

REVIEW ARTICLE

Current practice and recent developments of shear connectors for timber concrete composite applications: A state of the art review

Hussien Alkasim Soalih¹, Serhat Demir^{1*} ¹ Karadeniz Technical University, Department of Civil Engineering, Trabzon, Türkiye

Article History

Received 31 July 2023

Accepted 30 November 2023

Keywords

Timber

Concrete

Composite structures

Shear connectors

Push-out test

Abstract

Several studies have been made on timber concrete composite shear connectors and most of these connectors are brittle at failure. Ductile shear connectors are not studied as extensively as ordinary shear connectors and the interest to study high ductility shear connectors increased in the past two decades. Recent literature references were chosen and reviewed on construction techniques of timber concrete composite shear connectors. A detailed summary of timber concrete composites, the mechanical properties of connectors, and types of connection systems are presented. Experimentally validated design guides available for timber concrete composite systems are presented and the potential for the development of new simplified connectors is discussed. Finally, recent applications of timber concrete composite connectors and possible areas of future research regarding the development of high ductility and energy dissipation capacity shear connectors are stated.

1. Introduction

Composite construction combines two or more different materials to effectively utilize the superior qualities of each material. Timber-concrete composite (TCC) construction combines the benefits of timber and concrete to provide a structurally sound and environmentally friendly structure [1]. TCC can be used to rehabilitate ancient wooden structures and to construct new ones, including residential floors, and mid-span bridges [1-6]. In Europe, America, Brazil, Australia, and New Zealand TCC has been practiced for years and got interest from other parts of the world to design economical and environmental friendly structures [1].

In TCC construction, connectors such as notches, dowels, screws, nails, steel plates, and epoxy glue are used to create a single piece that can resist loads [4,7-11]. Mostly concrete resists compression stresses and timber elements carry tensile stresses.

TCC has greater strength and stiffness, less vibration, higher seismic and fire resistance, and better acoustic isolation, and thermal mass than conventional timber floors. Compared to reinforced concrete systems TCC is lightweight, lower carbon footprint, and takes shorter construction time [8-12].

TCC floors can be built by in-situ concrete casting on timber or installing prefabricated TCC elements from manufacturing sites. Prefabricated items reduce the time for concrete hardening, reduce creep as concrete cures, and remove the usage of props for in-situ construction [12-15].

* Corresponding author (s.demir@ktu.edu.tr)

The tensile strength of concrete is ignored in reinforced concrete structures and replaced by reinforcement bars. At the ultimate limit state, concrete cracks about 2/3 of its height in bending, and timber replaces the cracked region in TCC shown in Fig. 1. The larger area of timber gives a bigger section modulus that increases its bending stiffness which upgrades the moment capacity and bending stiffness of the TCC cross-section [16].

Yeoh et al. [17] stated three main design requirements for an effective TCC system: (1) The neutral axis must be close to the interface, (2) To transfer shear force and for efficient composite action, connectors must be strong and stiff enough, and (3) Timber should be strong enough to withstand tensile stresses.

2. Mechanical behavior of TCC connectors

Connectors have unique strength, stiffness, ductility, and durability [18]. Strength and stiffness are determined by pushout tests [4,19] as shown in Fig. 2. Strength is the maximum load resisted, and stiffness is the slip modulus at service, ultimate, and near-collapse loads which are 40%, 60%, and 80% of mean maximum load, respectively [16].

The connectors' horizontal shear transfer causes beam members to experience axial force. The resultant resistance moment improves the stiffness and load-bearing capacity of the TCC systems [18,20].

The stiffness of a composite system is controlled by two limits: (1) No composite action - A lower limit below which no horizontal shear force will be transferred between layers and each layer slide as two independent elements with higher slip value, and (2) Full composite action - An upper limit where stiffness of connection is infinite such that, there is complete horizontal shear transfer with no slip. The section has a clear neutral axis, such that bending stresses/ strains at the interfaces will be similar [17]. Shear connection in TCC is highly flexible, such that there is non-negligible slip at the interface [11,20] and structural performance falls between two limits stated in Fig. 3 called partial composite action [4,11,21].

Plastically designed structures are able to redistribute internal stresses and provide safety warnings before collapse [11,22,23]. A hierarchy of failure is expected in plastically designed TCC so that connections experience inelastic deformations before the brittle collapse of timber beam shown in Fig. 4 [3,22,24].

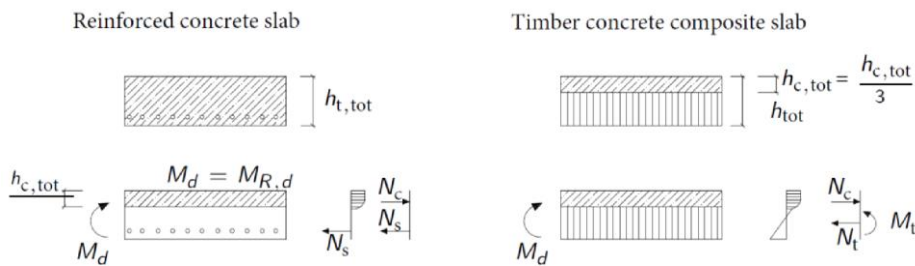


Fig. 1. Load transfer of reinforced concrete slab (left), timber-concrete composite slab (right) from [16]

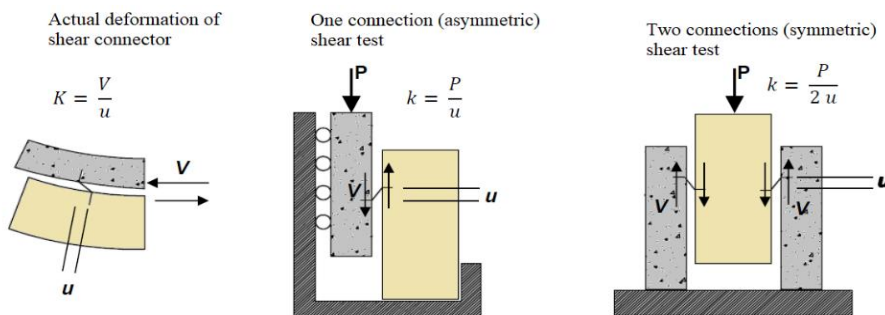


Fig. 2. Configurations for determining the load-slip behavior of a TCC connection system [1]

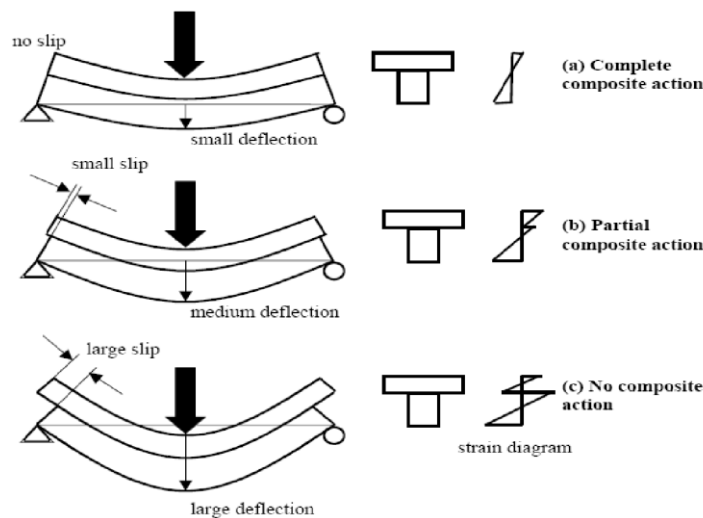


Fig. 3. a) Full composite action, b) Partial composite action c) No composite action [25]

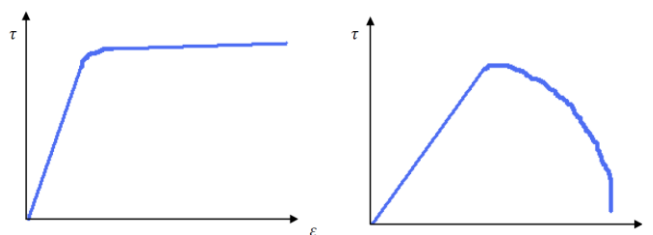


Fig. 4. Load-displacement diagram of connectors. Left: desirable, Right: undesirable connector [24]

3. Types of shear connectors

An ideal connection should be strong enough to transfer shear at the interface, stiff enough to carry loads with a small slip, ductile enough for load distribution, reliable, easy, and quick to manufacture [4,11,13,14]. Generally, there are dowel type connections, notched connections, concrete based connections, friction-based connections, glued connections or glue laminated plates [14,20,26,27] in discrete or continuous form, vertical, or sloped, depending on the arrangement along slab or beam element [17].

3.1. Dowel type connectors

Dowel-type connectors are most commonly used connectors like; screws, nails, bolts, staples, glued rods, dowels mechanically driven to timber and mainly designed to transmit loads through bending and shear [16]. Taazount et al. [28] studied interlayer slip of nail connectors between concrete and timber using lightweight concrete with wood particles and traditional concrete. Comparison of experimental and analytical results show that connection used did not have the expected slip modulus defined by Eurocode-5.

Dias et al. [29] examined capacity of dowels taking (1) shear tests using different timber species, concrete mixtures, and fasteners, and (2) linear elastic, linear-elastic with crushing, and elastic-perfectly plastic concrete properties. Material strength and fastener types had a significant impact on capacity of joints.

For peak performance SFS-screws must be placed in pairs, inclined at 45° and 135° in Fig. 5. Screws inclined in direction of shear force carries tensile load, while screw tilted in opposite direction serves as a stiffener [24].

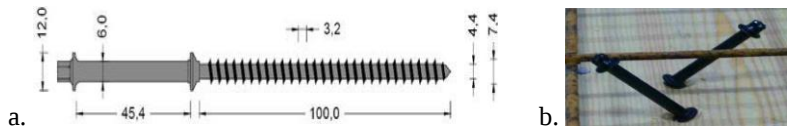


Fig. 5. a) SFS-screw b) Screws installed pair-wise at angles of 45° and 135° [30]

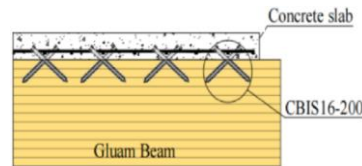


Fig. 6. Cross inclined coach screw connectors used by [14]



Fig. 7. A T-section glulam-concrete deconstructable connection [31]

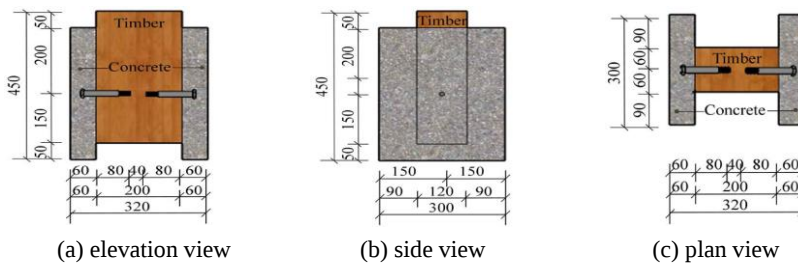


Fig. 8. Dimensions of TCC reversed cyclic specimens (in mm) [32]

Haotian et al. [33] examined effective width of TCC floors in serviceability limit state with cross inclined coach screws as shown in Fig. 6. TCC beams of different slab widths taken to evaluate shear lag effect and its impact on bending performance. Also, ABAQUS 6.14 nonlinear FE model created and a parametric analysis conducted. There was shear lag effect, and it had a greater impact on tension strain at bottom of the concrete slab than compression strain at upper surface. Numerical models agreed with experimental results in terms of macro and micro bending performances. Parametric analysis suggested that load type, slab width-to-span ratio, slab thickness, and connection stiffness have a significant impact on effective width of TCC beams.

Deconstructable connectors in TCC floors enables reuse of timber at the end of a building's lifespan. Derikvand et al. [31] studied a de-constructable TCC connection consisting of a self-tapping screw shown in Fig. 7. Shear resistance of four different configurations examined and compared to that of a permanent connection constructed using the same self-tapping screw. Permanent screws resisted higher load and stiffness values compared to de-constructable connectors. Slight concrete crushing observed at glulam and slab interface. Permanent connector exhibited rigid behavior in concrete zone with deformations in glulam and screw.

A recent study by Xie et al. [32] examined hysteretic behavior of bolt connections in TCC bridge as shown below in Fig. 8. FE models prepared and cyclic loading tests made on six identical specimens to examine hysteretic responses, stiffness degradation, strength degradation, and failure mechanisms. The

controlling failure mode was a dual-hinge mechanism in the bolts. Samples showed acceptable energy dissipation and achieved a mean ductility factor of 6.76. FE model and experimental data were in good agreement.

3.2. Notched connectors

Notches are made in timber cutting rectangular, trapezoidal, or triangular shapes, or notches on concrete using solid wooden blocks and hollow steel blocks [34] as shown below in Fig. 9. Notches in timber can be reinforced with screws, bolts, dowels, or nails [25,26] to increase ductility and prevent separation of elements [11]. So far, reinforced notches cut in timber are the best shear connectors in strength and stiffness [4,11].

Lamothe et al. [20] investigated ductile notch connector for Glulam Laminated Timber (GLT) beam or Cross Laminated Timber (CLT) slab connected with a High-Performance Concrete (HPC) or Ultra-High Performance Fiber Reinforced Concrete (UHPFRC). Shear tests made on 14 connection configurations by varying notch shape, concrete type, and adding acoustic insulation. The insulating layer decreased connection stiffness but it amplified structural stiffness due to larger lever arm of composite system. The connection ductility enhances structural ductility for GLT-(U)HPC and CLT-(U)UPC floors. The connector is shown below in Fig. 10.

On the other hand, Yuchen et al. [11] made an analytical model, numerical model, and experimental on notched connectors as shown in Fig. 11. Connectors had significant stiffness and shear capacity before fracture in concrete and floors had high composite action. At failure, only a tiny concrete crack developed near supports. The γ -method used for calculations and ABAQUS finite element program used to create three-dimensional FE models. Unlike shear capacity, stiffness of connectors grows linearly with depth of the notch. Also, adjustment in notch depth from 15 mm to 35 mm, had a negligible impact on load-deflection response of composite floors. Also, Jiang et al. [35] made six sets of push-out tests on notched connectors considering various concrete types, shear length of timber, and notches with/without lag screws as shown in Fig. 12. Connections had limited shear capacity and low ductility, resulting shear fracture of concrete or timber. Notches reinforced with lag screws had highest shear capacity which enhanced strength, ductility, and post-peak behavior. There was no difference in slip modulus of connectors based on concrete type, shear length of timber, or whether notch was reinforced.

Boccardo et al. [36] made an analytical model and full-scale bending tests on slabs using laminated veneer lumber (LVL) and concrete with notched connections. The model is based on simple equilibrium formulas and provides a ductile and reliable design approach based on notch yielding. However, due to LVL and concrete material properties difference, local LVL deformations inside notches weaken shear capacity of concrete, resulting in premature failure. Vertical reinforcements provided to solve this problem.

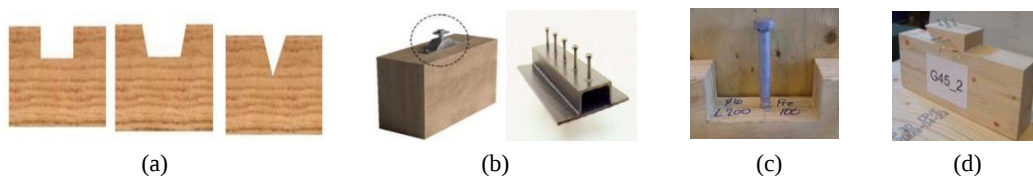


Fig. 9. Notched connectors. a) notches on timber element, b) hollow steel block for notches in concrete, c) notch reinforced with fastener, d) solid wooden block as a notch [11,25,34]

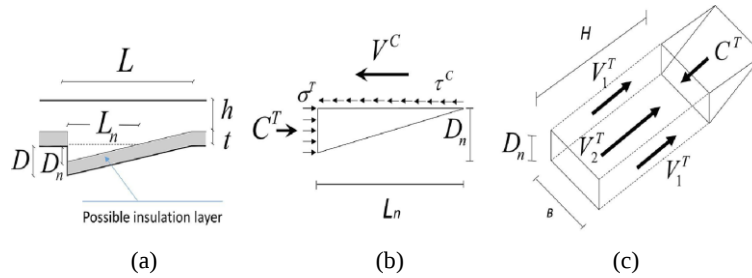


Fig. 10. (a) lateral view of the notch geometry; (b) Stress distribution at shear failure on the horizontal concrete surface of the triangular notch; (c) three-dimensional view of the stress distribution at shear failure of timber between two adjacent notches [20]

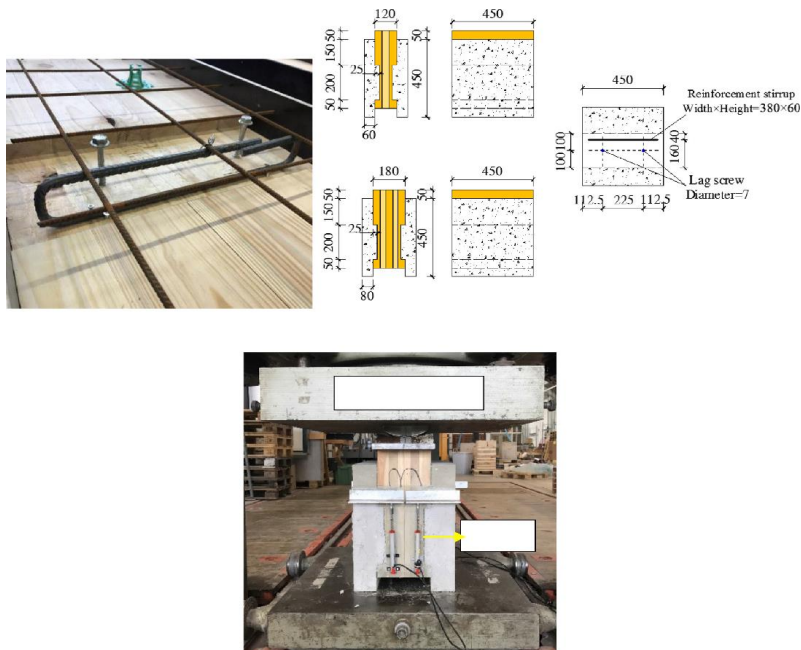


Fig. 11. Reinforced notched connector and push out test set up [11]

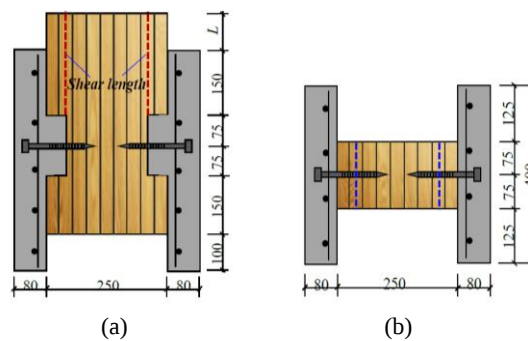


Fig. 12. Dimensions of push out specimens a) front view; b) top view [35]

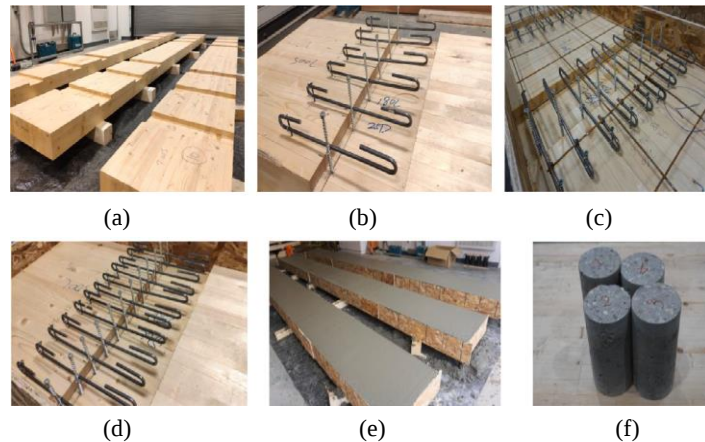


Fig. 13. (a) Timber with notch, (b) Six rows of reinforcement in notch, (c) Nine rows of reinforcement in notch, (d) Twelve rows of reinforcement in notch, (e) Concrete casting, (f) Concrete cylinders [37]

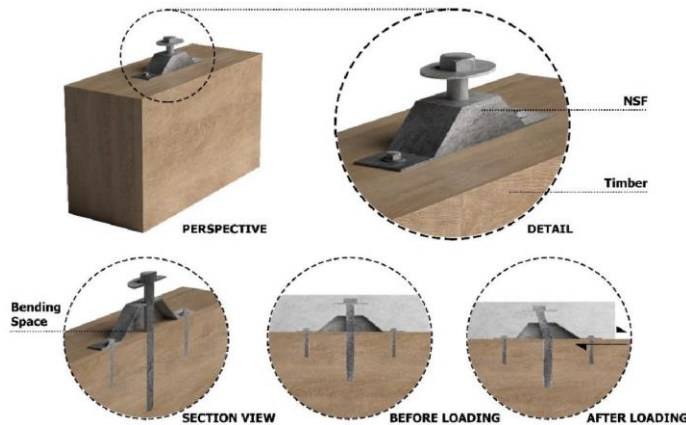


Fig. 14. Detailed view and deformed shape of notched-slab fastener (NSF) [34]

Zhang et al. [37] proposed a reinforcing method for notches to limit concrete cracking as shown in Fig. 13. Four-point bending test made on TCC floors with varying amounts of reinforcement. Reinforced notches increased floor's ultimate bending stiffness and load-bearing capacity, but serviceability bending stiffness was not changed. Three reinforced floor samples failed in bending, while notches only sustained slight damage.

A new notched connector was developed for TCC floors by Yilmaz et al. [34]. The notch is placed in concrete slab to avoid cross-sectional loss in timber. It provided a moment arm, concentrating damage in the connector. Tests results revealed that the connector demonstrated stable load-carrying capacity under push-out tests, with high-energy dissipation and no sudden strength reduction. The connectors outline is shown below in Fig. 14.

3.3. Glued in plates, nail plates and perforated steel mesh connectors

Steel plate connectors have various forms including nail plates, perforated plates with half its depth glued in timber slots and half its depth in concrete with opening for higher degree of bonding. Clouston et al. [38] developed a continuous steel mesh connector shown in Fig. 15 which is attached in a timber slot and driven into concrete. Test results show that steel mesh serves as a stiff and ductile shear connection. European standard was used to predict failure load for bending. Beams had almost full composite action, with 97%

effective stiffness and 99% of the full composite action. It stands out from other connectors due to its high structural efficiency, ease of installation, and cost-effectiveness.

Recently, Haotian et al. [39] examined the applicability of glued steel plate and perforated glued steel plate (GSP/PGSP) connections in prefabricated TCC and cast-in-situ TCC structures as shown in Fig. 16 below. Three-dimensional finite element model was developed to confirm the orthotropic elastic-plastic damage behavior of timber, damage plasticity characteristics of concrete, adhesive fracture, and nonlinear shear-slip behavior of connections. Bonded perforated steel plate connections had excellent slip stiffness and shear capacity but low ductility due to brittle fracture of adhesive. The stiffness and strength of PGSP were higher than GSP due to excellent anchoring performance of grouting cements and low shrinkage behavior of dry construction method. Likewise, PTCC beams exhibited better bending performance than cast-in-situ TCC beams due to higher slip stiffness of PGSP. FE computational findings agree with test results regarding failure modes, shear-slip behavior of connections, and bending performance of composite beams.

Similarly, Otero-Chans et al. [40] tested discrete perforated steel plates with/ without reinforcing bars. Six connector types, with two lengths and three configurations shown in Fig. 17 were tested. Discrete plates are extremely strong and stiff, and it can be designed for ductile failure. It is also found that failure occurs in the longest connection in timber at lower average shear stresses. However, there is no significant difference between discrete plates and those strengthened with extra bars. Adopting this connection would enable construction of TCC elements with composite actions near to 100%, according to the high slip moduli values.

Another recent study by Elif et al. [41] made on perfobond connection originally designed for steel-concrete composite beams and extended to TCC as shown in Fig. 18. Push-out tests made with variable connector surface roughness, concrete type, and concrete strength. Although, the ultimate slip is limited for the geometries explored, perfobond connections offer promising strength and stiffness. The higher stiffness and strength of the connection showed a potential for use in TCC.

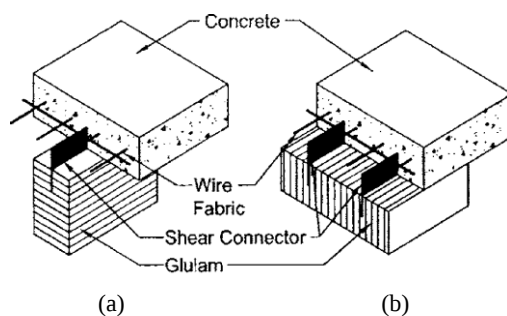


Fig. 15. Components of TCC: a) T-beam system and b) floor system [38]



Fig. 16. Perforated glued steel plate (PGSB) installed in timber [39]

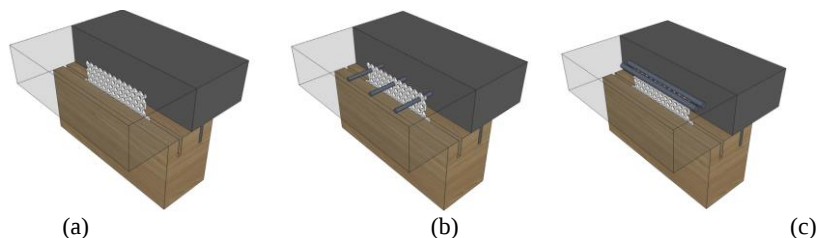


Fig. 17. Perforated steel plates with a) no reinforcement, b) with transverse reinforcement, c) with longitudinal reinforcement [40]



Fig. 18. PerFOBOND connection [41]

3.4. Adhesive connectors

Adhesives offer high stiffness, develop nearly a full composite action, transfer uniform shear force and suitable for connecting timber and prefabricated concrete slabs. But its long-term performance does not fulfil requirements, also difficult for quality control, onsite application and connection fail in brittle manner. As shown in Fig. 19 Frohnmüller et al. [42] used a continuous bonding using polymer mortar and epoxy resin. Both adhesives were suitable, but polymer mortar had distinct advantages in applicability and gap bridging. Quasi-static and cyclic loading tests made on the 8m span full-scale beams, and full bond was achieved in all beams. Also, analytical and FE models made and results agreed in deformation behavior and failure load.

Similarly wet and dry bonding techniques was conducted by Bajžecarov et al. [43] as shown in Fig. 20. Wet-on-wet gluing technique showed high efficiency in creating a strong connection. However, there is a notable deflection due to concrete shrinkage. To minimize deflection, researchers developed prestressed panels using wet-on-wet approach. After prestressing load-bearing capacity increased by 20 percent.

Likewise, Nemati et al. [44] examined effects of type and amount of adhesive on bond strength of wet and dry bonding techniques. Polyurethane thickness of 0.25mm, 1mm, 3mm and epoxy thicknesses of 1mm, 2mm, and 3mm used as shown in Fig. 21. Hardener and resin of two-component polyurethane and epoxy applied to timber before casting concrete for wet TCC with varying delay times. From oscillation test, gel time of adhesive was found 72 min for polyurethane and 221 min for epoxy. Shear test was conducted to investigate the influence of adhesive type and amount on bond strength and failure modes. Increasing adhesive thickness led to higher shear strength. Longer delayed time improved bond strength of wet TCC glued with 1mm and 3mm thick polyurethane. However, bond strength of wet TCC glued with epoxy decreased with a longer delay time. For same adhesive amount and type wet bonding technique produced higher shear strength.

Kong et al. [45] made an experimental and analytical study on creep behavior of Timber- ultra-high-performance fiber reinforced concrete (UHPFRC) beams with adhesive connection with/without carbon fiber reinforced polymers (CFRP). Experimental investigation on creep behavior was carried out in indoor and outdoor environment under constant load for about a year. Results displayed that heterogeneous glulam-UHPFRC beams improved in strength, stiffness, and reduced creep deflection of timber beams.

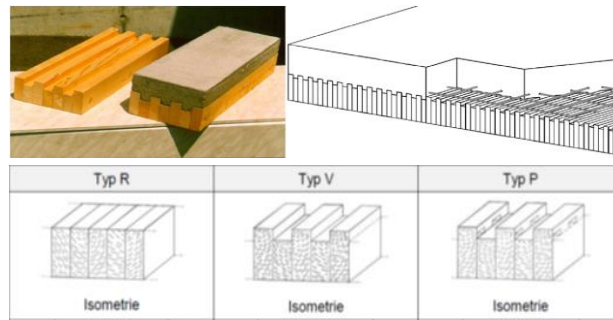


Fig. 22. Friction based connection [16]

This method combines concrete-like adhesive and wide drill holes or slots to overcome uncertainties related with bond line quality in glued-in rods and structural performance of inadequately glued connections [16]. Samuel et al. [46] introduced a new CTA connector to enhance structural ductility without compromising stiffness at serviceability limit state as presented in Fig. 23. This connector has ultra-high-performance fiber-reinforced concrete (UHPFRC) shell with a steel cylindrical core. Shear tests show that stiffness of the connector is mainly influenced by diameter of concrete shell, whereas its strength is mainly dependent on diameter of steel core.

The recent studies on shear connector types used for timber concrete composite applications are summarized in Tables 1-4, and the load-slip responses of different connection systems are shown in Fig. 24.

Table 1. Summary of recent studies on dowel type connectors

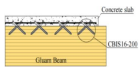
References	Shear connector	Mechanical properties	Advantages	Disadvantages
Taazount et al. [28]	Nails			
Manaridis [24]	SFS-screws 	Lower shear strength	Nails simple to install	Limited Load Capacity
Haotian et al. [33]	coach screws 	Low stiffness value as shown in Fig.-24	Easily replaced without significant disruption	Separation of timber and concrete or pullout of connector
Derikvand et al. [31]	Self-tapping screw 	Large deformation and slip for small loading magnitude	Large plastic deformation at failure	Limited Use in Heavy Structural Applications
Xie et al. [32]	Bolt connectors 		Enables reuse of timber	

Table 2. Summary of recent studies on notched type connectors

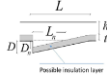
References	Shear connector	Mechanical properties	Advantages	Disadvantages
Lamothe et al. [20]	Notched connector 	High stiffness with lower slip		
Yuchen et al. [11]	Reinforced notch 	Enhanced shear strength	High load capacity than dowels and plates	Low shear capacity
Jiang et al. [35]	Reinforced notch 	Increased load-carrying capacity	Improved structural performance	Separation of elements for unreinforced notches
Boccardo et al. [36]	Notched connector		Simple to construct	Shear failure of concrete in notches
Zhang et al. [37]	Reinforced notch 	Improved durability	The fasteners in the notch increase ductility and prevent separation	
Yilmaz et al. [34]	Notch in concrete 	Large plastic deformation for notches in concrete		

Table 3. Summary of recent studies on glued in plates and perforated steel mesh connectors.

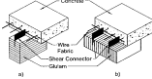
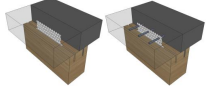
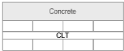
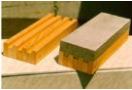
References	Shear connector	Mechanical properties	Advantages	Disadvantages
Clouston et al. [38]	Steel mesh glued in concrete 	Has almost full composite action		
Haotian et al. [39]	Glued Perforated plate 	Higher stiffness values than dowel types Carry high loads with lower slip	Improved ductility with high load capacity	Brittle failure of glues between plate and timber
Otero Chans et al. [40]	Plates with/ without reinforcement 	Larger plastic deformation after ultimate load capacity	Easy to install	Difficult to repair or replace
Elif et al. [41]	Perfobond connection 			

Table 4. Summary of recent studies on adhesive type, concrete type, and friction based connectors

References	Shear connector	Mechanical properties	Advantages	Disadvantages
Frohnmueller et al. [42]	polymer mortar and epoxy adhesive 	Develop nearly full composite action	Uniform distribution of shear forces	Limited long-term performance
Bajzecerov et al. [43]	Wet-on-wet gluing 	Have the highest stiffness with a small slip value	Allows easier calculation using the theory of full composite action	Difficult quality control
Nemati et al. [44]	Wet-on-wet gluing 			Connection fail in brittle manner
Samuel et al. [46]	Concrete type adhesive 	Improved stiffness than dowel systems Higher ductility with improved load carrying capacity	Easy to construct and replaced without significant disruption	Crushing of the concrete shell
Dias et al [16]	Friction based connector 	Develop almost full composite action High stiffness value	Simple to construct Resist higher loads with small slip	Brittle failure of connection Separation of timber and concrete

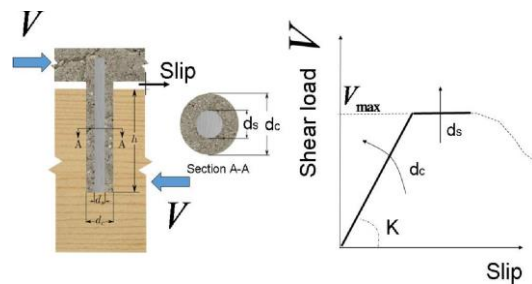


Fig. 23. A new concrete type connector [46]

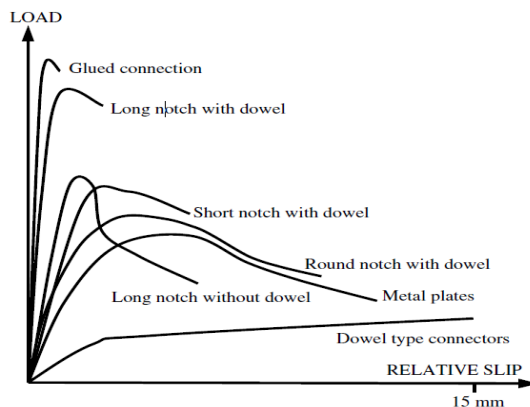


Fig. 24. Comparison of load – slip responses of different connection systems [25]

4. Guidelines for design of TCC structures

The key design steps for TCC are selection of appropriate materials, design of shear connectors, and optimization of cross-section. Although, some separate guidelines have been developed to answer particular issues such as for design of bridges [8], design of TCC is not supported by adequate standards. AASTHO codes, Australia and New Zealand design Guidelines, Brazil's manual for timber bridge design, Canadian Highway Bridge Design Code, and Eurocode-5 are currently available guidelines [16].

4.1. Eurocode 5

Eurocode 5 gives details about slip of TCC connections, recommended safety factors, influence of connection slip on composite action of decks, design of steel fasteners and grooved connections (Table 5). In absence of test data, Eurocode 5 provides values for slip modulus as a function of connection type, diameter, and weight of timber. K_{ser} value for screws and dowel type fasteners is determined by equation (7) for SLS and equation (8) for ULS. Equations are for timber-to-timber joints, and slip modulus values must be doubled for TCC modeling [47].

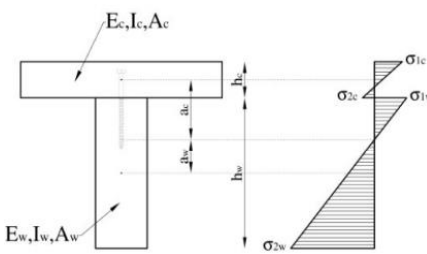
4.2. USA – AASHO/AASTHO codes

TCC bridges are covered by several AASTHO codes, particularly those from 1949 and 1983 versions. In the 1949 version internal forces are calculated assuming full composite action. Also, the connector must allow for concrete compaction and avoid a vertical separation between two materials [16]. According to the 1983 version, shear connection in TCC decks must bear the whole horizontal shear and designed to prevent two components from separating. Different connection configurations, such as nails or grooves are specifically permitted [16].

4.3. Australia and New Zealand Design Guidelines

Gerber [8] adopted a design guide from Eurocode 5 for TCC construction in Australia and New Zealand. But, it was modified to adhere timber design regulations in Australia and New Zealand. It has limitations regarding TCC floors long-term deflection, uses only notches and screw connections, and spans below 8 m as shown in Fig. 25. Connections' behavior is assumed linearly elastic in Ultimate and Serviceability Limit States [16].

Table 5. Cross-section of TCC and basic equations of "γ" method EC5

Composite TC cross section	"γ / Mohler" method	Eq. No
	$n = E_c/E_w$	(1)
	$\gamma = 1/(1 + k)$	(2)
	$k = (\pi^2 E_c A_c S)/(L^2 K_i)$	(3)
	$a_c = 0.5(A_w(h_w + h_c))/(\gamma n A_c + A_w)$	(4)
	$a_w = (h_w + h_c)/2 - a_c$	(5)
	$I_{ef} = n I_c + \gamma n A_c a_c^2 + I_w + A_w a_w^2$	(6)
"K _{ser} " value for screws and predrilled nails (EC5) in timber-concrete, SLS	$K_i = K_{ser} = 2\rho^{1.5}d/23$	(7)
"K _u " value for ULS	$K_i = K_u = 2/3K_{ser}$	(8)

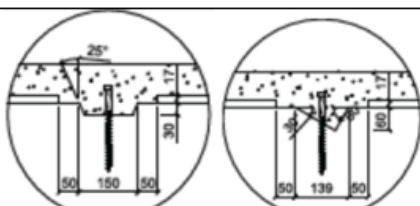
Connection types with geometry and dimensions	For beam thickness 50mm or less	For beam thickness more than 50mm
in mm		
	Coach screw Ø12 mm and l_p : 80 mm or at least the length of the thread	Coach screw Ø16 mm and l_p : 100 mm or at least the length of the thread

Fig. 25. Connection configurations in Australian and New Zealand design guidelines [3]

4.4. Canadian Highway Bridge Design Code

The Canadian Highway Bridge Design Code provides specific guidelines for the design of TCC bridges and connections. Two connection configurations are permitted and both are notches combined with steel fasteners with laminations of varying depths shown in Fig. 26.

4.5. Brazil – Manual for the design of timber bridges

The standards utilized in Brazil are same as those in European nations, notably Eurocode 5. The analysis and design of TCC bridges are specifically outlined in a bridge design code. The guideline is intended for TCC bridges that have round wood members to construct the timber deck systems [16].

5. Current practice and recent developments

To enhance load transfer efficiency, increase structural stiffness, and improve overall performance of TCC systems researchers have been investigating advanced materials such as fiber-reinforced polymers (FRPs), adhesive bonding or hybrid connectors combining mechanical fasteners and adhesives has gained attention. Also, Emilio et al. [48] developed a new flooring system with a TCC connection that does not require adhesives or special metal elements. It an inverted T shape made of a lower glulam flange and a central plywood rib with holes through the entire thickness of the plywood. The connection is achieved by penetrating concrete into the rib holes and corrugated steel bars were placed through side holes to achieve ductile behavior.

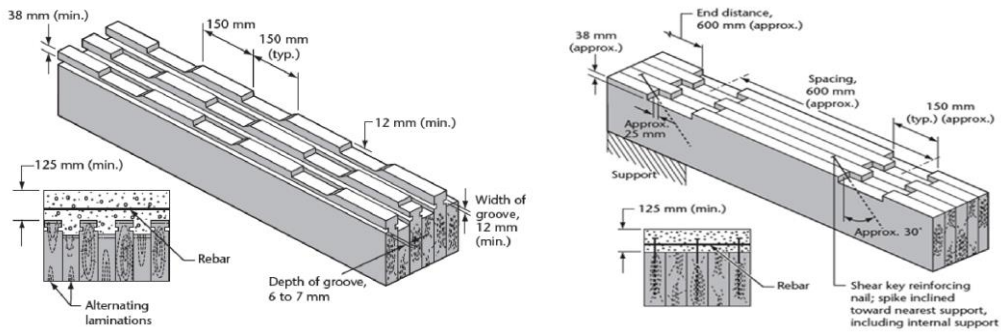


Fig. 26. Sketch of connection configurations indicated in Canadian Highway Bridge Design Code [40]

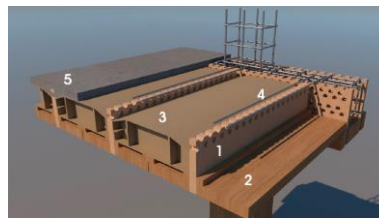


Fig. 27. (1) plywood rib, (2) glulam flange, (3) in-fill blocks, (4) rebars, (5) concrete slab [48]

6. Conclusion

Timber-concrete composite (TCC) structures have gained significant attention in the construction industry due to their numerous advantages, such as improved strength, stiffness, seismic resistance, and environmental friendliness. Shear connectors play a crucial role in achieving effective load transfer and enhancing the composite action between timber and concrete elements in TCC systems. This comprehensive review explored various types of shear connectors and their mechanical behaviors, providing valuable insights into their strengths, stiffness, ductility, and durability. Dowel-type connectors, notched connectors, glued-in plates, nail plates, perforated steel mesh connectors, and adhesive connectors were among the different connector types investigated. Each type exhibited unique advantages and limitations. The push-out tests, bending tests, and numerical simulations conducted in various studies allowed for a thorough assessment of the performance of these connectors.

The study highlighted the increasing interest in developing high ductility connectors for TCC applications to ensure better structural resilience and safety. Friction-based connections and concrete-type adhesives (CTA) were identified as innovative approaches to achieve enhanced structural ductility without compromising stiffness. Design guidelines from various countries, such as Eurocode 5, AASHTO/AASTHO codes, Australia and New Zealand design guidelines, Canadian Highway Bridge Design Code, and Brazil's manual for the design of timber bridges, were reviewed to provide design considerations for TCC structures. Each code offered specific provisions for the design of TCC bridges and connections, catering to the unique requirements of each region. Recent developments in TCC systems have seen researchers explore advanced materials, such as fiber-reinforced polymers (FRPs) and hybrid connectors combining mechanical fasteners and adhesives. These innovations aim to improve load transfer efficiency and overall structural performance.

In conclusion, this review consolidates current knowledge on shear connectors for timber-concrete composite applications, providing valuable insights for researchers, engineers, and practitioners in the field. As TCC structures continue to gain popularity worldwide, ongoing research and development in shear connectors and innovative connection systems will undoubtedly lead to further advancements in this field, opening new avenues for sustainable and resilient construction practices.

Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

This research received no external funding.

Data availability statement

No new data were created or analyzed in this study.

References

- [1] Lukaszewska E, Fragiaco M, Johnsson H (2010) Laboratory tests and numerical analyses of prefabricated timber-concrete composite floors. *Journal of Structural Engineering* 136(1):46-55.
- [2] Le Roy R, Pham HS, Foret G (2009) New wood composite bridges. *European Journal of Environmental and Civil Engineering* 13(9):1125–1139.
- [3] Lehan AR (2012) Development of a Slab-on-Girder Wood-Concrete Composite Highway Bridge. MSc. Thesis, University of Toronto.
- [4] Yeoh D, Fragiaco M, De Franceschi M, Boon KH (2011) State of the art on timber concrete composite structures: Literature review. *Journal of Structural Engineering* 137(10):1085-1095.
- [5] Dias A, Jorge L (2011) The effect of ductile connectors on the behavior of timber-concrete composite beams. *Engineering structures* 33(11):3033-3042.
- [6] Dias A, Skinner J, Crews K, Tannert T (2016) Timber-concrete-composites increasing the use of timber in construction. *European Journal of Wood and Wood Products* 74(3):443–451.
- [7] Bathon L, Graf M (2000) A continuous wood-concrete-composite system. In: *Proceedings of World Conference of Timber Engineering*. Whistler, BC.
- [8] Gerber AR (2016) Timber-Concrete Composite Connectors in Flat-Plate Engineered Wood Products. MSc. Thesis, University of British Columbia.
- [9] Nicolas J, Ulf AG (2012) Tests on shear connections in prefabricated composite cross-laminated-timber and concrete elements. In: *Proceedings of WCTE: World Conference on Timber Engineering*, Auckland, New Zealand.
- [10] Ceccotti A (2002) Composite concrete–timber structures. *Structural Engineering and Materials* 4:264–275.
- [11] Yuchen J, Crocetti R (2019) CLT-concrete composite floors with notched shear connectors. *Construction and Building Materials* 195:127–139.
- [12] Jiang Y, Hong W, Hu X, Crocetti R, Wang L, Sun W (2017) Early-age performance of lag screw shear connections for glulam-lightweight concrete composite beams. *Construction and Building Materials* 151:36–42.
- [13] Crocetti R, Sartori T, Tomasi R (2015) Innovative Timber-Concrete Composite Structures with Prefabricated FRC Slabs. *Journal of Structural Engineering* 141(9):04014224.
- [14] Lukaszewska E, Johnsson H, Fragiaco M, (2008) Performance of connections for prefabricated timber–concrete composite floors. *Materials and Structures* 41:1533–1550.
- [15] Khorsandnia N, Valipour HR, Bradford M (2018) Deconstructable timber-concrete composite beams with panelized slabs: Finite element analysis. *Construction and Building Materials* 163:798-811.
- [16] Dias A, Schänzlin J, Dietsch P (2018) Design of Timber-Concrete Composite Structures. A State-of-the-Art Report by COST Action FP1402 / WG 4. Shaker Verlag Aachen.
- [17] Yeoh D, Fragiaco M, De Franceschi M, Buchanan AH (2010) Experimental tests of notched and plate connectors for LVL-concrete composite beams. *Journal of Structural Engineering* 137(2):261-269.
- [18] Samuel C A (2020) Design Guide for Timber-Concrete Composite Floors in Canada. Pointe-Claire: FP Innovations.
- [19] EN 26891 (1991) Timber structures – Joints made with mechanical fasteners – General principles for the determination of strength and deformation characteristics. Comité Européen de Normalisation.

- [20] Lamothe S, Sorelli L, Blanchet P, Galimard P (2020) Engineering ductile notch connections for composite floors made of laminated timber and high or ultra-high performance fiber reinforced concrete. *Engineering Structures* 211(3):110415.
- [21] Lukaszewska E (2009) Development of Prefabricated Timber-Concrete Composite Floors. PhD Dissertation, Luleå Tekniska Universitet.
- [22] Zhang C, Gauvreau P (2014) Timber-Concrete Composite Systems with ductile connections. *Journal of Structural Engineering* 141(7): 04014179.
- [23] Plüss Y, Zwicky D (2011) Plastic design of timber concrete composite girders. In: Proceedings of Taller, Longer, Lighter – Meeting growing demand with limited resources. IABSE/IASS Symposium, London, UK
- [24] Manaridis A (2010) Evaluation of Timber Concrete Composite Floors. MSc. Thesis, Lund University.
- [25] Chuan DYE (2010). Behaviour and Design of Timber-Concrete Composite Floor System. PhD Dissertation, University of Canterbury.
- [26] Dias AMPG (2011) Analysis of the nonlinear behavior of timber-concrete connections. *Journal of Structural Engineering* 138(9):1128–1137.
- [27] Monteiro SRS, Dias AMPG, Negrao JHJO (2013) Assessment of timber—concrete connections made with glued notches: Test set-up and numerical modeling. *Experimental Techniques* 37:50–65.
- [28] Taazount M, Amziane S, Moutou PR, Molard D (2011) Timber-lightweight concrete composite flooring element. 20th French Congress of Mechanics.
- [29] Dias A, Lopes S, Van de Kuilen J, Cruz H (2007) Load-carrying capacity of timber–concrete joints with dowel-type fasteners. *Journal of Structural Engineering* 133(5):720–727.
- [30] Kanócz J, Bajzeczová V (2015) Timber – concrete composite elements with various composite connections. *Wood Research* 60(6):939-9521.
- [31] Derikvand M, Fink G (2020) Deconstructable timber-concrete composite connectors. In: Proceedings of the Society of Wood Science and Technology Convention, Aalto University.
- [32] Xie L, He G, Wang AX, Crocetti R, Shen L, Tang X (2023) Hysteretic behavior of bolt connections in timber concrete composite bridges: Experimental and numerical research. *Journal of Bridge Engineering* 28(1):1–9.
- [33] Haotian T, Yang H, Ju G, Xu J, Shi B (2022) Effective width of timber-concrete composite beams with crossed inclined coach screw connections at the serviceability state. *Engineering Structures* 267:114716.
- [34] Yılmaz S, Demir S, Vural N (2021) Experimental investigation of a prefabricated timber-concrete composite floor structure: Notched-slab approach. *Advances in Concrete Construction* 12(1):13-23.
- [35] Jiang J, Hu X, Hong W, Zhang J, He F (2020) Experimental study on notched connectors for glulam lightweight concrete composite beams. *BioResources* 15(2):2171-2180.
- [36] Boccadoro L, Zweidler S, Steiger R, Frangi A (2017) Calculation model to assess the structural behavior of LVL-concrete composite members with a ductile notched connection. *Engineering Structures* 153:106–117.
- [37] Zhang L, Zhou J, Chui YH (2022) Development of high-performance timber concrete composite floors with reinforced notched. *Structures* 39:945–957.
- [38] Clouston P, Bathon LA, Schreyer AC (2005) Shear and bending performance of a novel wood–concrete composite system. *Journal of Structural Engineering* 131(9):1404-1412.
- [39] Haotian T, Shi B, Yang H, Wang C, Ling X, Xu J (2022) Experimental and finite element studies of prefabricated timber-concrete composite structures with glued perforated steel plate connections. *Engineering Structures* 128:114778.
- [40] Otero-chans D, Estévez-Cimadevila J, Suárez Riestra F, Martín-Gutierrez E (2018) Experimental analysis of glued-in steel plates used as shear connectors in Timber-Concrete-Composites. *Engineering Structures* 170:1–10.
- [41] Elif A, Vandoren B, Henriques J (2022) Push-out tests on adhesively bonded perfobond shear connectors for timber-concrete composite beams. *Journal of Building Engineering* 57(4):104833.
- [42] Frohn Müller J, Fischer Ji Seim W (2021) Full-scale testing of adhesively bonded timber-concrete composite beams. *Materials and Structures* 54:187.
- [43] Bajzeczová B, Kanócz J, Rovňák M, Kováč M (2022) Prestressed CLT-concrete composite panels with adhesive shear connection. *Journal of Building Engineering* 56:104785.
- [44] Nemati A, Fu Q N, Yan L, Kasal B (2022) The effect of adhesive amount and type on failure mode and shear strength of glued timber-concrete joints. *Construction and Building Materials* 345(1):128375.

- [45] Kong K, Ferrier E, Michel L (2015) Creep behaviour of heterogeneous timber-UHPFRC beams assembled by bonding: experimental and analytical investigation. *World Academy of Science, Engineering, and Technology International Journal of Civil and Environmental Engineering* 9(9):1205-1212.
- [46] Samuel C A, Sorelli L, Salenikovich A (2016) A new composite connector for timber-concrete composite structures. *Construction and Building Materials* 112:84–92.
- [47] Tatjana K, Dragan M (2015) Modeling of composite timber-concrete system with inclined cross screws. In: *Proceedings of 13th International Scientific Conference iNDIS2015: Planning, Design, Construction and Renewal in the Civil Engineering*, Novi Sad, Serbia.
- [48] Emilio M G, Javier E C, Félix S R, Dolores O C (2022) Flexural behaviour of a new timber-concrete composite structural flooring system. Full scale testing. *Journal of Building Engineering* 64 (2023) 105606