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Subject Review

Screw Connection Systems in Timber-Concrete Composite Structures: A Literature Review

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Abstract: This paper reviews the type of engineered timbers and connection systems used in timber concrete composite structures. The literature references were selected and reviewed carefully to get a detailed overview of the use of timber and connections systems in timber-concrete composite structures. The list of connection systems used in the timber-concrete composite structures was reviewed from the previous works to perceive its advantages and disadvantages. It was found that the glued joint is the stiffest connection but low in ductility. Mechanical fasteners such as screw connections have moderate stiffness and ductility compared to the hardwood studs which have the lowest stiffness and the highest ductility. The design models of connection strength and stiffness of the screw connections were assembled and discussed to recognise their limitations to the design of timber-concrete composite structures.

Keywords: cross-laminated timber; glulam; LVL timber; screw connections; timber-concrete composite

1 HISTORY OF THE TIMBER CONCRETE COMPOSITE STRUCTURES

Insufficient steel for reinforcement in concrete after World War 2 led to the introduction of timber-concrete composite (TCC) structures in Europe [47]. Muller [22] introduced a system of nails and steel braces to provide a connection between concrete slabs and timber joists. Schaub [35] also invented the timber layer floor system under the concrete layer that can rely on I and Z-sections of steel as shear connectors. In 1960 in Bratislava, Slovakia, TCC structures were applied on existing ceilings by installing nails as shear connectors [32]. The project was examined in subsequent years between the years 1975 to 1988. The result showed that no large deflection was found [31]. Starting from the mid-1980s in Germany, intensive research began in addition to the various fasteners development, analysis, and design methods for the applications of TCC systems [41]. In 1930 in the USA at the University of Oregon, steel connectors between timber and concrete were introduced [3].

In New Zealand, TCC bridges have been built since 1970 with 150 mm thick reinforced concrete slabs to support heavy traffic [23]. TCC application in the bridges could reduce the timber beam size by almost 20%. Godycki et al. [11] published the document of a combination of the practice and the theory for the existing timber floors added with the concrete slabs for repairing method. The research focused on connections for TCC by using wire nails as shear connectors. Similarly, in India, Pillai and Ramakrishnan [27] also investigated the application of wire nails to TCC. In the Persian Gulf (with salty airflow), most of the buildings were made of reinforced concrete structures. This environment has resulted in corrosion of the steel reinforcements that weakens the performance of the structural concrete. The builders have decided to use TCC to solve the problem [1].

2 ENGINEERED TIMBER IN CONSTRUCTIONS

Innovation in timber technology has resulted in the development of stiffer and stronger timber materials in construction. The development of TCC structures has been increasing in the construction field [50]. As it is used more widely in many countries, the technology for making the engineered timber has improved [4].

2.1 Engineered Timbers

In the early 1890s, the first engineered timber introduced in Europe was glulam [2]. This type of engineered timber comprised several parallel layers with thicknesses between 40 mm to 45 mm and is usually made from spruce and larch wood species [40]. Sebastian et al. [36] stated that there are defects (e.g., knots) normally found on the glulam that may affect its strength. In the production of glulam, the layers are glued together under pressure with the grain in the laminates running parallel to the longitudinal axis of the section [16].

Another type of engineered timber currently commonly used worldwide is cross-laminated timber (CLT) [2]. Since 2000, the use of CLT in construction has increased significantly due to better efficiency, product approvals, and improved marketing and distribution channels [17]. The European experience has been good in dealing with CLT by applying it to mid-rise and high-rise buildings and via the simplified handling during construction [8]. CLT panels are made from a few layers of lumber boards stacked (normally from spruce). In the making of CLT panels, there should be at least three layers of board glued together [17]. In CLT, layers of timber are bonded perpendicularly to one another, resulting in structural strength across two dimensions and improving structural integrity and dimensional stability [44].

While most engineered timbers only comprise a few thicker layers of timber, thinner laminations can improve the consistency and performance of engineered timber [36]. Modern rotary cutting machinery has been developed to produce very thin laminations by peeling layers off from original round hardwoods such as beech [30]. The machine produces lamination of 4 mm thickness, and this leads to another form of engineered timber known as laminated veneer lumber (LVL), which has more consistency in its material properties and fewer defects. LVL started to be used as a structural application in 1978 in the United States [51]. But the types of wood species in the production of LVL were sourced from the softwood species such as Douglas-fi and Pine [48]. There has not been much research done involving the use of LVL joists made of hardwood as structural application. Most LVL hardwood is applied in the production of furniture. Two recent studies by Boccardo et al. [5] and Sebastian et al. [36] investigated the use of LVL hardwood in structural application for simply supported and indeterminate beams, respectively.

2.2 Comparison Between all Engineered Timbers

The very high strength and stiffness of LVL hardwood (Baubuche) permit for smaller cross-sections, which results in major savings in material consumption [28, 29]. Tab. 1 shows the comparison between engineered timber, where the smaller sizes of timber width are required by LVL hardwood to achieve similar bending strength, shear strength, compressive strength, tensile strength, and modulus of elasticity with other types of engineered timber. As an example, the LVL hardwood (GL75) requires only 57 mm width to achieve similar bending strength to the 200 mm width of solid timber (C24).

Table 1 Comparison between engineered timbers [28, 29]

Material / Properties	Solid timber: 200 mm (width)	Glulam	LVL softwood	LVL hardwood
Bending strength, f_m / MPa	200 mm /100%	154 mm /77%	92 mm /46%	57 mm /29%
Shear strength, F_v / MPa	200 mm /100%	240 mm /120%	112 mm /56%	104 mm /52%
Compressive strength, $f_{c,t}$ / MPa	200 mm /100%	152 mm /76%	102 mm /51%	56 mm /28%
Tensile strength, $f_{t,t}$ / MPa	200 mm /100%	129 mm /64%	68 mm /34%	44 mm /22%
Modulus of Elasticity, E_t / MPa	200 mm /100%	175 mm /87%	159 mm /80%	132 mm /66%

*(Required width to achieve same strength / % material consumption)

2.3 Application of Engineered Timber in TCC structures

There are many application examples of engineered timber in TCC structures.

2.3.1 Timber-Concrete Composite Bridge, Wippra, Germany

This bridge is the earliest TCC bridge for heavy load traffic in Germany, as shown in Fig. 1. It was built in 2008 with a length and width of 16.4 m and 4.5 m, respectively. The main reason this bridge was constructed was for lorry traffic for forestry purposes. This bridge consists of glulam beams and concrete slab composite. The composite was connected by screws and bolts.

Figure 1 Pioneer of TCC bridges in Germany [34]

2.3.2 Timber-concrete composite bridge, Nordrhein-Westfahlen, Germany

This TCC bridge was built in 2014 to replace the previous bridge that required frequent repairs due to flood damages, as can be seen in Fig. 2. The new bridge has only two columns on the river banks, and the timber structure is set high enough to prevent any damage caused by floods. The glulam beams were designed in wave shape, corresponding to the load and creates a scenery view. The bridge consists of a spruce glulam with a span length and width of 40 m and 4.75 m, respectively. The bridge has a stepped cross-section on its main carrier. The bridge was also made of concrete slab with mastic asphalt and steel railing. The accoya handrail used on the bridge also includes a safety rope. The notched connections were used as the shear connector in this TCC bridge.

Figure 2 Agger TCC bridges in Germany [43]

Figure 3 Three-storey building in New Zealand [33]

2.3.3 College of Creative Arts (CoCA), Massy University, Wellington, New Zealand

This triple-storey building was built in 2012 and named Te Ara Hihiko, which can be broadly translated into 'a pathway to creativity', as can be seen in Fig. 3. This building has long-span TCC floors creating open spaces to provide and maintain a warm environment for the students. Notched connections were used as composite resistance between LVL timber to concrete. A seismic analysis was done on this building by a consultant company to show its resistance and showed that it worked well in what would be expected in an earthquake.

3 CONNECTION SYSTEMS IN TCC STRUCTURES
3.1 Timber Fasteners in TCC

Sebastian et al. [38] reported on using timber connectors in timber-limecrete composite floors. The timber stud connectors used were from the hardwood variaton iroko, which was designed as a circular section shank and square section head. The studs were applied into a simply supported timber composite beam with a slope of 45° to the slab-joist interface towards the sense of slip before limecrete was poured as shown in Fig. 4. Limecrete of 5 N/mm^2 compressive strength was used for the slab and whitewood (spruce) glulam joists were used in this experiment. The composite beam connection recorded a stiffness of about 13 kN/mm and a shear strength of 35 kN per stud. It was found that when the studs were fitted in 45° reversed (tension) to the interface, against the sense of slip, the connection stiffness dropped to 3 kN/mm and shear strength dropped to 22 kN.

This research was continued by Sebastian and Thomson [37] comparing bonded and dowelled hardwood studs in timber-limecrete composite, using different stud angles. The iroko studs were fitted into timber joist as shown in Fig. 5 for both methods. The studs were also applied in various inclinations between 40° to 90° to evaluate the effect of angle on the connection behaviour. Two methods used to install the studs were bonding by using epoxy and restraint by using a dowel. By using the dowel, the 9 mm diameter dowel made from hardwood ramin was used to fit the studs in connection as shown in Fig. 5.

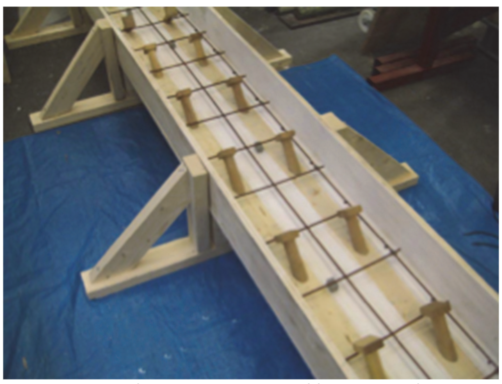

Figure 4 Iroko studs fitted into timber joist [38] Reprinted from Journal of Structural Engineering, 136 (12), Sebastian, W., Bishop, R., & Evans, R, Timber-Limcrete Composite Floors Using Timber Connectors Sloped Toward or Against Slip, 1585 - 1595., Copyright (2010), with permission from ASCE

From the tests at all stud angles, the bonded stud connection showed more scatter of stiffness about the mean value as compared to the dowelled stud connections. At lower inclinations of the studs, the bonded fastening was more effective than the dowels in restraining the connection.

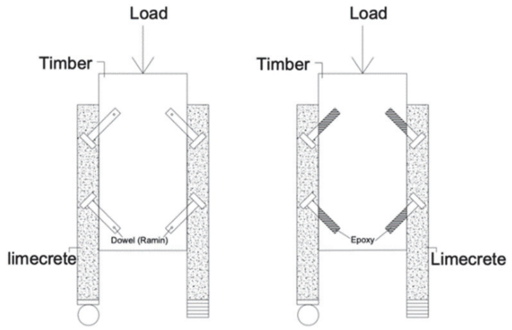

Figure 5 Layout of limecrete-timber connection in shear test [37] Reprinted from Engineering Structures, 45, Sebastian, W., & Thompson, S., Indicative Comparisons Between Bonded and Dowelled Hardwood Studs for Limecrete-Spruce Connections Under Load-Unload-Reload Double -Shear Testing, 151 - 165., Copyright (2012), with permission from ASCE

3.2 Inclined Screws in TCC

Sebastian et al. [36] carried out the double shear test for hardwood-concrete specimens. The hardwood used in the study was made from laminations of 4 mm thick layers of beech species. Partially threaded (PT) and fully threaded (FT) screws were chosen as shear connectors. For each type of screw, *X*-formation of screws into the timber joist was used. Firstly, screws were driven into the joist at 45° in the *X* layout as presented in Fig. 6 for double shear specimens. After that, concrete of 32 N/mm^2 was poured on the timber surface on one side and to the other side after the prior side was hardened. In summary of their tests, for double shear-compression testing, the stiffness of specimens connected with FT screws was 20% higher than partially threaded screws. But, the longitudinal shear force by FT screws was about 20% lower than partially threaded screws at 39 kN.

Furthermore, Sebastian et al. [37] investigated the mechanics of externally indeterminate hardwood-concrete composite full-scale beams. In this research, FT and PT screws were used to compare connection behaviours inside the composite beams. The screws were driven into the timber joists in X pairs at ±45° before concrete of 32.7 N/mm^2 compressive strength was poured. The TCC beam based on PT screw connections failed at a significantly higher load of 170 kN as compared to that of the PT screws which failed at 125 kN.

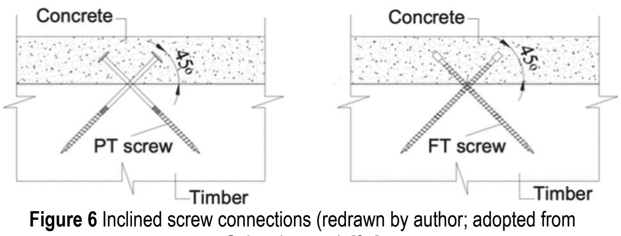

Figure 6 Inclined screw connections (redrawn by author; adopted from Sebastian et al. [37]

3.3 Notches Connection in TCC

Yeoh et al. [49] investigated a variety of notched connections for TCC structures. A notched connection is made by engraving a notch from the timber beam and filling it with concrete during the pouring of the concrete slab. This connection type provides high stiffness and strength when compared to mechanical fasteners such as screws. In the study, LVL hardwood was used for the timber part. Four main types of notch connections were used in fabricating the double shear test. There were rectangular notches, rectangular notches with screws, triangular notches and triangular notches with screws, as shown in Fig. 7. Rectangular and triangular notches reinforced with a coach screw were found to perform satisfactorily on their shear force capacity.

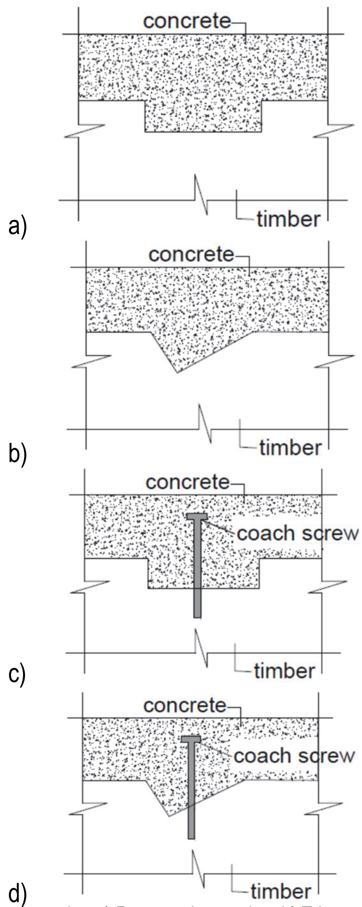

Figure 7 Notches connection a) Rectangular notches b) Triangular notches c) Rectangular notches with coach screw d) Triangular notches with coach screw (redrawn by author; adopted from Yeoh et al. [49])

3.4 Epoxy Bonded Connections in TCC

Shrestha et al. [39] carried out an experimental investigation on epoxy-bonded shear connections for TCC, with and without mechanical fasteners. A set of ten shear test specimens with LVL hardwood joist and concrete slab were fabricated. Five specimens had the joist and slab bonded together using epoxy and for the remaining five specimens, a long coach screw was subsequently fitted through the concrete slab and into the joist before the epoxy was applied on the interface between the timber and concrete. The results of the tests showed that connections of using the epoxy for bonding timber and concrete can produce similar high stiffness and strength to the notch type connections. The ductility was higher on the connection when the metal fasteners were used together with the epoxy bonded connection. It avoided the brittle failure mode that is normally associated with the epoxy bonded connection. Observation of the failed specimens showed that failure in all connections was concentrated either in the LVL or concrete close to the interface and no interface failure was observed.

3.5 Steel Type Connectors in TCC

Lukaszewska et al. [15] investigated six types of steel shear connectors for TCC structures by using the small-scale double shear test. The types of shear connectors used in that research were nail plate, steel mesh, steel tube, bent steel plate, and dowel. There were seven methods of connector fitted on TCC shear test specimens from Lukaszewska et al. [15]. All these methods of connectors are compared with the other type of connectors from other researchers' works to compare their performance. All comparisons and details are discussed and provided in the next section.

3.6 Summary of Comparison Between all Types of Connectors

A comparison can be made by summarising the results of the tests carried out by Sebastian & Thompson [37], Sebastian et al. [36], Shrestha et al. [39], Yeoh et al. [49], and Lukaszewska et al. [15]. The plot was made as shown in Fig. 8 for all types of connectors. From all plots of shear force versus slip, it was found that the glued joint, glued joint with screw, steel mesh, and steel tube with notch and screw provide very stiff connection and very small slip. The fasteners connection made from hardwood showed the lowest stiffness and large slip. The inclined screws, notches, nail plates, bent steel connections presented intermediate stiffness and small slip.

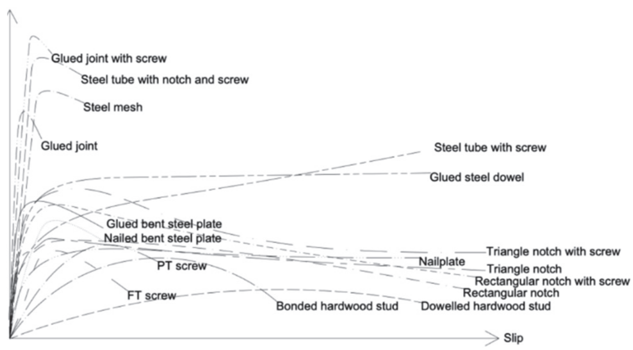

Figure 8 Shear force vs slip of all connectors (made by author by adopting from previous work data) [15, 36, 37, 39, 49]

4 COMPOSITE ACTIONS IN TCC STRUCTURES

The bonding between two different elements in TCC structures is vital to be deliberated. According to Monteiro et al. [19], to guarantee good connection systems, the efficiency of the connection between two elements must be ensured. In TCC systems, the concrete tends to behave well in compression, meanwhile, the timber is acting to resist the tensile stress. Casting the concrete as a composite on timber elements such as joists can increase the stiffness and strength of these existing timber joists [25]. By utilizing the resistances in tension and compression of timber and concrete respectively, the TCC structure works more efficient. The use of a concrete layer on the surface of timber enables the tensile resistance of the timber to perform as steel in conventional reinforced concrete [14].

Many types of shear connectors being used in TCC structures are to transfer longitudinal shear, which prevents a relative movement (slip) between the two elements (concrete and timber) and avoid vertical separation between the two, especially at high loads. Zakaria et al. [52] stated that interaction between timber and concrete can be no composite, partial composite, and full composite actions. The full composite action is considered when two elements are fastened by using epoxy, while partial interaction occurs for the elements connected by using other types of fasteners e.g., mechanical ones (see Fig. 9 and Fig. 10). No composite actions mean there is no connection between the timber and concrete (see Fig. 11). Normally, the design moment capacity and second moment of area of a composite beam with full-composite action will be higher than those of the non-composite beam [9]. The shear connector is essential in any composite beam to avoid huge deflection and deformation and provide better stiffness of the connection between both materials [12, 42].

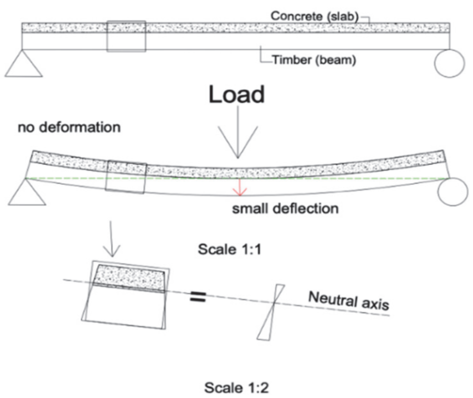

Figure 9 Full composite action

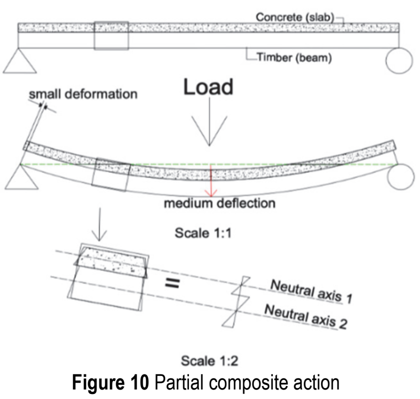

Figure 10 Partial composite action

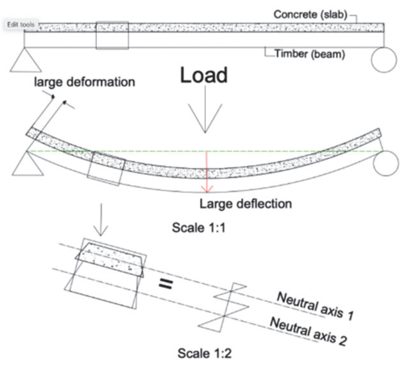

Figure 11 No composite action

4.1 Design of TCC Structure According to Eurocode 5

The use of mechanical fasteners, e.g., screws, as the shear connector between timber and concrete can allow the slip to occur at the interface. The assumption of plane sections remaining plane (compatibility) does not apply to the whole composite section [26]. When the loads are imposed on the slab, they will be transmitted to the joist through the shear connectors. There is slip and shear stress in between the two elements of composite that should be considered in the design. Newmark, et al. [24] and Mohler [18] were the people that initiated the theory of composite beam in Eurocode 5 (EC5) [7] and known as γ-method. Eq. (1) shows the fundamentals of the γ-method. In EC5, the timber and concrete are connected to each other by mechanical fasteners with a slip modulus K_S. The connection between two composite members is considered to behave in a linear elastic fashion, and the stiffness between the fasteners is constant or varies uniformly according to the shear force. Based on the cross-sectional area of the T-beam of TCC, effective bending stiffness can be written as Eq. (2). Eq. (2) is vital to obtain the fastener strength, shear stress, normal stress, and midspan deflection of the beam. Stiffness and strength of the connections in TCC can be observed by using double shear test as used by Sebastian et. al [37] (see Fig. 5 for test set-up illustration).

$$\gamma_{t-c} = \left[1 + \frac{\pi^2 E_c A_c S}{K_s L_{span}{}^2}\right]^{-1} \tag{1}$$

$$\left(EI\right)_{ef} = E_c I_c + \gamma_{t-c} E_c A_c a_c^2 + E_t I_t + E_t A_t a_t^2 \tag{2}$$

K_s stands for the joint stiffness for the serviceability limit states calculations, and K_u, for the ultimate limit states calculations in EC5 with K_u = $2K_s/3$. K_s is also known as the slipmodulus of the joint according to EN 26891 [6]. E_c and E_t are the mean values of the elasticity modulus of concrete and timber, respectively. S is the spacing of the fasteners along the beam axis, L_{span} is the span of the beam. A_c and A_t are the cross-sectional areas of concrete and timber respectively. a_t and a_c are the distance from the centroid of the element to the neutral axis of the composite section for timber and concrete respectively.

In the finite element analysis done by Huber and Deix [55], the gamma method has been concluded as a model-rate unprecise method for the computational determination of timber-concrete interaction with common design features, especially for predominantly eccentrically located load situations compared to the more stringent method.

4.2 Slip Modulus in TCC

Slip modulus or stiffness of connection is an important parameter in designing a TCC structure. In the γ-method, as discussed in the previous section, the slip modulus K_s has a significant effect on the value of gamma which also affects the strength of the connection. As stated in clause 7.1 in EC5, the slip modulus for connection timber to concrete for serviceability limit states can be calculated based on the density value of the timber and can be taken as double. However, this clause is presented with a limit to the fasteners driven vertically. In 2002, Gelfi et al. [10] developed the slip modulus model for vertical screw-in TCC structure. In order to produce a more updated slip modulus model, Symons et al. [45] proposed the slip modulus model for the inclined fasteners that can be used in the design of TCC structures.

4.2.1 Slip Modulus [10]

Gelfi et al. [10] established a slip modulus model by taking into account the characteristic of the entire screw embedded in the timber and concrete vertically. There was a plank wood between timber and concrete acting as the formwork in that mode, as shown in Fig. 12. The basic theory used by Gelfi et al. [10] was to adapt the flexibility method in the compatibility method as shown in Eq. (3) and Eq. (4). The displacements (η_{11}, η_{12}, η_{10}) and rotations (φ_{21}, φ_{22}, φ_{20}) incompatibility equations, are solved by the semi-infinite beam method known as the Winkler foundation method. From Fig. 12, η_v and η_m represent the displacement caused by shear force V and moment M respectively. Meanwhile, φ_v and φ_m represent the rotation caused by shear force and moment respectively. These displacements and rotations are influenced by the flexibility coefficient in concrete, timber, and plank wood (between timber and concrete), see Eq. (5) for the example of flexibility coefficients in displacement η_{11}. Meanwhile, stiffness coefficients for concrete α_c and timber α_t are presented in Eq. (6).

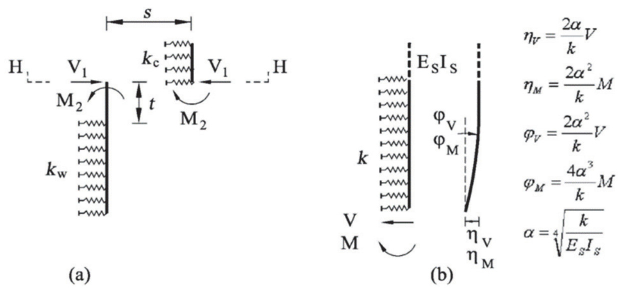

Figure 12 Scheme for stud stiffness calculus [10]. Image reprinted from the Journal of Structural Engineering, Gelfi, P., Giuriani, E., & Marini, A., Stud Shear Connection Design for Composite Concrete Slab and Wood Beams, 128 (12), Copyright (2012), with permission from ASCE

$$\eta_{11}V_1 + \eta_{12}M_2 + \eta_{10} = 0 \tag{3}$$

$$\varphi_{21}V_1 + \varphi_{22}M_2 + \varphi_{20} = 0 \tag{4}$$

$$\eta_{11} = \frac{2\alpha_c}{K_c} + \frac{2\alpha_t}{K_t} + \frac{4\alpha_t^2}{K_t} + \frac{4\alpha_t^2}{K_t}t^2 + \frac{t^3}{3E_sI_s} \tag{5}$$

Where K_c = concrete stiffness, K_t = timber stiffness, E_s = stud modulus of elasticity, I_s = stud moment inertia and t = plank wood thickness.

$$\alpha_c = \sqrt[4]{\frac{k_c}{4E_sI_s}};\ \alpha_t = \sqrt[4]{\frac{k_t}{4E_sI_s}} \tag{6}$$

By solving the compatibility equations, the stud connection stiffness can be written as in Eq. (7). This stiffness is applicable only for the screw of 90°.

$$K_s = \frac{V_1}{s} = = \frac{12(\alpha_c\alpha_t)^3 E_sI_s}{3(\alpha_c^2+\alpha_t^2)(\alpha_c+\alpha_t)3t\alpha_c\alpha_t(\alpha_c+\alpha_t)^2+3(t\alpha_c\alpha_t)^2(\alpha_c+\alpha_t)(t\alpha_c\alpha_t)^3} \tag{7}$$

4.2.2 Slip Modulus [45]

Symons et al. [45] proposed a slip modulus model for TCC structures by assuming the inclined screws embedded in timber behave perfectly as plastic but ignored the part embedded in concrete. They also considered two limiting cases: a short screw where axial deformation can be neglected, and a very long screw where axial deformation is significant but bending of the screw may be neglected. Then, these cases are then merged into a general model for screws of any length. In validation of the model of stiffness, they used a set of data from their experimental works of shear tests and showed good agreement. But, on average, the model overestimates by 20% from the experimental result. The fundamental of this model is the use of the Winkler foundation modulus to model the deformation of the inclined screw-in TCC. The stiffness from this model was only based on the formation screw in tension and is shown in Eq. (8).

$$K_s = \frac{k_p\cos\theta}{1+\beta_k\tan^3\theta}\left[\lambda\frac{\left(\dfrac{\sin h2L_t}{\lambda+\sin\dfrac{2L_t}{\lambda}}\right)}{\cos h\dfrac{2L_t}{\lambda}+\cos\dfrac{2L_t}{\lambda}+2}+L_t\beta_k\tan^3\theta\right] \tag{8}$$

where, $\lambda = \sqrt{\dfrac{4E_sI_s}{k_p\cos^3\theta + k_t\sin^3\theta}}$, L_t = screw length embedded within the timber, E_s = Young's modulus of the screw, I_s = moment inertia of screw, k_p = foundation moduli of timber parallel, k_t = foundation moduli of timber transverse and $\beta = k_t/k_p$.

4.2.3 Slip Modulus [21]

The slip modulus model was also introduced by Moshiri et al. [21] where the X-formation is the basis of the formulation. The stiffness model can predict the stiffness of the screw connections with the angle of ±30°, ±45°, ±60°. But it could not predict any stiffness with the screw angle of 90°. Eq. (9) shows the stiffness model derived by Moshiri et al. [21].

$$K_s = \frac{F_v}{\delta} =$$
$$= \frac{E_s A_s}{\sqrt{\frac{\left(1+\beta_k \tan^3(90-\theta) E_s A_s \cos(90-\theta)\right)}{k_p \beta_k \tan(90-\theta)}}} \tan h \cdot \qquad (9)$$
$$\cdot \frac{L_t}{\sqrt{\frac{\left(1+\beta_k \tan^3(90-\theta) E_s A_s \cos(90-\theta)\right)}{k_p \beta_k \tan(90-\theta)}}}$$

where F_v = shear force capacity, δ = slip, L_t = screw length embedded within the timber, E_s = Young's modulus of the screw, A_s =area of screw, k_p= foundation moduli of timber parallel, k_t =foundation moduli of timber transverse, and and $\beta_k = k_t/k_p$.

4.2.4 Slip Modulus [53]

In 2020, Du et al. [53] proposed the stiffness model of the inclined screw connection in timber-concrete structures. The model was developed by ignoring any significant effect of concrete on the connection and the concrete remained undamaged. The screw connector within the timber and concrete was regarded as a semi-infinite beam method which was similar to the theory used by Gelfi et al. (2002), but, at this time Du et al. (2020) included the inclination angle to the stiffness model. The model was developed based on the elastic foundation modulus to obtain the flexibility coefficients. In the end, the model was proposed as in Eq. (10).

$$K_s = \gamma_{t-c}\left(\frac{\varphi_{22}\sin^2\theta}{\eta_{11}\varphi_{22}-\eta_{12}^2}+\frac{\cos^2\theta}{\lambda}\right) \qquad (10)$$

4.2.5 Slip Modulus [54]

Mirdad and Chui (2020) proposed the stiffness prediction of the mass timber panel-concrete composite connection with inclined screws and a gap. In their stiffness prediction model, all the assumptions and the early hypotheses were focused on the local characteristic of the screws embedded within the timber. The models were proposed without any significant effect on the local behaviour of the screw embedded within the concrete by assuming that the screw inside the concrete is rigid with no deformation. It was also found that the models can predict the stiffness within 18% of the experimental value.

4.3 Strength Model in TCC Structure

Connection strength is also an important parameter to be considered in the design of TCC structures. Strength means the longitudinal shear force capacity of the connection in the TCC structure. In EC5 part 1-1, the strength of the connection is based on Johansen's (1949) theory. But the strength model is restricted for the screw-driven vertically. The equations to predict the strength of the connection by using EC5 are listed below. In order to upgrade the strength model, Symons et al. [45] and Moshiri et al. [21] proposed the predictive strength model for the screw that is driven in different inclination angles. The list of fastener strength models in EC5 (guideline for timber-timber connection) can be found in clause 8.2.2.

4.3.1 Strength model [46]

The predictive strength model proposed by Symons et al. [46] was derived based on Johansen's [13] theory. The innovation in the model was to take into account the inclination angle of the screw within the timber. The model is published only for the screw that is assembled in shear-tension formation (see Fig. 13) and assumed that the concrete remains undamaged.

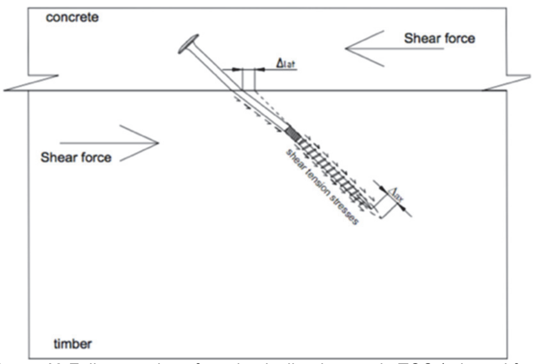

Figure 13 Failure modes of tension inclined screw in TCC (adopted from Symons et al.[46])

Fig. 13 shows the longitudinal shear force that causes the screw to deform in lateral Δ_{lat} and axial Δ_{ax} in timber. Derivation of the model is based on kinematic plastic collapse and an upper bound on the plastic collapse obtained from the calculation of work. Four failure modes considered in the model are the screw pulling from timber (Mode 1), lateral displacement of the screw (Mode 2), a single plastic hinge in the screw (Mode 3), and double plastic hinges in the screw (Mode 4). Eq. (11) to Eq. (14) show the strength model for all failure mode types.

Mode 1:

$$F_v = \frac{f_{ax,t,\theta}}{\sin\theta} \qquad (11)$$

Mode 2:

$$F_v = f_{h,t,0°} d L_t \cos\theta \qquad (12)$$

Mode 3:

$$F_v = f_{h,t,\theta}\cos\theta\left(2\sqrt{\frac{M_y}{f_{h,t,\theta}}+\frac{L_t^2}{2}}-L_t\right)+f_{ax,t,\theta}\sin\theta \qquad (13)$$

Mode 4:

$$F_v = \cos\theta\sqrt{4M_y f_{h,t,\theta} d} + f_{ax,t,\theta}\sin\theta \tag{14}$$

where $f_{ax,t,\theta}$ = axial withdrawal load within the timber, θ = inclination angle of the screw, $f_{h,t,\theta}$ = embedment strength of timber, d = diameter of the screw, L_t = embedded length of the screw within the timber, and M_y = yield moment of screw.

4.3.2 Strength Model [20]

Research by Moshiri et al. [20] also introduced a predictive model for screw connections in crossed or *X*-formation which means the screws resist the shear tension and shear compression stresses. Fig. 14 shows the axial and lateral deformation in timber caused by the longitudinal shear force while the concrete remains undamaged. Extended from Symons et al. [46], Moshiri et al. [21] added another failure mode in deriving the strength model. The combination of timber bearing failure and withdrawal of screw was considered in the model and is shown in Eq. (15). Despite the formation of the screw being in *X*-formation, the models were derived based on the shear-tension screw failure.

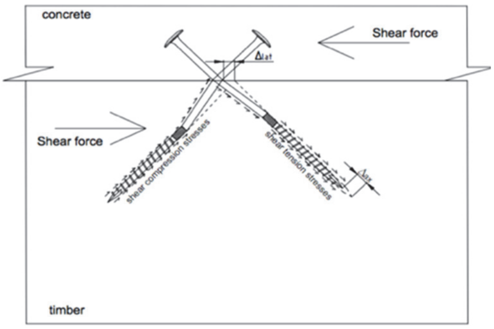

Figure 14 Failure modes of tension and compression inclined screw in TCC (adopted from Moshiri et al. [20])

$$F_v = f_{h,t,\theta} dL_t \cos\theta + \frac{\pi dL_t f_{ax,t,\theta}}{\sin\theta} \tag{15}$$

4.3.3 Strength Model [10]

All the existing published predictive models of strength and slip modulus to date ignore any significant effect of concrete on the behaviour of screw connections with the exception of Gelfi et al. [10]. This is at odds with the observations made by Sebastian et al. [36] showing there is a significant effect on the behaviour of screws within the concrete. Sebastian et al. [36] stated that the rcrew exhibited plastic hinges near the interface between timber and concrete.

Meanwhile, Gelfi et al. [10] stated theoretically that the length of screws embedded vertically within the concrete and timber affects the load-bearing capacity of the screw. The load-bearing capacity of the screw is the resultant of the concrete bearing stress $f_{h,c}$ acting on the effective length l_c or the resultant of the timber bearing stress $f_{h,t}$ acting on the effective length l_t, as shown in Fig. 15a and Fig. 15b. It can also be seen in Fig. 15a and Fig. 15b where the additional length within the timber and concrete need to be added to balance the resultant of bearing stress acting on the timber and concrete when the double plastic hinges are considered (see, Fig. 15c and Eq. (16)). In the design of strength of screw connections, Gelfi et al. [10] considered the additional effective length in the model of the vertical screw. The equations related to the design model derived by Gelfi et al. [10] are listed from Eq. (17) to Eq. (20). The limitation found from Gelfi et al. [10] was that the screw angle was only applicable for 90°. This also means that the formation of the screw was only for parallel orientation.

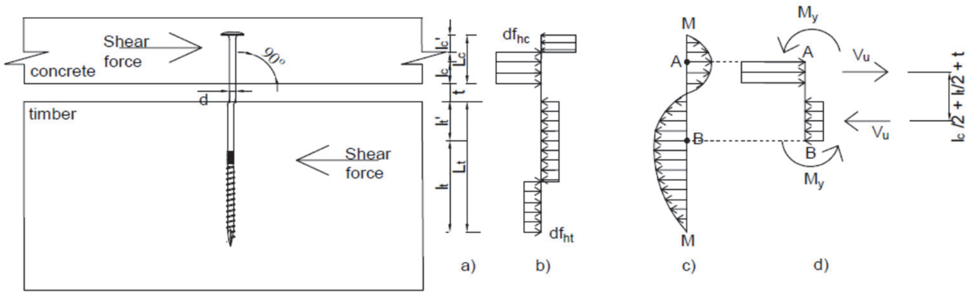

Figure 15 Collapse mechanism and model for stud resistance calculation a) Dimension b) Timber and concrete bearing stress along the screw c) Bending moment along the screw d) Shear force capacity and moment, redrawn based on Gelfi et al. [10].

$$V_u\left(\frac{l_c}{2} + \frac{l_t}{2} + t\right) - 2M_y = 0 \tag{16}$$

$$M_y = \frac{f_{y,s} d^3}{6} \tag{17}$$

$$l_t = \frac{d}{1 + f_{h,t}/f_{h,c}}\left(\sqrt{\frac{2M_y}{f_{h,t} d} + \frac{\beta}{1+\beta}\frac{t^2}{2}} - \frac{\beta}{1+\beta}t\right) \tag{18}$$

$$\beta = \frac{f_{h,c}}{f_{h,t}} \tag{19}$$

$$V_u = F_v = f_{h,t} l_t d \tag{20}$$

where t and $f_{y,s}$ is the interlayer thickness and yield stress of stud, respectively. From Gelfi et al. [10], the effective length l_c is also known as the location of the plastic hinge on the fastener from the interface of the concrete.

4.3.4 Strength Model [54]

Mirdad et al. (2020) developed analytical models of the shear strength of the screw connections within the mass timber panel (MTP) to concrete. MTP is another new engineered timber recently developed in the USA. Mirdad et al. (2020) used the basis of Johansen's theory in their models to come out with the model that is capable to predict the strength of the inclined screw connection in the MTP to concrete structures. In the test, the developed models predicted within 10% of connection strengths for solid timber and 12% for layered timber. The failure modes were also accurately predicted by the models except the cracking of the concrete, which was not an input parameter in the models.

5 NUMERICAL ANALYSIS OF TCC STRUCTURES

There are numbers of researchers who used the numerical analysis to investigate the behaviour of the TCC structures. Cvetkovic et al. [56] investigated the behaviour of the timber-concrete coupling technique that was used in strengthening the historical building named the Diocese in Pancevo. In the numerical analysis, Cvetkovic et al. [56] utilized Abacus software to apply the design theory of composite which was adopted from EC5 to get the proper stress-strain analysis between timber and concrete. The connection system in TCC structures is the important part to be modelled in finite element software. In modelling of the connection system between timber and concrete, they used 'embedded element'. From the numerical analysis, it was found that the results of, theoretically, stress deformation parameters from EC5 to the numerical are almost identical to each other.

Khorsandnia et al. [57] examined the failure mode of the TCC beams by using the numerical approach by using Abacus to see insight of the failure structures in details. They used nonlinear discrete springs to model the partial interaction between RC slab and timber beam. The load-displacement relationships which represent the connectors are derived from the available push-out test results undertaken on the connections then assigned to the spring model. Comparison between numerical model to the available experimental results shows that the developed numerical model and adopted constitutive laws for timber and concrete can obtain the ultimate load and deflection of TCC beams up to failure with sufficient accuracy.

Pulasand Szumigala [58] studied the behaviour of the connection for timber-concrete composite structures by using the numerical approach. The proposed TCC system, the concrete slab was attached to the timber girder beams with the mechanical fasteners. Non-linear 3D finite element models of the tested joints were validated with the experimental results. In modelling, a zero-length spring and the load-slip model from the laboratory tests was used to model the connection between timber and concrete. The comparison showed that the adopted 3D finite element model can capture the response of the TCC joints sufficiently.

6 CONCLUSIONS

The topics discussed in this paper are the history of TCC systems since 1990, the development of engineered timber, the use of TCC systems in buildings and bridges, the effects of type of connectors on composite actions and discussions about parameters that affect the design of TCC. The history of TCC systems in the structure from 1990 showed that this type of system is very useful to retrofit old buildings and as the solution for buildings in salty environments such as those nearby the sea. With the increasing number of the use of timber as structural materials, the development of engineered timber has attracted industries to produce high quality engineered timber such as Glulam, CLT and LVL. The use of these types of engineered timber in TCC systems can reduce the size and weight of the structure.

There are many types of connectors that can be used in TCC systems. Normally, the glued joint and mechanical fasteners are chosen by researchers as their research interests. From the discussion in this paper on the types of connectors, the glued joint which acts as full composite has very high stiffness and extremely small slip. Mechanical fasteners like a screw have high stiffness and small slip acting as partial composite.

Design of TCC considers the EC5 as the main guideline. The two main parameters that are vital in the design are slip modulus and strength of the connection. Some researchers have attempted to predict the slip modulus and strength of connection such as Gefli et al. [10], Symons et al. [45] and [46], and Moshiri et al. [20] and [21]. However, Gelfi et al. [10] is the only work that considers the behaviour of screw within the concrete in its slip modulus model and strength. This model is able to predict both parameters for the screw-driven vertically. Du et al. (2020) developed a stiffness model for the inclined screw connections in TCC structures which is an extended work from Gelfi et al. (2002). But the model did not include the significant effect of concrete on the screw connections as what Gelfi et al. [10] considered. Mirdadet al. (2020) proposed the strength model by considering the Johansen theory for the MTP to concrete structures. The model was able to predict the strength of the connection with only 12% difference to the actual experimental results. Sebastian et al [36] stated that the screw behaved quite significant in the concrete in the TCC structure. Gelfi et al. [10] stated that the length of the screw embedded within the concrete had a significant effect on the load-bearing capacity of the screw connections and the effective length which is the length of the hinge to the interface between the timber and concrete. However, the effective length proposed by Gelfi et al. [10] was developed for determining the shear force capacity only for connections with 90° angle screw.

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