State of the Art on Timber-Concrete Composite Structures: Literature Review

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Abstract: This paper presents a survey on the state-of-the-art of timber-concrete composite research in the past and recent years. The most important literature references were carefully selected and reviewed to provide an overview and some depth in the development of this construction technique. After highlighting the advantages of the composite system, the standards and design methods currently available are presented. An extensive description of the connection systems developed around the world is also provided. The experimental and numerical investigations performed on connections and beams in both the short- and long-term (at collapse and under sustained load, respectively) are discussed at length in the paper. Other aspects covered are prefabrication, the influence of concrete properties, fatigue tests, fire resistance, vibrations, and acoustics. **DOI: 10.1061/(ASCE)ST.1943-541X.0000353.** *© 2011 American Society of Civil Engineers.*

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Introduction

The timber-concrete composite (TCC) structure is a construction technique in which a timber beam or deck is connected to an upper concrete flange using different types of connectors. The best properties of both materials can be exploited because bending and tensile forces induced by gravity loads are resisted primarily by the timber and compression by the concrete topping. Medium- to long-span (7–15 m) floor systems can be constructed as a result of an effective composite action between the two materials provided through the interlayer connection.

The objective of this paper is to provide an up-to-date literature review of TCC that covers the different aspects related to the interlayer connection, the influence of concrete properties, short- and long-term behavior, design approaches, and numerical modeling. The paper also gives a general insight into the history and recent developments of TCC systems.

For this construction technique to be efficient, three fundamental design criteria must be satisfied: (1) the neutral axis of the composite cross section should be located near the timber-concrete interface to ensure both components act efficiently with concrete purely compressed (and therefore uncracked) and the timber mostly subjected to tensile stresses; (2) the connection system must be strong and stiff enough to transfer the design shear force and provide an effective composite action; and (3) the timber part (joist/beam or solid deck made from individual planks nailed together on the edge) must be strong enough to resist bending tensile stresses induced by gravity loads applied on the composite beam. Awareness of and familiarity with the behavior and design methods of TCC are important for this type of construction to permeate into the building industry.

After World Wars I and II, there was a shortage of steel for reinforcement in concrete. This initiated the development of TCC systems in Europe. A system of nails and steel braces to form the connection between concrete slab and timber beams was patented by Muller (1922). Subsequently, in 1939, a patent of steel Z-profiles and I-profiles as the interlayer connection system was filed in Switzerland (Schaub 1939). TCC application was primarily a refurbishment technique for old historical buildings in European cities, such as Leipzig in Germany (Holschemacher et al. 2002). The floors designed at earlier times did not comply with current regulations and failed to meet the requirements of building physics with regards to sound insulation and fire resistance.

In the last 50 years, interest in TCC systems has increased, resulting in the construction of bridges (United States, New Zealand, Australia, Switzerland, Austria, and Scandinavian countries), upgrading of existing timber floors (Europe), and the construction of new buildings (Natterer et al. 1996). One prime example is the Vihantasalmi bridge built in 1999 in Finland, which spans 168 meters with an 11-m-wide roadway and 3-m sidewalk (Finnish Road Administration 1999). Since the early 1990s, TCC construction has found important structural applications throughout several European countries, including Italy (Turrini and Piazza 1983a, b). The applications include refurbishment of existing timber floors, floors for new buildings, and deck systems for timber bridges (Natterer et al. 1996; Mettern 2003). Examples of composite bridges can also be found in the United States after composite design and construction were introduced into the American Association of State Highway Officials specifications in 1944 (Cook 1976); in New Zealand, where the first experimental bridge was built in 1957 for the New Zealand Forest Service across Mangahareke Stream near the northern boundary of Kaingaroa Forest (Cone 1963); and in Australia, where the first major

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composite system was built on a highway bridge in the 1950s on the Pacific Highway in New South Wales over the Maria River (Benitez 2000).

Advantages of the Composite System

Traditional light timber frame floors may suffer from excessive deflection, susceptibility to vibrations, insufficient acoustic separation, and low fire resistance. These problems can be resolved by using TCC floors. TCC construction is still developing at this stage; however, it is sufficiently advanced to be applied in different ways (Natterer et al. 1996). There are many advantages of TCC over timber-only or reinforced concrete floors. For new buildings, by connecting an upper concrete slab to timber joists and beams it is possible to (1) significantly increase the stiffness compared to timber-only floors; (2) considerably improve the acoustic separation; and (3) increase the thermal mass, important to reduce the energy consumption needed to heat and cool the building. On the other hand, by replacing the lower part of a reinforced concrete section, which is ineffective because of the cracking induced by tensile stresses, with timber joists or a solid timber deck, it is possible to achieve the following advantages: (1) rapid erection of the timber part, particularly if prefabricated off-site, due to its lower weight, with a function of permanent formwork for the concrete topping; (2) reduced load imposed on the foundation; (3) reduced mass and, hence, reduced seismic action; (4) the possibility of using the timber as a decorative ceiling lining; (5) low embodied energy; and (6) reduced CO_2 emissions because timber is carbon-neutral. For refurbishment of old buildings, the following advantages can be obtained by connecting a concrete topping of approximately 50 mm to the existing timber floor: (1) increased stiffness and load-bearing capacity; (2) preservation of historical buildings for future generations; and (3) better seismic performance because of the improved diaphragm action. TCC floors are significantly lighter and more economical when compared to their counterparts, reinforced concrete and steel-concrete composite floors, which are characterized by a nonregenerative manufacturing process with high energy demands and high emissions of carbon dioxide.

Standards and Design Methods

The design of TCC is not addressed by most of the timber standards around the world except the Eurocode 5, Part 2, on timber bridges (CEN 2004a). Because the interlayer shear connection is not usually fully rigid, the assumption of plane sections remaining plane does not apply to the composite section as a whole due to a relative slip between the bottom fiber of the concrete and the upper fiber of the timber. Hence, the method of the transformed section from conventional principles of structural analysis cannot be used in design.

The design of TCC must account for two main phenomena: (1) the partial composite action resulting from the flexibility of the shear connection, and (2) the time-dependent properties of the component materials.

To account for the first phenomenon, two approaches have been proposed: the linear-elastic method (Möhler 1956; CEN 2004a; Ceccotti 2002) and the elastoplastic method (Frangi and Fontana 2003). The linear-elastic method is based on the assumption that all materials (concrete, timber, and connection) remain within the linear-elastic range until the timber beam fails. This is appropriate in many cases of technical interest, particularly for TCC with very strong and stiff connectors such as notches cut in the timber and filled with concrete. The corresponding approximate solution derived by Möhler (1956) for timber-timber composite beams with flexible connection and proposed in the Annex B of the Eurocode 5 (CEN 2004a) was recommended by Ceccotti (2002) for linear-elastic analysis of TCC. This approach, known as the gamma method, makes use of an effective bending stiffness, $(EI)_{ef}$, to account for the semirigidity of the timber-concrete shear connection. For simplification, an effective spacing of the shear connection is assumed such that they are smeared equally along the span instead of the actual case in which the shear connections are positioned closer near the supports and spaced further toward the midspan. A reduction factor γ that ranges from 0 for no composite action between the timber and concrete interlayers to 1 for fully composite action is used to evaluate the effective bending stiffness:

$$(EI)_{ef} = E_1 I_1 + E_2 I_2 + \gamma_1 E_1 A_1 a_1^2 + \gamma_2 E_2 A_2 a_2^2 \tag{1}$$

where subscripts 1 and 2 refer to concrete and timber elements, respectively; E = Young's modulus of material; A and I = area and the second moment of area of the cross section; a = distance from the centroid of the element to the neutral axis of the composite section; and γ = shear connection reduction factor. Using the effective bending stiffness, the maximum stresses in bending, tension, and compression for both the timber and concrete elements can then be calculated. Ceccotti et al. (2002) provided a detailed description of the design of TCC at ultimate and serviceability limit state, with emphasis on the influence of creep in the long-term, including two worked examples. Span tables for semiprefabricated TCC systems together with a detailed worked example can be found in Yeoh (2010).

The elastoplastic solution (Frangi and Fontana 2003) has been proposed specifically for cases in which the failure of the TCC is attained after connector plasticization. This is fairly common when the connectors are low strength, low stiffness, and high ductility, such as for mechanical fasteners. The failure load is evaluated by assuming a rigid-perfectly plastic connection. Frangi and Fontana (2003) claimed that this method provides an accurate prediction of the failure load. However, the linear-elastic solution (gamma method) is widely used for TCC design.

Different approaches were proposed to account for the time-dependent phenomena of timber, concrete, and connection, i.e., creep, mechano-sorption, drying shrinkage, and thermal and hygroscopic strains. Ceccotti (2002) suggested the use of the effective modulus method to account for the creep deformation of the different materials. In this method, the elastic and slip moduli in Eq. (1) are replaced by effective moduli. They are calculated by dividing the elastic and slip moduli of concrete, timber, and connection by one plus the pure creep coefficient of the material at the end of the service life, defined as the ratio between the delayed and the elastic strain in a test under sustained, constant load. This approach neglects the effect of environmental strains caused by the different thermal expansion and shrinkage of concrete and timber on the internal forces and the deflection of TCC, resulting in an underestimation of the deflection at the end of service life.

To resolve this issue, Fragiacomo (2006) derived rigorous closed-form solutions to account for the effects of environmental strains and drying shrinkage of concrete on TCC. In an attempt to further simplify the design procedure, Schänzlin (2003) proposed formulas to transform environmental strains and drying shrinkage of concrete into an equivalent uniformly distributed load to combine with the gravity loads. In addition, the use of the extended effective modulus method was recommended to account for the different creep rates of timber, concrete, and connection, which lead to interactions among them (Schänzlin 2003; Schänzlin and Fragiacomo 2007). In this case, the elastic or slip moduli of the materials are divided by one plus the effective creep coefficients, which are obtained for timber, concrete, and connection by multiplying their pure creep coefficients with a ψ coefficient provided in tables (Schänzlin 2003).

Connection Systems

The connectors in a TCC are usually positioned along the beam according to the shear force distribution so that they are concentrated near the supports where the internal shear force is higher and spaced out gradually into the span as the shear force reduces to zero in the middle for a simply supported beam subjected to a uniformly distributed load. The structural efficiency of a TCC highly depends on the stiffness of the interlayer connection. A connection system that results in high composite action allows a significant reduction of the beam depth and longer span length when compared with a noncomposite system. A generalized form of efficiency for composite beams and slabs can be estimated by the quantity E, expressed in percentage, given by (Gutkowski et al. 2010)

$$E = \frac{\Delta_{NC} - \Delta_{PC}}{\Delta_{NC} - \Delta_{FC}} \cdot 100 \tag{2}$$

where Δ = midspan deflection; and the subscripts NC, PC, and FC refer to no, partial, and fully rigid connection, respectively. Ceccotti (1995) presented a large number of fasteners that can be used to connect the concrete slab to the timber. He sorted the connectors in relation to their stiffness or slip modulus: nails, screws, and dowels are the most flexible, whereas notches cut in the timber and continuous connectors glued to the timber are the most rigid. Fig. 1 provides a comparison of the shear force-slip relationship for different categories of connection systems. To characterize a connection system, the strength and stiffness are obtained by means of push-out tests, which provide the load-slip response of a connection under shear load, carried out in accordance to EN26891 (CEN 1991). The strength is quantified as the maximum load applied when failure occurs in the push-out specimen, and stiffness is quantified by the slip modulus at three different load levels (40, 60, and 80% of the mean maximum load) corresponding to the service, ultimate, and near-collapse load levels.

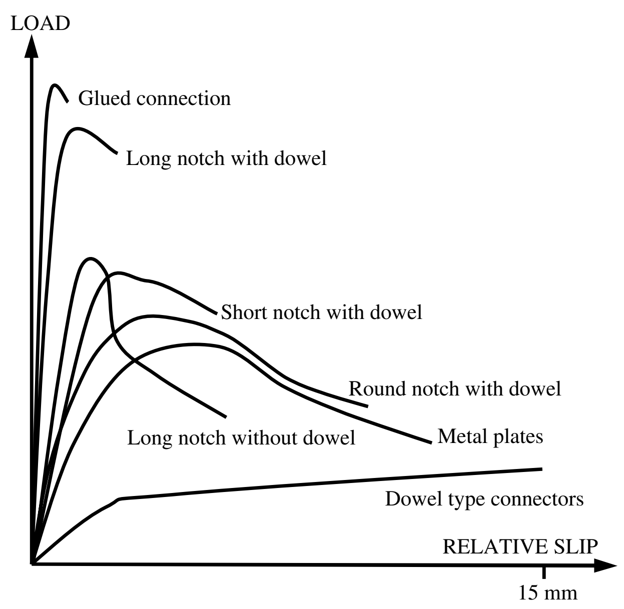

Fig. 1. Comparisons of different categories of connection systems

A wide range of connection systems have been developed in different parts of the world and throughout the century. The connectors can be metal or timber fasteners, or notches cut in the timber and filled by concrete. Based on their arrangement along the beam, the connectors can be categorized as discrete/continuous and vertical/inclined. They can also be categorized as glued/nonglued and prestressed/nonprestressed based on the way they are inserted in the timber. Research on connection systems traces back to the 1940s (McCullough 1943; Richart and Williams 1943) and 1970s (Pincus 1970; Pillai and Ramakrishnan 1977). Notches cut in the timber beam and reinforced with a steel screw or dowel, as illustrated in Figs. 2(a) and 2(b), is by far the best connection for TCC with respect to strength and stiffness performance, although it may not be altogether economical if the notches must be cut manually (Kuhlmann and Schänzlin 2001; Van der Linden 1999; Deam et al. 2007). The length of the notch, the presence of a lag screw, and its depth of penetration into the timber were found to be the most important factors affecting the performance of the connection. It was found that the notch length affects the strength and stiffness of the connection, and the lag screw provides ductility and improves the postpeak behavior (Yeoh et al. 2009b, 2011). Notched connections reinforced with dowels or metal anchors that allow tightening after the concrete curing [Fig. 2(c)] have the advantage of reducing the gap between the concrete and timber caused by the concrete shrinkage within the notch (Gutkowski et al. 2004).

Alternatively, mechanical connectors such as nailplates [Fig. 2(d)] that do not require any cutting in the timber can be used (Aicher et al. 2003). They were found to be efficient in strength and stiffness, although significantly less efficient than a notched connection. An important difference between mechanical and notched connections is that in the first case the slip modulus largely depends on the flexibility of the fastener and the timber in contact with the fasteners; in the second case, conversely, the slip modulus mostly depends on the stiffness of the wood in the inclined surface of the notch and also on the stiffness of the concrete inside the notch (Balogh and Gutkowski 2008; Kuhlmann and Michelfelder 2006). The posttensioning of the dowel [Fig. 2(f)] increases the strength and stiffness of the connection (Capozucca 1998); however, the relaxation because of the creep of the timber perpendicular to the grain is expected to significantly reduce this benefit over time. The mechanical properties of the connection can be further improved by inclining the dowels to 45° [Fig. 2(h)] to subject them primarily to axial force instead of shear, as shown by Pillai and Ramakrishnan (1977), Meierhofer (1993), Steinberg et al. (2003), and Grantham et al. (2004).

The use of glue and epoxy resin in the connection system is not entirely encouraged because of the stringent quality control and complexity of on-site application. However, there has been some research interest over the last few years by Clouston et al. (2005) in Fig. 2(e), Brunner et al. (2007), Miotto and Dias (2008), and Kuhlmann and Aldi (2008) in Fig. 2(i).

With the aim of developing a fully demountable composite system in which the concrete slab is prefabricated off-site, Lukaszewska et al. (2008) chose seven types of connectors to build 28 asymmetrical shear specimens. Among these connectors, three were investigated for the first time: (1) a steel tube with a welded flange embedded in the concrete slab with a hexagon-head lag screw; (2) a modified steel tube with two welded flanges and a hexagon-head lag screw in conjunction with a notch cut in the timber beam; and (3) a mechanical connector consisting of a pair of folded steel plates embedded into the concrete slab and connected to the glulam beam by means of annular ringed shank nails. Because of their simplicity and inexpensiveness, the first and third

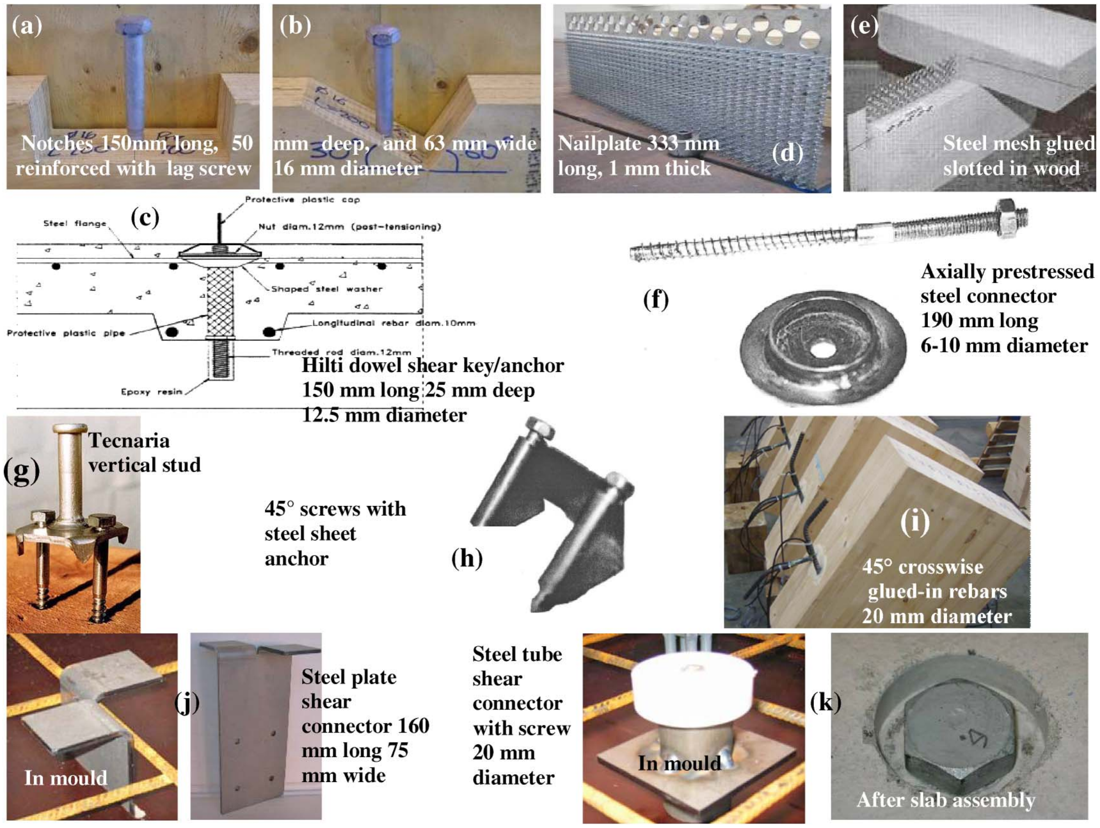

Fig. 2. Different connection systems: (a), (b), and (d) reprinted from Yeoh (2010); (c) reprinted from Gutkowski et al. (2004, ASCE); (e) reprinted from Clouston et al. (2005, ASCE); (f) Fig. 4: Axial prestressed steel connector, reprinted from Capozucca (1998) with permission from RILEM; (g) Fig. 1: "Tecnaria" connector, reprinted from Fragiacomo et al. (2007a) with permission from RILEM; (h) reprinted from Steinberg et al. (2003, ASCE); (i) reprinted from Kuhlmann and Aldi (2008) with permission from author; (j) and (k) Fig. 9: Steel plate shear connector SP+N and Fig. 7: Steel tube shear connector SST+S, reprinted from Lukaszewska et al. (2008) with permission from RILEM

connector types were found to be the most suitable for prefabricated timber-concrete composite systems [Figs. 2(j) and 2(k)].

Influence of Concrete Properties

The influence of concrete properties on the performance of timber-concrete composite connections has been addressed in a number of investigations. In some push-out connection tests, Steinberg et al. (2003) used a lightweight concrete with a density of 1.6 kN/m^3 (instead of a normal concrete of 2.4 kN/m^3) to minimize the permanent load on the timber. They concluded that timber-lightweight concrete composite structures are affected by the modulus of elasticity of the lightweight concrete, which leads to a lower effective bending stiffness of the structure. Consequently, the connectors must be positioned at a closer spacing in lightweight concrete compared to normal-weight concrete. The design, therefore, depends on the compromise between the higher cost due to the use of lightweight concrete and the closer setting of the connectors, and the reduction in permanent load. Koh et al. (2008) tested 12 push-out specimens built from lightweight foamed concrete and Malaysian hardwood connected using different types of nails. The higher grade of lightweight concrete was recommended to fully exploit the efficiency of the connection.

The potential upgrade of timber frame buildings using timber-concrete composites has been investigated by Grantham et al. (2004). SFS (1999) inclined connectors and lightweight concrete made from recycled sewage sludge with a density of 1,760 kg/m^3 were used to reinforce an existing timber floor, which was subjected to a full-scale long-term and collapse test. The results highlighted on the one hand the larger sensitivity of lightweight concrete to rheological phenomena compared to normal-weight concrete, and on the other hand the favorable lower self-weight and high strength. On the contrary, in the tests performed by Fragiacomo et al. (2007a) on the head stud proprietary connector marketed as Tecnaria [Fig. 2(g)], half of the specimens were constructed using normal-weight concrete and, in the remaining half, the slabs were constructed from lightweight aggregate concrete. This variation was found to not significantly affect the performance of the connection system either in the long-term or in the short-term collapse tests because the failure took place in both cases in the timber.

To reduce the thickness of the concrete slab and consequently the self-weight, Holschemacher et al. (2002) used steel-fiber-reinforced concrete with wood screws as shear connectors. From a 60-mm-thick concrete slab using conventional reinforcement with minimum 20-mm cover, a 48-mm slab thickness was achievable with the application of steel-fiber-reinforced concrete. Push-out tests showed that the strength of the connection increased 1.3 times and initial stiffness 2.8 times as opposed to the use of normal reinforced concrete.

Shrinkage of concrete during the early days from the time of curing will result in a gap at the outer edge of the connection in the case of a notch cut in the timber. As the concrete shrinks, the notched connection pushes inward, causing an undesired initial permanent deflection of the composite beam, particularly in the case of a very stiff connection. To prevent this issue, the use of low-shrinkage concrete is recommended (Yeoh et al. 2008).

Tests to Failure of TCC Floor Beams

Quite a number of short-term collapse tests have been performed to date on TCC floor beams. Collapse tests are important to quantify the actual composite action of the system, the load-bearing capacity, and the failure mechanisms. There is in general a close relationship between the collapse load and the failure mechanism and the type of connection system. A push-out test of the connection should always precede a beam collapse test in order to obtain important information on the mechanical properties of the connection. A summary of the state-of-the-art concerning short-term collapse tests of TCC in recent years is presented in Table 1.

Long-Term Tests

The time-dependent behavior of TCC requires careful consideration to accurately predict the deflection in the long-term. Although

Table 1. Summary of the State-of-the-Art of Short-Term Collapse Test of TCC in Recent Years

Reference	Test description	Remarks
Grantham et al. 2004	Existing timber floor in a full-scale light frame multistory platform building converted to a TCC floor using SFS connectors.	1. Long-term test of 34 days under 2.5 kN/m^2 live load with deflection limit of span/333 met and structural collapse at 11.9 times the design imposed load.
Persaud and Symons 2005	7.3-m span glulam T-beam with 10 vertical lag screw connectors tested under three-point bending. Collapse load was 173 kN with 74.9-mm midspan deflection and 5.7-mm maximum end slip.	1. The composite system was more than three times stiffer and almost twice as strong as the one without composite action. 2. Gamma method was found to overestimate the experimental ultimate strength by 20%, and the elastoplastic method showed the closest estimate.
Clouston et al. 2005	Solid glulam deck-concrete system, 10 m long with three rows of continuous steel mesh along the span, each 1 m long, tested under four-point bending. Ultimate failure occurred at 291 kN with a maximum deflection of more than 80 mm.	1. Nearly fully composite action of the system was reported in the conclusion. 2. Using the gamma method, the failure load was estimated as 312 kN compared to 315 kN for fully composite action, which is just 1% less.
Ceccotti et al. 2006	Double 6 m span glulam T-beam with 18 corrugated rebars glued to each beam with epoxy resin. Beam was twice loaded and unloaded prior to four-point bending collapse test after a 5-year-long-term monitoring. Collapse load was $2P = 500$ kN with a 33.2 and 2.47 mm of maximum deflection and end slip, respectively.	1. Beam collapsed at 2.44 times the service design load due to tension failure in timber with a very stiff behavior. Composite efficiency of 87–93% was reported. 2. Experimental results were compared with analytical solutions using the gamma method with the connection secant slip moduli $K_{0.4}$, $K_{0.6}$, and $K_{0.8}$ corresponding to service, ultimate, and collapse level, respectively, obtained from push-out tests. Good approximation was reported.
Gutkowski et al. 2008	Multiple timber-concrete layered beams connected with notch shear/key anchor details, each with a clear span of 3.51 m, were tested to collapse under four-point bending.	1. The reported composite efficiency ranged from 54.9–77%. 2. Collapse occurred because of flexural failures of wood. 3. Poor construction of the notched connections due to concrete segregation resulted in low performance of the system.
Deam et al. 2008	Four 6 m long full-scale TCC beams with LVL joists and lag screw connection tested in four-point bending. Two specimens prestressed with unbounded draped tendons and straight tendons, respectively, and one specimen nonprestressed.	1. Stiffness of the nonprestressed composite beam was three times that of a bare LVL joist, but only 74% stronger. 2. The prestressing tendons were shown to have little effect on the stiffness and strength, but they reduce the deflection due to permanent load, particularly when they are draped.
Lukaszewska et al. 2010	Five 4.8 m span full-scale TCC floors of triple T-section glulam joists tested to failure in four-point bending. The concrete slab of specimens was prefabricated off-site with mounted connectors. Three specimens had lag screws surrounded by steel pipes embedded in the concrete, and two specimens had metal plates nailed to the glulam joists.	1. Composite action of only 60% and 30% achieved in the beams with lag screws and metal plates, respectively. 2. The use of a notched connection together with the steel pipe and lag screw is a possible way suggested by the authors to improve the connection efficiency.
Yeoh et al. 2009a; Yeoh 2010	11 LVL-concrete composite T-beams with 8 and 10 m span, 600 and 1,200 mm widths, and notched lag screw and toothed metal plate connections were tested to failure under four-point bending. Low shrinkage and normal concrete were used.	1. Six beams were well-designed and five beams were underdesigned for the targeted nonstructural permanent load of 1 kN/m^2 and imposed load of 3 kN/m^2. Composite action of 87.6–99.23% at SLS was achieved. 2. Well-designed and underdesigned beams collapsed at a range of 2.29–2.91 and 1.17–2.31 times the ultimate design load, respectively.

long-term tests are expensive and require a lot of preparation, they are needed to validate approximate design procedures and calibrate existing analytical and numerical models. Few long-term tests have been performed to date. Long-term tests on connections and floor beams are reviewed in the following subsections.

Connections

The evaluation of the connection creep coefficient, $\phi(t)$, is the main motivation for long-term creep connection tests:

$$\phi(t) = \frac{\Delta(t) - \Delta_{el}}{\Delta_{el}} \tag{3}$$

where $\Delta(t)$ = relative slip of the connection at time t; and the subscript el denotes the instantaneous elastic slip immediately after the application of load.

Döhrer and Rautenstrauch (2006) tested nine push-out specimens made from two concrete slabs and one interior timber member, three for each type of connector [notches cut in the timber, vertical stud connectors, and inclined (X) connectors]. A sustained load of approximately 30% of the ultimate load in the short-term test was applied by means of a spring load apparatus to simulate the quasi-permanent load condition at serviceability limit state [Fig. 3(a)]. All specimens were stored in outdoor, sheltered conditions (Service Class 2 according to Eurocode 5). The elastic slips in the tested connections increased from 10–24% after 120 days from the beginning of the test. Further long-term tests in both uncontrolled and controlled climatic conditions were performed on dowel-type fasteners and notched connections by Dias (2005). For all the connection types, the creep coefficients after 285 days in uncontrolled climatic condition were approximately twice the values measured in controlled climatic conditions.

Capozucca (1998) also used a spring apparatus to investigate the stress losses that might occur in the connector, both in the case of high humidity levels and when humidity and temperature conditions change. A single connector inserted in untreated wood was kept in tension by a contrast spring, showing a loss of stress estimated as approximately 6–10% of the initial load after 3 months. In another specimen with wood treated on the surface using protective resin, no significant difference on the stress loss because of humidity changes was found when compared with the untreated wood.

Bonamini et al. (1990) performed push-out tests in controlled, variable relative humidity conditions on mechanical connectors, recognizing the significant increase in creep coefficient because of variation of moisture content (mechano-sorption). Fragiacomo et al. (2007a) performed long-term tests on the head stud proprietary Tecnaria connector using a lever apparatus to apply a sustained load on 12 push-out specimens [Fig. 3(b)]. The 2-year test consisted of three phases: (1) creep tests in constant environmental conditions to measure the creep coefficient; (2) creep tests in variable environmental conditions to measure the increase in delayed slip due to the variation of relative humidity (mechano-sorption); and (3) unloading of the specimens to measure the creep recovery. It was found that the connection system is influenced by the hygroscopic behavior of wood at the interface between the timber and the connector. The creep coefficient at the end of service life (50 years) was estimated as 0.5 in constant relative humidity and 2 in variable humidity.

Long-term push-out tests on notched connections for timber-concrete composite deck systems were performed at the University of Stuttgart under an uncontrolled, sheltered condition (Kuhlmann and Michelfelder 2004). Creep coefficients of 0.44 and 0.53 for notches with hexagon-head and self-drilling timber screws, respectively, and 0.56 for notches without screws were measured after 8 months from the beginning of the test. Push-out long-term tests are also being performed at the University of Canterbury (UC), New Zealand (Yeoh 2010). A different test setup was adopted using a C-shape lever frame to apply 30% of the ultimate load in the short-term by using concrete weights [Fig. 3(c)]. Three types of connection (rectangular and triangular notches reinforced with a lag screw, and toothed metal plates) were loaded in indoor, unconditioned environment, with the relative slips recorded over time. The toothed metal plate connection crept the most under sustained load, and the rectangular notched connection reinforced with lag screw the least, with creep coefficients of 2.81 and 0.54 after 1 year, respectively. Long-term beam tests on these corresponding connections were also performed under the same environmental conditions and are discussed in the following section. These tests at UC are still ongoing.

In sum, it is imperative to note that connection creeps at least 2–4 times more in variable uncontrolled conditions as opposed to constant, controlled conditions (Dias 2005; Fragiacomo et al. 2007a).

Beams

Yeoh (2010) tested three TCC beams built from laminated veneer lumber (LVL). Two of the beam specimens had connections made from rectangular notches cut in the LVL and reinforced with a lag screw [see Figs. 2(a) and 2(b)]. Of these, one beam had normal-weight concrete and another beam had low-shrinkage concrete, with half the drying shrinkage of normal-weight concrete. The third beam had a connection of toothed metal plates pressed on the lateral surface of the LVL joist and low-shrinkage concrete. A 2.2 $\mathrm{kN/m^2}$ superimposed load representing the quasi-permanent part of the serviceability load condition was applied 36 days after concrete placement using sealed buckets of water. After 1 year, the midspan deflection of the beam with normal-weight concrete was approximately 20% larger than the two other beams with low-shrinkage concrete. Although these two beams had different connections, rectangular notches and toothed metal plate,

Fig. 3. Long-term push-out tests: (a) spring system (reprinted from Döhrer and Rautenstrauch 2006 with permission from author); (b) lever apparatus (Fig. 8: Picture of the Push-out Specimens in climate chamber during the long-term process, reprinted from Fragiacomo et al. 2007a with permission from RILEM); and (c) C-shape frame at University of Canterbury (reprinted from Yeoh 2010)

respectively, with the lowest (0.54) and highest (2.81) connection creep coefficient, they exhibited similar midspan deflection after 1 year. Such phenomenon implied that the connection creep coefficient had no significant effect on the deflection of the TCC beams. For example, although the metal plate connection resulted in a creep coefficient five times larger than the rectangular notch after 1 year, no similar increment was observed in the deflection of the corresponding beam.

Kenel and Meierhofer (1998) tested for 4 years a composite beam made of solid timber with SFS screw connectors in sheltered outdoor conditions (SFS 1999). Some results of a full-scale long-term test performed on a timber floor strengthened with SFS screws and lightweight aggregate concrete were reported by Grantham et al. (2004). Bou Said et al. (2004) monitored for 2 years a composite beam with glued-in mechanical connectors loaded in sheltered outdoor conditions. Fragiacomo et al. (2007b) tested eight floor/deck system beams with shear-key connection details in an uncontrolled indoor environment under sustained load applied at the thirds of the span for a period of 133 days. Ceccotti et al. (2006) performed a 5-year long-term test on a TCC beam with glued-in rebar connectors subjected to sustained load in unsheltered, outdoor conditions. The midspan deflection increased in the first two years of the test with fluctuation of all quantities (deflection, relative slip, strains, moisture content, temperature, and relative humidity) throughout the five-year period of monitoring. The experimental findings were compared to the existing analytical regulations found in Eurocode 5 for different service classes (CEN 2004b). Lukaszewska et al. ("Time-dependent behaviour of prefabricated timber-concrete composite floors. Part 1: Experimental testing," manuscript submitted to *Engineering Structures*, 2011) tested for 1 year two TCC beams subjected to sustained load evaluated as 13% of the failure load in the short-term collapse test. The beam specimens were located in an indoor, unconditioned environment and were made from glulam joists and prefabricated concrete slabs with mounted connectors (steel metal plates nailed to the glulam and lag screws connectors surrounded by metal pipes embedded in the concrete). The specimens increased the instantaneous deflection by approximately 50 and 80%, respectively, whereas the slip only increased very little.

An interesting issue is the relative contribution of creep in components (connection and materials) to the overall creep deflection of composite beam. This contribution is difficult to identify because the creep coefficient of the TCC is a system effect that depends not only on the creep coefficients of the component materials, but also on the stiffness ratios among the different parts of the composite section (timber, concrete, and connection system). In addition, it is also governed by the environmental fluctuations and conditions the composite beam is exposed to. For instance, Yeoh (2010) observed that the slip of connection and the beam deflections increased and fluctuated in response to extreme environmental conditions and environmental changes, respectively. Hence, the long-term deflection of TCC structures is most effectively minimized by reducing the initial deflection as much as possible through different methods. These can possibly include propping or precambering of the timber joist, use of low-shrinkage concrete (Yeoh 2010), or the introduction of some form of prefabrication, for example the use of precast concrete slabs allowed to shrink before connection to the timber joist (Lukaszewska et al. 2008).

Repeated Loading Tests

To extend the application of TCC to bridges, it is important to quantify any stiffness and strength degradation in the connection system after many loading cycles. Limited research has been performed to investigate the behavior of TCC subjected to repeated loading. Weaver et al. (2004) carried out 2 million fatigue load cycles on wood-concrete composite bridges and push-out specimens with dowel-type shear connectors. The effect on strength was insignificant, but stiffness decreased with rapid deflection increment in the tested bridge beam, indicating connection damage at the first few hundred thousand cycles. Döhrer and Rautenstrauch (2006) reported that there is no loss in ultimate strength and stiffness for notched and stud connectors after 2 million fatigue cycles. Balogh et al. (2008) conducted 21,600 loading cycles on a timber-concrete deck with shear key/anchor connection and found a 9% reduction in stiffness at the end of the repeated loading test. At the University of Stuttgart, push-out specimens with crosswise glued-in rebars and small-span TCC were subjected to fatigue tests to failure under different load amplitude cycles (Kuhlmann and Aldi 2008). Based on the outcomes of the tests, the *S-N* curves of the two tested connectors were drawn (Kuhlmann and Aldi 2009). Repeated loading tests up to 2 million cycles on push-out specimens with notched connection reinforced with lag screw and toothed metal plate connections are currently in progress at UC.

Finite-Element Modeling

In parallel with experimental tests, finite-element (FE) models were developed to reproduce the behavior of composite systems both in the short- and long-term. Fragiacomo et al. (2004) and Fragiacomo (2005) presented an accurate one-dimensional (1D) FE model for nonlinear analyses to failure and long-term analyses of TCC beams. The FE model is made from two parallel beam elements, the concrete slab and the timber joist, connected at their interface with a continuous spring system that models the connection system and accounts for its flexibility. This nonlinear mechanical model considers concrete as a viscoelastic material in compression and tension before cracking with allowance for thermal expansion, creep, and drying shrinkage in accordance with the CEB-FIP Model Code 90 [Comité Euro-International du Béton (CEB) 1993]. Tension-stiffening is considered through a softening law after concrete cracking. Timber is modeled as a hydroviscoelastic material in which creep, mechano-sorption, shrinkage/swelling due to temperature and relative humidity variation of the environment, and dependency of the Young's modulus on moisture content can be taken into account using the Toratti's rheological model (Toratti 1992). For connection, a nonlinear shear force-relative slip relationship can be implemented for the analyses to collapse. A hydroviscoelastic behavior based on the Toratti's rheological model was considered for long-term analyses. This FE model was validated against two long-term tests performed in outdoor, unsheltered conditions, providing good accuracy (Fragiacomo and Ceccotti 2006). Further validation of this model by Yeoh et al. (2008) against two TCC beams built and monitored indoor and outdoor respectively also found good agreement.

Another 1D numerical program was developed by Schänzlin (2003) based on the use of the finite-difference method, which rigorously accounts for the time-dependent phenomena using the Hanhijärvi (1995) rheological model for timber and connection and a viscoelastic model for concrete. Three-dimensional (3D) FE models for long-term analyses were implemented in the Abaqus software package by To (2008) and Chassagne et al. (2006), and Dias et al. (2007) and Aldi (2008) implemented a 3D FE model for short-term nonlinear analyses in Abaqus and Ansys, respectively. The actual connection detail is schematized using 3D brick-type elements rather than a global spring. Advantages over 1D models include the possibility to predict the actual stiffness and failure mechanisms of the connection and elimination of the need for many push-out tests to evaluate the spring properties (stiffness, strength, and creep coefficient) even though some push-out tests are still needed to calibrate the 3D model. An experimental-numerical comparison between Fragiacomo's 1D model, To's 3D model, and the outcomes of an experimental test performed in Colorado on a composite beam with notched connection revealed that similar accuracy can be achieved by both models, with the 1D model requiring far less computational time (To 2008).

Prefabrication

To reduce the construction cost and make TCC structures more competitive in the market, it is believed that a high degree of prefabrication should be achieved. Lukaszewska and Fragiacomo (2008) and Lukaszewska (2009) introduced a fully demountable TCC system. The off-site prefabrication of a concrete slab with shear connectors already inserted and the connection to the timber beams at the building site significantly reduce some drawbacks of the traditional system, such as the time needed for the concrete curing, the lower stiffness and higher creep during the concrete curing, the higher cost of a concrete slab cast in situ, and some possible problems of quality control.

In Germany, a fully prefabricated modular TCC panel (Fig. 4) has been proposed by Bathon et al. (2006). The panel connected with glued-in metal plates was reported as a cost effective system competitive with contemporary reinforced concrete and steel-concrete composite floors. The modular elements can be used in floors, walls, and roofs in both residential and commercial buildings. More information on the system can be found in TICOMTEC (2007). In Finland, two TCC prefabricated systems labeled SEPA-2000 are currently in production for multistory buildings, both using nailplates as shear connectors. The first system is used in floors cast in situ and the second is a prefabricated floor with the concrete cast upside down in a factory without formwork (Toratti and Kevarinmäki 2001, http://www.sepa.fi).

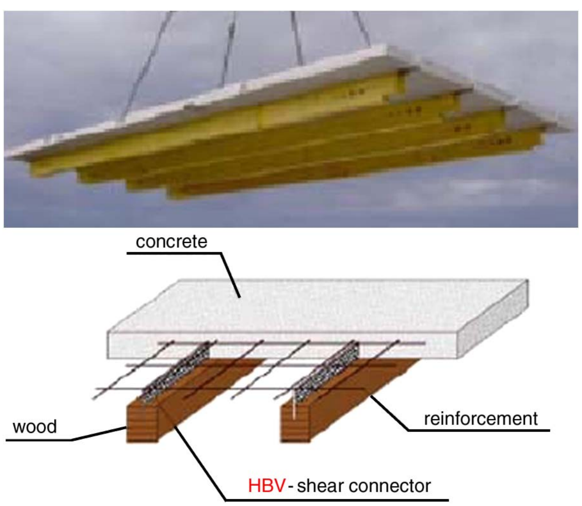

Fig. 4. Fully prefabricated TCC panels developed and used in Germany (reprinted from Bathon et al. 2006 with permission from author)

A semiprefabricated floor system (Fig. 5) was proposed at UC (Yeoh et al. 2008; Yeoh 2010). The system consists of M-section panels built with LVL joists and a plywood interlayer, prefabricated off-site and then transported to the building site, where the concrete can be poured. Despite the introduction of a wet component, advantages of this solution include (1) ease of transport and lifting of the low weight panels of approximately 1 kN/m; (2) construction of a monolithic concrete slab with better in-plane strength and stiffness and no need for additional connections between adjacent panels; (3) high strength and stiffness achievable with reduced number of connectors (6–8 connectors) because of the effectiveness of the notched connection detail; (4) medium- to long-span floors, in the range of 6–12 m; and, therefore, (5) a system capable of competing with traditional precast concrete solutions.

Fire, Acoustics, and Vibrations

Issues related to low fire resistance, insufficient acoustic separation, and susceptibility to vibrations of timber floors are significantly reduced in TCC. The fire performance of a TCC floor is competitive with that of common reinforced concrete floors. Natterer (2002) described engineered timber structures all across Europe from 1974 to 2001 and pointed out that apart from a significant reduction in self-weight, the fire resistance of TCC increased from 60 to 90 min when compared with a conventional reinforced concrete slab. In a TCC structure, the concrete layer acts as a protective cladding for timber, reducing the effect of temperature and delaying the start of charring. On the other hand, the char that develops from the wood of the beams provides insulation to protect the concrete and the connectors against high temperatures (Frangi et al. 2008). In any case, the fire resistance of TCC is significantly increased with respect to that of a timber-only joisted floor. Two full-scale 4-m-span TCC M-section floors of 300 and 400 mm deep LVL joist with notched and toothed metal plate connections subjected to 1.56 and 3.06 kN/m^2 gravity load, respectively, were tested under fire in accordance with the fire curve from ISO834 (ISO 2000) by O'Neill (2009). The first floor collapsed after 75 min, and the fire was stopped after 60 min for the second floor to measure the charring rate (O'Neill et al. 2010). Frangi and Fontana (2001)

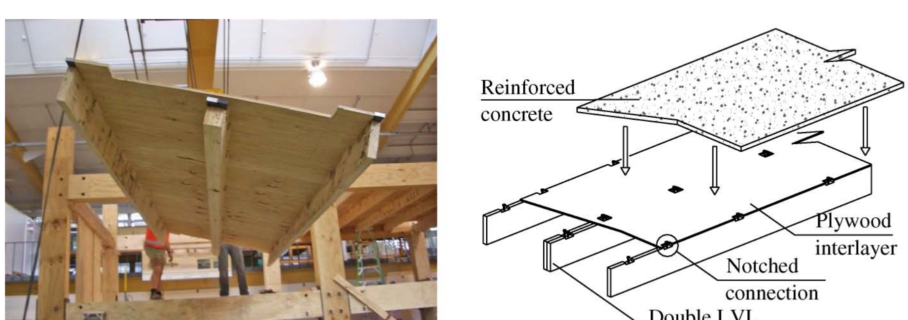

Fig. 5. Semiprefabricated TCC floor system in New Zealand (reprinted from Yeoh et al. 2009a with permission from author)

developed a simplified method for calculating the fire resistance of TCC and suggested relationships for the reduction of stiffness and strength of connections with the temperature as a function of the connection cover. With regards to vibrations and acoustics, the concrete slab increases the mass and stiffness of the timber floor and, thus, improves its overall vibration and impact sound insulation behavior (Sipari 2000). Detailed investigations into the dynamic/vibration behavior of semiprefabricated LVL-concrete composite floors are ongoing at UC (Abd Ghafar et al. 2008).

Conclusions

In this paper, the state-of-the-art on research of TCC structures has been presented. Several aspects, such as the advantages of the system, the standards and design methods available, the types of connections developed around the world, the experimental and numerical investigations performed on connections and beams, in both the short- and long-term (at collapse and under sustained load, respectively) have been discussed. The most important literature references were carefully selected and quoted in the paper. TCC has vast potential as a sustainable and effective floor solution, which however is hindered by the lack of awareness in town planners, architects, engineers, and builders. Although the subject has been investigated at length and considerable knowledge has been acquired, an effective yet economical connection system that takes advantage of the prefabrication process characterized by fast erection and complemented with a user-friendly design package is still needed for the TCC to extensively and competitively penetrate into the construction industry. A few prefabricated TCC systems were referenced and briefly described in the paper. The still limited information on the behavior of TCC in the long-term deserves further research. A precamber of the timber beam to offset initial deflection caused by the self-weight of the fresh concrete and additional deflection because of concrete shrinkage is a possible solution to realize long-span TCC floors to comply with long-term deflection limits suggested by current codes of practice. Research data on fire resistance, acoustic separation, and susceptibility to vibrations behavior are almost absent and still needed for implementation of TCC floors in multistory buildings.

References

Abd Ghafar, H., Deam, B., Fragiacomo, M., and Buchanan, A. (2008). "Vibration performace of LVL-concrete composite floor system." *Proc., 10th World Conf. on Timber Engineering*, Miyazaki, Japan.

Aicher, S., Klock, W., Dill-Langer, G., and Radovic, B. (2003). "Nails and nailplates as shear connectors for timber-concrete composite constructions." *Otto-Graf J.*, 14, 189–209.

Aldi, P. (2008). "Timber-concrete composite beams: A numerical approach to investigate the behaviour of grooved connections." *Proc., 7th FIB Ph.D. Symp.*, Stuttgart, Germany.

Balogh, J., Fragiacomo, M., Gutkowski, R. M., and Fast, R. S. (2008). "Influence of repeated and sustained loading on the performance of layered wood-concrete composite beams." *J. Struct. Eng.*, 134(3), 430–439.

Balogh, Z., and Gutkowski, R. (2008). "Modelling of shear transfer in wood-concrete notch connections." *Proc., 10th World Conf. on Timber Engineering*, Miyazaki, Japan.

Bathon, L., Bletz, O., and Schmidt, J. (2006). "Hurricane proof buildings—An innovative solution using prefabricated modular wood-concrete-composite elements." *Proc., 9th World Conf. on Timber Engineering*, Portland, OR.

Benitez, M. F. (2000). "Development and testing of timber/concrete shear connectors." *Proc., 6th World Conf. on Timber Engineering*, Vancouver, BC, Canada.

Bonamini, G., Ceccotti, A., and Uzielli, L. (1990). "Short- and long-term experimental tests on antique larch and oak wood-concrete composite elements." *Proc., C.T.E. Conf.*, Bologna, Italy, 241–251 (in Italian).

Bou Said, E., Jullien, J-F., and Ceccotti, A. (2004). "Long term modeling of timber-concrete composite structures in variable climates." *Proc., 8th World Conf. on Timber Engineering*, Vol. 2, Lahti, Finland, 143–148.

Brunner, M., Romer, M., and Schnüriger, M. (2007). "Timber-concrete-composite with an adhesive connector (wet on wet process)." *Mater. Struct.*, 40(1), 119–126.

Capozucca, R. (1998). "Bond stress system of composite-concrete timber beams." *Mater. Struct.*, 31(9), 634–640.

Comité Euro-International du Béton (CEB). (1993). "CEB-FIP model code 90." *CEB Bulletin No. 213/214*, Lausanne, Switzerland.

Ceccotti, A. (1995). "Timber-concrete composite structures." *Timber engineering STEP 2*, H. Blass, et al., ed., 1st Ed., Centrum Hout, Netherlands, E13/1–E13/12.

Ceccotti, A. (2002). "Composite concrete-timber structures." *Prog. Struct. Eng. Mater.*, 4(3), 264–275.

Ceccotti, A., Fragiacomo, M., and Gutkowski, R. (2002). "Design of timber-concrete composite structures according to EC5-2002 version." *Proc., 35th Meeting of Working Commission W18—Timber Structures*, International Council for Research and Innovation in Building and Construction (CIB), Rotterdam, Netherlands, 10.

Ceccotti, A., Fragiacomo, M., and Giordano, S. (2006). "Long-term and collapse tests on a timber-concrete composite beam with glued-in connection." *Mater. Struct.*, 40(1), 15–25.

Chassagne, P., Bou Saïd, E., Jullien, F. J., and Galimard, P. (2006). "Three dimensional creep model for wood under variable humidity—Numerical analyses at different material scales." *Mech. Time-Depend. Mater.*, 9(4), 203–223.

Clouston, P., Bathon, L., and Schreyer, A. (2005). "Shear and bending performance of a novel wood-concrete composite system." *J. Struct. Eng.*, 131(9), 1404–1412.

Comité Européen de Normalisation (CEN). (1991). "Timber structures—Joints made with mechanical fasteners—General principles for the determination of strength and deformation characteristics." *EN 26891*, Brussels, Belgium.

Comité Européen de Normalisation (CEN). (2004a). "Design of timber structures—Bridges." *Eurocode 5: Part 2*, Brussels, Belgium.

Comité Européen de Normalisation (CEN). (2004b). "Design of timber structures—General rules and rules for buildings." *Eurocode 5: Part 1-1*, Brussels, Belgium.

Cone, C. M. (1963). "A composite timber-concrete bridge." *TDA Bulletin*, 1(9).

Cook, J. P. (1976). "Composite construction methods." *J. Constr. Div.*, 102(1), 21–27.

Deam, B., Fragiacomo, M., and Buchanan, A. (2007). "Connections for composite concrete slab and LVL flooring systems." *Mater. Struct.*, 41(3), 495–507.

Deam, B. L., Fragiacomo, M., and Gross, L. S. (2008). "Experimental behavior of prestressed LVL-concrete composite beams." *J. Struct. Eng.*, 134(5), 801–809.

Dias, A. M. P. G. (2005). "Mechanical behaviour of timber-concrete joints." Ph.D. thesis, Univ. of Coimbra, Portugal.

Dias, A. M. P. G., Van de Kuilen, J. W., Lopes, S., and Cruz, H. (2007). "A non-linear 3D FEM model to simulate timber-concrete joints." *Adv. Eng. Software*, 38, 522–530.

Döhrer, A., and Rautenstrauch, K. (2006). "Connectors for timber-concrete composite-bridges." *Proc., 35th Meeting of Working Commission W18—Timber Structures*, International Council for Research and Innovation in Building and Construction (CIB), Rotterdam, Netherlands, 10.

Finnish Road Administration. (1999). "The Vihantasalmi Bridge—Mäntyharju, Finland 1997–1999." 〈http://www.underwater.pg.gda.pl/didactics/ISPG/Mosty/Vihantasalmi%20bridge.htm〉.

Fragiacomo, M. (2005). "A finite element model for long-term analysis of timber-concrete composite beams." *Struct. Eng. Mech.*, 20(2), 173–179.

Fragiacomo, M. (2006). "Long-term behaviour of timber-concrete composite beams. II: Numerical analysis and simplified evaluation." *J. Struct. Eng.*, 132(1), 23–33.

Fragiacomo, M., Amadio, C., and Macorini, L. (2004). "A finite element model for collapse and long-term analysis of steel-concrete composite beams." *J. Struct. Eng.*, 130(3), 489–497.

Fragiacomo, M., Amadio, C., and Macorini, L. (2007a). "Short- and long-term performance of the 'Tecnaria' stud connector for timber-concrete composite beams." *Mater. Struct.*, 40(10), 1013–1026.

Fragiacomo, M., and Ceccotti, A. (2006). "Long-term behaviour of timber-concrete composite beams. I: Finite element modeling and validation." *J. Struct. Eng.*, 132(1), 13–22.

Fragiacomo, M., Gutkowski, R., Balogh, J., and Fast, R. (2007b). "Long-term behaviour of wood-concrete composite floor/deck systems with shear key connection detail." *J. Struct. Eng.*, 133(9), 1307–1315.

Frangi, A., Erchinger, C., and Fontana, M. (2008). "Charring model for timber frame floor assemblies with void cavities." *Fire Saf. J.*, 43(8), 551–564.

Frangi, A., and Fontana, M. (2001). "A design model for the fire resistance of timber-concrete composite slabs." *Proc., IABSE Conf. on Innovative Wooden Structures and Bridges*, International Association for Bridge and Structural Engineering, Zürich, Switzerland.

Frangi, A., and Fontana, M. (2003). "Elasto-plastic model for timber–concrete composite beams with ductile connection." *Struct. Eng. Int.*, 13(1), 47–57.

Grantham, R., Enjily, V., Fragiacomo, M., Nogarol, C., Zidaric, I., and Amadio, C. (2004). "Potential upgrade of timber frame buildings in the UK using timber-concrete composites." *Proc., 8th World Conf. on Timber Engineering*, Vol. 2, Lathi, Finland, 59–64.

Gutkowski, R., Brown, K., Shigidi, A., and Natterer, J. (2004). "Investigation of notched composite wood-concrete connections." *J. Struct. Eng.*, 130(10), 1553–1561.

Gutkowski, R., Brown, K., Shigidi, A., and Natterer, J. (2008). "Laboratory tests of composite wood-concrete beams." *Constr. Build. Mater.*, 22(6), 1059–1066.

Gutkowski, R., Balogh, J., and To, L. G. (2010). "Finite element modeling of short-term field response of composite wood-concrete floors/decks." *J. Struct. Eng.*, 136(6), 707–714.

Hanhijärvi, A. (1995). "Modelling of creep deformation mechanisms in wood." *VTT Publications 231*, VTT Building Technology, Helsinki, Finland.

Holschemacher, K., Klotz, S., and Weibe, D. (2002). "Application of steel fibre reinforced concrete for timber-concrete composite constructions." *LACER*, 7, 161–170.

ISO. (2000). "Fire resistance testing." *834*, Geneva.

Kenel, A., and Meierhofer, U. (1998). "Long term performance of timber concrete composite structural elements." *Rep. No. 115/39*, EMPA Abteilung Holz, Dübendorf, Germany (in German).

Koh, H. B., Mohamad Diah, A. B., Lee, Y. L., and Yeoh, D. (2008). "Experimental study on shear behaviours of timber-lightweight concrete composite shear connectors." *Proc., 3rd Brunei Int. Conf. on Engineering and Technology*, Bandar Seri Begawan, Brunei.

Kuhlmann, U., and Aldi, P. (2008). "Fatigue of timber-concrete-composite beams: Characterization of the connection behaviour through push-out tests." *Proc., 10th World Conf. on Timber Engineering*, Miyazaki, Japan.

Kuhlmann, U., and Aldi, P. (2009). "Prediction of the fatigue resistance of timber-concrete composite connections." *Proc., 42nd Meeting of Working Commission W18—Timber Structures*, International Council for Research and Innovation in Building and Construction (CIB), Rotterdam, Netherlands, 10.

Kuhlmann, U., and Michelfelder, B. (2004). "Grooves as shear-connectors in timber-concrete composite structures." *Proc., 8th World Conf. on Timber Engineering*, Lahti, Finland, 1, 301–306.

Kuhlmann, U., and Michelfelder, B. (2006). "Optimised design of grooves in timber-concrete composite slabs." *Proc., 9th World Conf. on Timber Engineering*, Portland, OR.

Kuhlmann, U., and Schänzlin, J. (2001). "Grooves as shear connectors for timber-concrete composite decks." *Proc., RILEM Conf. on Joints in Timber Structures*, RILEM, Bagneux, France, 283–290.

Lukaszewska, E. (2009). "Development of prefabricated timber-concrete composite floors." Ph.D. thesis. Luleå Univ. of Technology, Luleå, Sweden.

Lukaszewska, E., and Fragiacomo, M. (2008). "Static performance of prefabricated timber-concrete composite systems." *Proc., 10th World Conf. on Timber Engineering*, Miyazaki, Japan. CD copy.

Lukaszewska, E., Fragiacomo, M., and Johnsson, H. (2010). "Laboratory tests and numerical analyses of prefabricated timber-concrete composite floors." *J. Struct. Eng.*, 136(1), 46–55.

Lukaszewska, E., Johnsson, H., and Fragiacomo, M. (2008). "Performance of connections for prefabricated timber-concrete composite floors." *Mater. Struct.*, 41(9), 1533–1550.

McCullough, B. (1943). "Oregon tests on composite (timber-concrete) beams." *J. Am. Concr. Inst.*, 14(5), 429–440.

Meierhofer, U. (1993). "A timber/concrete composite system." *Struct. Eng. Int.*, 3(2), 104–107.

Mettern, C. (2003). "Structural timber-concrete composites—Advantages of a little known innovation." *Struct. Eng.*, February, 17–19.

Miotto, J., and Dias, A. (2008). "Glulam-concrete composite structures: Experimental investigations into the connection system." *Proc., 10th World Conf. on Timber Engineering*, Miyazaki, Japan.

Möhler, K. (1956). "On the load carrying behavior of beams and columns of compound sections with flexible connections." *Habilitation*, Technical Univ. of Karlsruhe, Germany (in German).

Muller, P. (1922). "Decke aus hochkantig stehenden Holzbohlen oder Holzbrettern und Betondeckschicht." *Patentschau aus dem Betonbau und den damit verwandten Gebieten, Auszuge aus den Patentschriften, Beton und Eisen*, H. XVII, S. 244 (in German).

Natterer, J. (2002). "New technologies for engineered timber structures." *Prog. Struct. Eng. Mater.*, 4, 245–263.

Natterer, J., Hamm, J., and Favre, P. (1996). "Composite wood-concrete floors for multi-story buildings." *Proc., Int. Wood Engineering Conf.*, Vol. 3, New Orleans, 431–435.

O'Neill, J. (2009). "The fire performance of timber-concrete composite floors." M.S. thesis. Univ. of Canterbury, New Zealand.

O'Neill, J., Carradine, D., Moss, P., Buchanan, A., and Fragiacomo, M. (2010). "Fire performance of timber-concrete composite floors." *Proc., 11th World Conf. on Timber Engineering WCTE 2010*, Riva del Garda, Italy, 10.

Persaud, R., and Symons, D. (2005). "Design and testing of a composite timber and concrete floor system." *Struct. Eng.*, 84(4), 22–36.

Pillai, U., and Ramakrishnan, P. (1977). "Nail shear connectors in timber-concrete composites." *J. Inst. Eng. (India), Civ. Eng. Div.*, 58(CI1), 34–39.

Pincus, P. (1970). "Behaviour of wood concrete composite beams." *J. Struct. Div.*, 96(7), 2009–2019.

Richart, F. E., and Williams, C. B. (1943). "Tests of composite timber-concrete beams." *J. Am. Concr. Inst.*, 14(4), 253–276.

Schänzlin, J. (2003). "Time dependent behavior of composite structures of board stacks and concrete." Ph.D. thesis, Univ. of Stuttgart, Germany (in German).

Schänzlin, J., and Fragiacomo, M. (2007). "Extension of EC5 Annex B formulas for the design of timber-concrete composite structures." *Proc., 40th Meeting of Working Commission W18—Timber Structures*, International Council for Research and Innovation in Building and Construction (CIB), Rotterdam, Netherlands, 10.

Schaub, O. (1939). "Verbunddecke aus Holzrippen und Betonplatte." *Patentschrift No. 673*, 556 Deutsches Patentamt (in German).

SFS. (1999). "SFS Verbundsystem VB Holz Beton Verbund [SFS connection system for timber–concrete composite structures]." *PS50099D*, SFS Unimarket AG, Switzerland.

Sipari, P. (2000). "Sound insulation of multi-storey houses—A summary of Finnish impact sound insulation results." *Build. Acoust.*, 7(1), 15–30.

Steinberg, E., Selle, R., and Faust, T. (2003). "Connectors for timber-lightweight concrete composite structures." *J. Struct. Eng.*, 129(11), 1538–1545.

TICOMTEC Holz-Verbund-Systeme. (2007). "Holz-Verbund systeme—The wood-concrete-composite system (HBV-System)." ⟨http://www.hbv-system.de⟩.

To, L. G. (2008). "3D finite element modelling of time-dependent behaviour of wood-concrete composite beams." Ph.D. thesis. Colorado State Univ., Fort Collins, CO.

Toratti, T. (1992). "Creep of timber beams in a variable environment." *Rep. No. 31*, Helsinki Univ. of Technology, Helsinki, Finland.

Toratti, T., and Kevarinmäki, A. (2001). "Development of wood-concrete composite floors." *Proc., Innovative Wooden Structures and Bridges Conf.*, International Association for Bridge and Structural Engineering, Lahti, Finland, 513–518.

Turrini, G., and Piazza, M. (1983a). "A technique for stiffness and strength upgrading of wooden floors." *Recuperare*, 5, 224–237 (in Italian).

Turrini, G., and Piazza, M. (1983b). "Static behavior of timber-concrete composite structures." *Recuperare*, 6, 214–225 (in Italian).

Van der Linden, M. (1999). "Timber-concrete composite floor systems." Ph.D. thesis, Delft Univ., Netherlands.

Weaver, C. A., Davids, W. G., and Dagher, H. J. (2004). "Testing and analysis of partially composite fiber-reinforced polymer-glulam concrete bridge girders." *J. Bridge Eng.*, 9(4), 316–325.

Yeoh, D. (2010). "Behaviour and design of timber-concrete composite floor system." Ph.D. thesis, Univ. of Canterbury, New Zealand.

Yeoh, D., Fragiacomo, M., Buchanan, A., Crews, K., Haskell, J., and Deam, B. (2008). "Development of semi-prefabricated timber-concrete composite floors in Australasia." *Proc., 10th World Conf. on Timber Engineering*, Miyazaki, Japan. CD copy.

Yeoh, D., Fragiacomo, M., Buchanan, A., and Deam, B. (2009a). "Experimental behaviour at ultimate limit state of a semi-prefabricated timber-concrete composite floor system." *Proc., Int. Symp. on Timber Structures from Antiquity to the Present*, Istanbul, Turkey, June 25-27, 287–298.

Yeoh, D., Fragiacomo, M., Buchanan, A., and Gerber, C. (2009b). "Preliminary research towards a semi-prefabricated LVL-concrete composite floor system for the Australasian market." *Aust. J. Struct. Eng.*, 9(3), 225–240.

Yeoh, D., Fragiacomo, M., De Franceschi, M., and Buchanan, A. (2011). "Experimental tests of notched and plate connectors for LVL-concrete composite beams." *J. Struct. Eng.*, 137(2), 261–269.