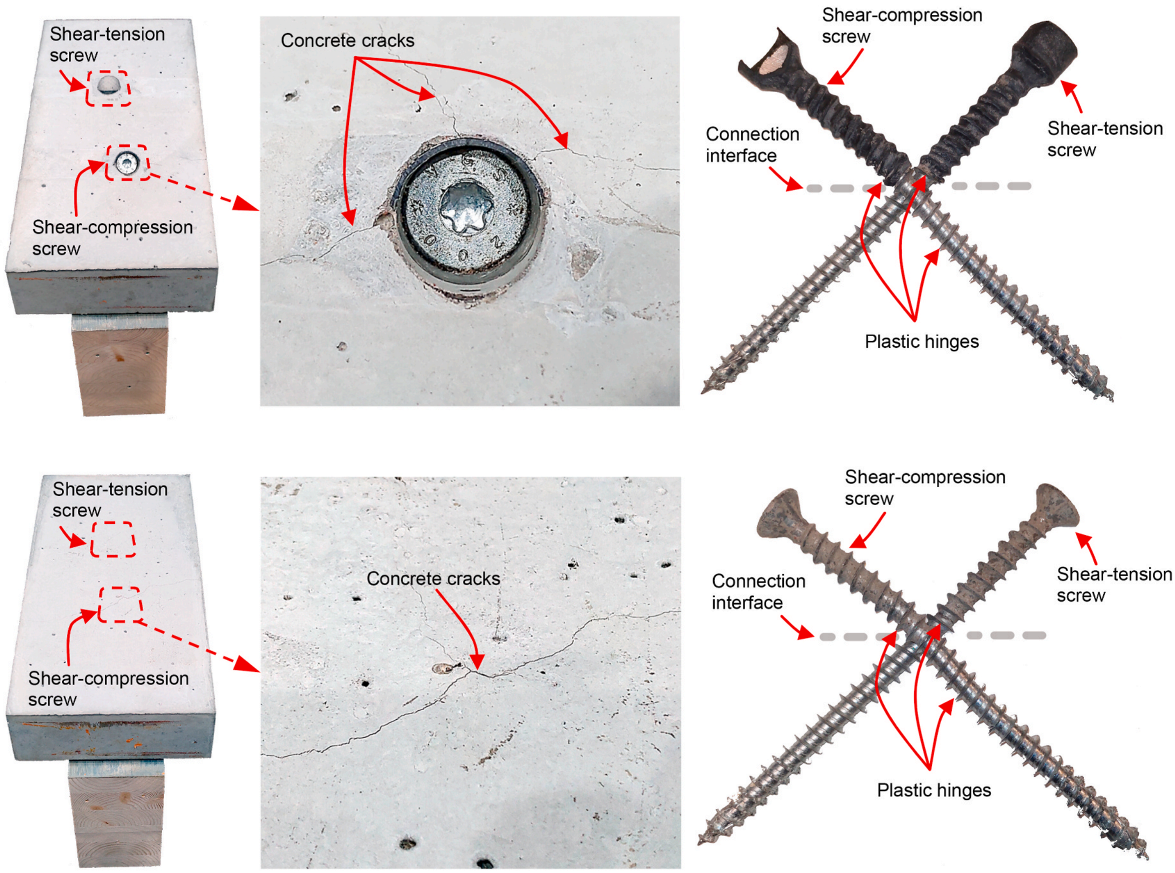

Fig. 14. Failure modes of the deconstructable (top) and permanent connections (bottom) with cross-paired screws and α = 45°.

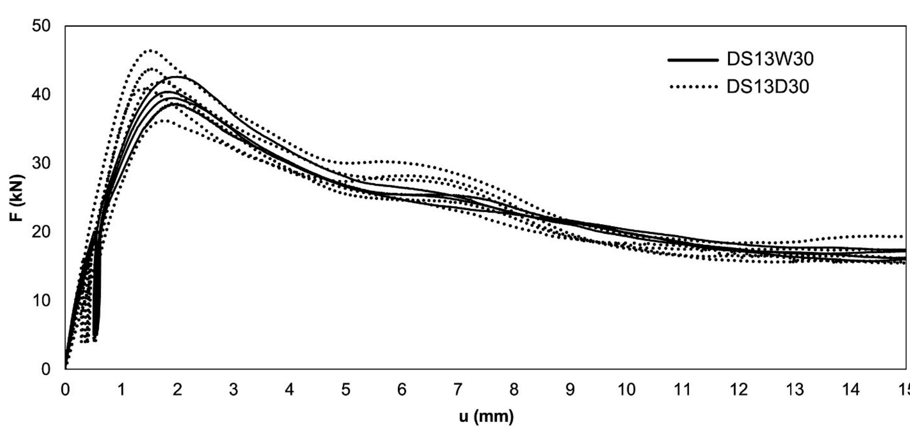

Fig. 15. The load-slip curves of the dry-dry and wet-dry connections with α = 30°.

4.7. Glulam and concrete

The average values of ρ and MC of the glulam member in each test group are given in Table 4. The COV was quite small for both ρ and MC, which indicates the consistency in the physical properties of the glulam.

The 21 concrete samples had a compressive strength of 51.1 ± 2.3 MPa and an average density of 2400.4 ± 19 kg/m^3.

5. Conclusions and outlook

The concept of a deconstructable connector using self-tapping screws that can be used for the construction of TCC connections in both wet-dry and dry-dry systems is introduced in this paper. The shear properties of the connector were experimentally investigated on glulam-concrete composite connections for 8 different screw configurations. Reference samples using equivalent permanent connections were also tested for validation.

The load-slip curves of the deconstructable connectors were similar to those of the permanent ones. The shear strength and stiffness were marginally lower in the deconstructable connectors. For small insertion angles, the differences are smaller.

The observed failure modes of the deconstructable and permanent connectors with single screw were similar. In the deconstructable connections with cross-paired screws, however, at a high load level the shear-compression screw tended to slightly move upward through the connector hole. In the permanent connections, this upward movement was mostly resisted by the concrete above the head of the shear-compression screw.

The application of the connector in the dry-dry system was investigated for one screw arrangement. For the dry-dry system slightly higher strength and stiffness properties were observed, resulting from the different initial frictions between glulam and concrete. Furthermore, the result also indicated larger variation of the stiffness properties compared to the wet-dry system.

Two different screw types were investigated and the geometry of the drilling tip was identified to have a significant influence on the stiffness properties of both deconstructable and permanent connectors.

The connections were disassembled after testing. Connections without significant screw deformation, such as single screw connections up to $\alpha = 30^{\circ}$, could be easily disassembled using an electric screwdriver even after 15 mm slip is reached.

Based on the experimental results and their analysis, the shear behaviour of the deconstructable connector is promising for application in both wet-dry and dry-dry systems. Exploring new opportunities in prefabrication of timber structures with the possibility of disassembly might well justify the use of deconstructable solutions. The future phases of this research will focus on investigating the long-term performance and ease of disassembly of connections and floor systems made with the proposed concept when subjected to variable environmental conditions and load scenarios as well as developing analytical models for predicting their mechanical properties.

CRediT authorship contribution statement

Mohammad Derikvand: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing, Project administration. **Gerhard Fink:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] A.M. Dias, J. Skinner, K. Crews, T. Tannert, Timber-concrete-composites increasing the use of timber in construction, Eur. J.Wood Wood Prod. 74 (3) (2016) 443–451.

[2] D. Yeoh, M. Fragiacomo, M. De Franceschi, K. Heng Boon, State of the art on timber-concrete composite structures: literature review, J. Struct. Eng. 137 (10) (2011) 1085–1095.

[3] M. Fragiacomo, E. Lukaszewska, Time-dependent behaviour of timber–concrete composite floors with prefabricated concrete slabs, Eng. Struct. 52 (2013) 687–696.

[4] A. Frangi, M. Knobloch, M. Fontana, Fire design of timber-concrete composite slabs with screwed connections, J. Struct. Eng. 136 (2) (2010) 219–228.

[5] D. Otero-Chans, J. Estévez-Cimadevila, F. Suárez-Riestra, E. Martín-Gutiérrez, Experimental analysis of glued-in steel plates used as shear connectors in Timber-Concrete-Composites, Eng. Struct. 170 (2018), 1-0.

[6] T. Tannert, A. Gerber, T. Vallee, Hybrid adhesively bonded timber-concrete-composite floors, Int. J. Adhesion Adhes. 97 (2020) 102490.

[7] L. Boccadoro, S. Zweidler, R. Steiger, A. Frangi, Bending tests on timber-concrete composite members made of beech laminated veneer lumber with notched connection, Eng. Struct. 132 (2017) 14–28.

[8] A.M. Dias, U. Kuhlmann, K. Kudla, S. Mönch, A.M. Dias, Performance of dowel-type fasteners and notches for hybrid timber structures, Eng. Struct. 171 (2018) 40–46.

[9] A.M. Dias, S.M. Lopes, J.G. Van de Kuilen, H.M. Cruz, Load-carrying capacity of timber–concrete joints with dowel-type fasteners, J. Struct. Eng. 133 (5) (2007) 720–727.

[10] J. Daňková, P. Mec, J. Šafrata, Experimental investigation and performance of timber-concrete composite floor structure with non-metallic connection system, Eng. Struct. 193 (2019) 207–218.

[11] N. Khorsandnia, H. Valipour, M. Bradford, Deconstructable timber-concrete composite beams with panelised slabs: finite element analysis, Construct. Build. Mater. 163 (2018) 798–811.

[12] N. Khorsandnia, H. Valipour, J. Schänzlin, K. Crews, Experimental investigations of deconstructable timber–concrete composite beams, J. Struct. Eng. 142 (12) (2016), 04016130.

[13] E. Lukaszewska, H. Johnsson, M. Fragiacomo, Performance of connections for prefabricated timber–concrete composite floors, Mater. Struct. 41 (9) (2008) 1533–1550.

[14] M. Fragiacomo, E. Lukaszewska, Influence of the construction method on the long-term behavior of timber-concrete composite beams, J. Struct. Eng. 141 (10) (2015), 04015013.

[15] R. Crocetti, T. Sartori, R. Tomasi, Innovative timber-concrete composite structures with prefabricated FRC slabs, J. Struct. Eng. 141 (9) (2015), 04014224.

[16] Y. Zhang, G.M. Raftery, P. Quenneville, Experimental and analytical investigations of a timber–concrete composite beam using a hardwood interface layer, J. Struct. Eng. 145 (7) (2019), 04019052.

[17] M. Derikvand, G. Fink, Deconstructable timber-concrete composite connectors, in: Proceedings of the 63rd Society of Wood Science and Technology International Convention, July 2020, pp. 98–105.

[18] V.G.S. Rothoblaas, Fully threaded screw with countersunk or hexagonal head, Rothoblaas, [Online]. Available, https://www.rothoblaas.com/products/fastening/screws/screws-structures/vgs. (Accessed 16 October 2020).

[19] M.A. Mirdad, Y.H. Chui, Load-slip performance of mass timber panel-concrete (MTPC) composite connection with self-tapping screws and insulation layer, Construct. Build. Mater. 213 (2019) 696–708.

[20] ETA-Danmark, Rothoblaas Self-Tapping Screws, European Technical Assessment ETA-11/0030 of 2016-04-07, Danmark, 2016.

[21] EN 26891, Timber Structures—Joints Made with Mechanical Fasteners—General Principles for the Determination of Strength and Deformation Characteristic, European Committee for Standardization (CEN), Brussels, Belgium, 1991.

[22] EN 408, Timber Structures – Structural Timber and Glued Laminated Timber – Determination of Some Physical and Mechanical Properties, European Committee for Standardization (CEN), Brussels, Belgium, 2010.

[23] EN 13183-1, Moisture Content of a Piece of Sawn Timber—Part 1: Determination by Oven Dry Method, European Committee for Standardization (CEN), Brussels, Belgium, 2002.

[24] EN 12390-3, Testing Hardened Concrete–Part 3: Compressive Strength of Test Specimens, European Committee for Standardization (CEN), Brussels, Belgium, 2019.

[25] F. Moshiri, Structural Behaviour of Timber Concrete Composite Connections and Floors Utilising Screw Connectors, Doctoral dissertation, University of Technology, Sydney, Australia, 2014.

[26] J. Jaaranen, G. Fink, Frictional behaviour of timber-concrete contact pairs, Construct. Build. Mater. 243 (2020) 118273.