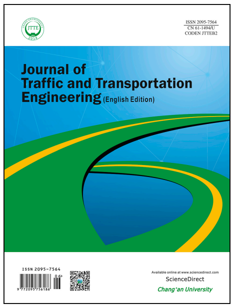

Timber-concrete composite bridges: three case studies

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Reviews

Timber-concrete composite bridges: three case studies

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Highlights

- Possibilities offered by timber-concrete composite structures for short-span bridge decks are discussed.
- Design procedure for timber-concrete composite beams is reviewed.
- Three case studies of timber-concrete composite bridges are illustrated and discussed.
- Advantages and drawbacks of timber-concrete composite structures are discussed.

Abstract

During the last years, timber-concrete composite (TCC) structures have been extensively used in Europe both in new and existing buildings. Generally speaking, a composite structure combines the advantages of both materials employed: the strength and stiffness of the concrete in compression and the tensile strength, lightweight, low embodied energy, and aesthetical appearance of the timber. The concrete slab provides protection of the timber beams from direct contact with water, which is crucial to ensure the durability of the timber beams, particularly when used for bridges. Different types of connectors can be used to provide force exchange between the concrete slab and the timber beam. The choice of a structurally effective yet cheap shear connection between the concrete topping and the timber joist is crucial to make the TCC structures a viable solution that can compete with reinforced concrete and steel structures. In this paper, the possibilities offered by TCC structures for short-span bridge decks are discussed. The technology of TCC structures and the general design rules are illustrated. Three case studies are reported, including a short-span bridge tested in Colorado, USA, with the timber layer being constructed from recycled utility poles and notch connection; a TCC bridge with glulam beams and triangular notches with epoxy-glued rebar connectors built in Portugal; and a TCC bridge with glulam beams and rectangular notches built in Germany. All the solutions were found to be structurally effective and aesthetically pleasing. They can all provide a sustainable option for short-span bridges.

Keywords:

Timber-concrete composite; Bridge; Design; Connection system.

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1 Introduction

Timber-concrete composite (TCC) beams consist of two parts, an upper concrete slab tied to a lower timber beam by means of shear connectors, as shown in Fig. 1. In the following, a bridge will be defined short if it has a span allowing being designed using standard procedures available in standards and code of practice. The shear connectors resist the shear and induce slab-to-beam composite action – the slab compression resistance complements the beam tensile capacity – so improving the stiffness and strength of the composite beam over those of the beams and slab acting without the connection. TCC beams are stiffer, less prone to vibrations due to the larger damping, and characterized by large shear and flexural strength than timber beams. TCC beams are up to 65% lighter than reinforced concrete (RC) beams as much of the cracked concrete in RC beams is replaced by lighter timber beams in TCC beams, leading to cheaper foundations, faster construction, and lower seismic forces. Since timber has approximately the same strength (in tension and compression) as concrete in compression, it should also be pointed out that timber structures are not bulkier than reinforced concrete structures. Timber is carbon neutral, with far less embodied energy than concrete and steel (glulam joists are only 17%-20% the energy costs of equal steel I-section or RC beams). Thus, timber is popular in sustainable construction and aesthetic appeal, even at cost.

TCC beams have been extensively used to date in Europe both in new and existing buildings (Ceccotti, 1995). In the latter case, better acoustic separation and improved thermal insulation are combined with increased stiffness and greater load-carrying capacity (Berardinucci et al., 2017a,b). Due to the aforementioned advantages, a number of research projects have been undertaken in different parts of the world including Europe (Bathon et al., 2006), North America (Balogh et al., 2008) and Australasia (Yeoh et al., 2009) to investigate applications in medium to long-span building floors.

More recently, applications have also been sought for short span bridge decks in several countries such as Germany (Döhrer and Rautenstrauch, 2006; Kuhlmann and Aldi, 2009), Portugal (Dias et al., 2011), and the United States (Gutkowski et al., 2011). The aforementioned advantages of TCC over all-timber and RC beams, in fact, extend to bridges, where the thin concrete slabs on deeper timber beams visually integrate well into rural landscapes. The concrete slab distributes traffic loads among beams and partly protects the beams from rain (which limits moisture variation in the timber) and wheel impact, so improving durability.

With reference to China, in the last decades, the restriction of the allowable timber materials due to government regulations has limited the number of applications. Recently, timber-concrete bridges and buildings are becoming more attractive and studied (Li et al., 2016). Some tests have been carried out to comprehensively investigate the mechanical behavior (Peng, 2010), and the response of timber-concrete beams have been experimentally compared with timber ones (Chen, 2011). Finally, it is worth noting that some interesting application to bridges in China was recently also realized using bamboo-concrete supporting system (Xiao, 2009).

In this paper, the connections commonly employed in TTC short span bridges are reviewed firstly (Section 2). Then, the design procedures adopted for TCC beams are presented with particular reference to Eurocodes (Section 3). The main applications of TCC bridges are discussed and three successful realizations are summarized in detail highlighting the positive aspects (Section 4). Finally, some conclusions and perspectives are drawn (Section 5).

2 Shear connections

In TCC bridges, the mechanical properties of the connections can strongly impact on the stiffness and strength of the composite component. The choice of a structurally effective yet cheap shear connection between the concrete topping and the timber joist is crucial to make TCC structures a viable alternative to more common RC, steel and steel-concrete composite bridges (Berardinucci et al., 2017a,b). Shear connectors should be sufficiently stiff in order to ensure an effective composite action between timber and concrete elements, and several connection systems have been developed to date.

A simple solution is a line of screws, either self-tapping or into pre-drilled holes, vertically placed at a certain spacing along the beam (Fig. 1). Screws have the advantage of being readily available off-the-shelf and easily installed. The recent availability on the market of self-tapping screws with continuous threads has given the opportunity to design a new geometrical configuration where screws are inclined at a certain angle in the vertical plane. Steel rebars and dowels glued to the timber represent one of the first types of connection used for the upgrading of existing floors (Fig. 2). It has the disadvantage of requiring on-site gluing and is generally fairly expensive. Although mechanical connectors such as coach screws, nails, dowels, etc. inserted in the timber without glue are considered to be a simpler way to fasten the concrete slab to the timber beam, they have the disadvantage of being quite flexible and, therefore, requiring a large number of connectors.

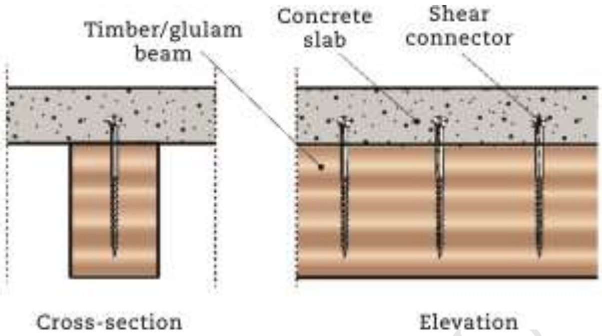

Fig. 1 TCC beam with screw shear connectors.

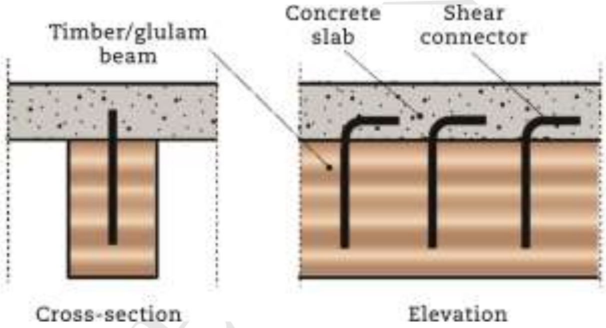

Fig. 2 TCC beam with steel rebars glued to the timber.

On the other hand, using screws inclined at 45° has been proved to result in higher values of stiffness and load-carrying capacities compared to the “traditional” vertical configuration. Several experimental and numerical studies (Bejtka and Blaß, 2002; Berardinucci et al., 2017a,b; Blaß and Bejtka, 2001; Fragiacomo and Lukaszewska, 2011; Kavaliauskas et al., 2007; Tomasi et al., 2010) have highlighted how the use of inclined screw provides an increase of the resistance and stiffness of the joints, allowing for a reduction of the number of the screws needed in a composite floor under the same geometrical and loading conditions. In addition, an extended model for predicting service and ultimate stiffness and strength of the connections when an interlayer is placed at the concrete-to-timber interface is proposed. In particular, results from pushout tests carried out on specimens consisting of a timber block connected to concrete slabs by means of inclined screws with an interlayer in Oriented Strand Board (OSB) have been presented (Figs. 3-4). The OSB interlayer was interposed to reproduce the timber flooring often used as permanent formwork for the placement of the concrete slab in new floors or the existing timber flooring when strengthening existing timber structures.

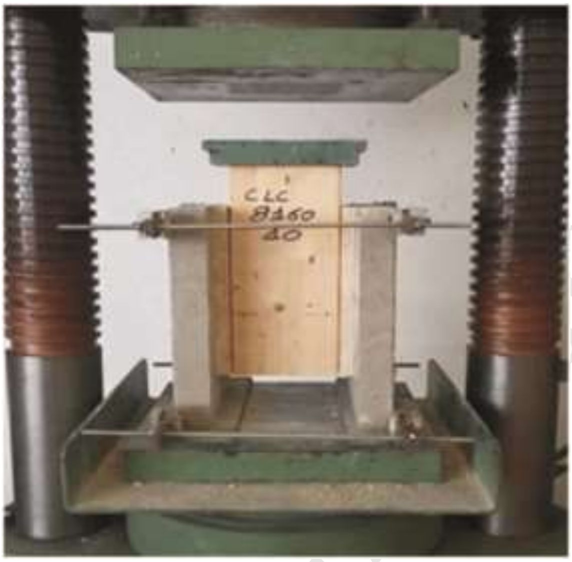

Fig. 3 Pushout test on specimen prepared with inclined screw connectors.

Fig. 4 OSB panel at the concrete-to-timber interface.

The use of continuous steel mesh glued to the timber (Fig. 5) represents an alternative connection method to the use of screws and other mechanical fasteners. This technique actually provides an excellent, almost rigid connection. However, it may suffer from high cost due to the gluing process. A cost-effective connection system can be obtained by cutting notches in the timber, which will be subsequently filled in by concrete (Fig. 6). The shear force is transferred by bearing at the timber-concrete vertical interface within the notch. A metal fastener such as a coach screw (Fig. 6), a metal anchor, or a glued rebar is generally used to reinforce the notch and to provide some ductility to an otherwise inherently brittle connection. The main advantage of the notch connection is the high stiffness and strength, which allows for the use of only few connectors to achieve high composite action reducing costs as opposed to mechanical connectors. This is the main reason why the notched connection is the preferred way of fastening the concrete slab to the timber beam, particularly for bridge decks.

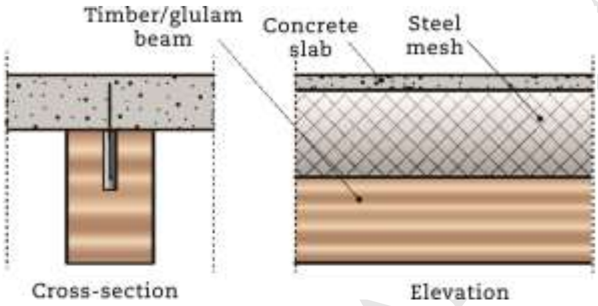

Fig. 5 TCC beam with steel mesh glued to the timber (Bathon et al., 2006).

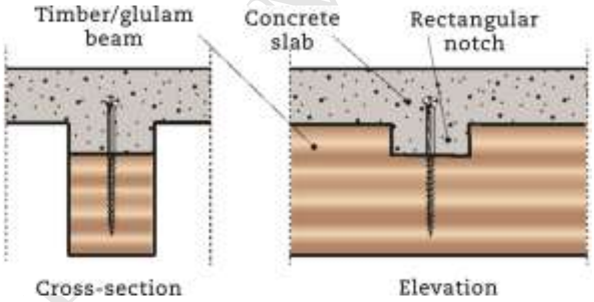

Fig. 6 TCC beam with rectangular notch connector reinforced with coach screw (Yeoh et al., 2009).

3 Design of TCC beams

Unlike steel-concrete composite beams, TCC beams are designed by taking into account the flexibility of the shear connection. The design procedure (Ceccotti, 1995) is based on the approximated elastic solution provided by the Annex B of the Eurocode 5 - Part 1-1 (Comité Européen de Normalisation, 2004) for simply supported composite beams with flexible elastic connections. In particular, the mid-span vertical displacement for a uniformly distributed load g can be evaluated as in Eq. (1).

$$V_{\max} = 5gl^4 / (384(\mathrm{EI})_{\mathrm{ef}}) \quad (1)$$

where l is the length of the beam and $(\mathrm{EI})_{\mathrm{ef}}$ is the effective flexural stiffness of the composite beam given by Eq. (2).

$$(\mathrm{EI})_{\mathrm{ef}} = E_{\mathrm{c}}I_{\mathrm{c}} + E_{\mathrm{w}}I_{\mathrm{w}} + \gamma_{\mathrm{c}}E_{\mathrm{c}}A_{\mathrm{c}}a_{\mathrm{c}}^2 + E_{\mathrm{w}}A_{\mathrm{w}}\alpha_{\mathrm{w}}^2 \qquad (2)$$

where E, A and I are the Young's modulus, cross-sectional area, and second moment of area for the single component beam (the subscripts c, w and f refer to concrete, timber and connection, respectively) given by Eqs. (3)-(6).

$$\gamma_{\mathrm{c}} = 1 / (1 + \pi^2 E_{\mathrm{c}}A_{\mathrm{c}}i_{\mathrm{f,ef}} / (k_{\mathrm{f}}l^2)) \qquad (3)$$

$$i_{\mathrm{f,ef}} = 0.75 i_{\mathrm{f,max}} + 0.25 i_{\mathrm{f,min}} \qquad (4)$$

$$a_{\mathrm{c}} = E_{\mathrm{w}}A_{\mathrm{w}}H / (\gamma_{\mathrm{c}}E_{\mathrm{c}}A_{\mathrm{c}} + E_{\mathrm{w}}A_{\mathrm{w}}) \qquad (5)$$

$$\alpha_{\mathrm{w}} = \gamma_{\mathrm{c}}E_{\mathrm{c}}A_{\mathrm{c}}H / (\gamma_{\mathrm{c}}E_{\mathrm{c}}A_{\mathrm{c}} + E_{\mathrm{w}}A_{\mathrm{w}}) \qquad (6)$$

where k_{f} is slip modulus of shear connectors, $i_{\mathrm{f,max}}$, $i_{\mathrm{f,min}}$ and $i_{\mathrm{f,ef}}$ are the maximum, minimum and effective spacing of connectors, respectively, and H is the distance between the centroids of the concrete and the timber cross-sections.

The connector shear force F_{f} and relative slip s_{f} can be evaluated as in Eqs. (7)-(8).

$$F_{\mathrm{f}}(x) = k_{\mathrm{f}}s_{\mathrm{f}}(x) \qquad (7)$$

$$s_{\mathrm{f}}(x) = V(x)\gamma_{\mathrm{c}}E_{\mathrm{c}}A_{\mathrm{c}}a_{\mathrm{c}}i_{\mathrm{f}}(x) / (k_{\mathrm{f}}(\mathrm{EI})_{\mathrm{ef}}) \qquad (8)$$

The concrete axial force and the bending moments can be evaluated as in Eqs. (9)-(10).

$$N_{\mathrm{c}}(x) = -N_{\mathrm{w}}(x) \qquad (9)$$

$$M_{\mathrm{c}}(x) = M(x)E_{\mathrm{c}}I_{\mathrm{c}} / (\mathrm{EI})_{\mathrm{ef}} \qquad (10)$$

The timber axial force and the bending moments can be evaluated as in Eqs. (11)-(12):

$$N_{\mathrm{w}}(x) = M(x)\, \gamma_{\mathrm{w}}E_{\mathrm{w}}A_{\mathrm{w}}a_{\mathrm{w}} / (\mathrm{EI})_{\mathrm{ef}} \qquad (11)$$

$$M_{\mathrm{w}}(x) = M(x)\, E_{\mathrm{w}}I_{\mathrm{w}} / (\mathrm{EI})_{\mathrm{ef}} \qquad (12)$$

where V and M are the global shear force and bending moment, x is the abscissa along the beam axis.

The shear strength and slip modulus k_{f} of the connector are determined by testing to failure (pushout tests) small timber-concrete composite blocks.

In addition, the rheological phenomena of the component materials (timber, concrete and the shear connection) should be considered in design as they affect both the stress distribution (ultimate limit state) and the deformation over time (serviceability limit state) (Fragiacomo, 2006; Fragiacomo et al., 2007; Gutkowski et al., 2011; Fragiacomo and Schänzlin, 2013). Concrete, timber and the connection creep over time with different rates, and the creep coefficients of both timber and the connection are also affected by the cycles of moisture content (mechano-sorptive effect) (Toratti, 1992). Concrete shrinkage cannot freely occur due to the connection with the timber beam and therefore causes self-equilibrated stresses (eigen-stresses) and downward deflection of the composite beam. Due to the different thermal expansion coefficients of timber and concrete, a temperature variation of the environment causes eigen-stresses and deformations of the composite beam. Shrinkage or swelling of the timber beam due to moisture content variations related to environmental (relative humidity) variations also leads to eigen-stresses and deformations of the composite beam. More details on the design process of TCC beams, including control of ultimate and serviceability limit states in the long-term, are provided (Ceccotti et al., 2002; Dias et al., 2018).

4 Timber-concrete composite bridges

Timber-concrete bridges are becoming more popular in many countries due to the easy construction and sustainable solution. Even if timber bridges have a very long history, as demonstrated by the ancient ones built in China and other counties, the TCC bridges first appeared in the United States in the early 20th century (Cook, 1976; Richart and Williams, 1943) and the first reported TCC dates back approximately to 1925 (DelDOT, 2000). The USA National Bridge Inventory (NBI) database indicates that over 1000 of this bridge type are still in service after many decades (Wacker et al., 2017). Since the beginning of the 1990s, traffic and pedestrian TCC bridges have been increasingly built and studied in many countries as Finland (Nordic Timber Council, 2002) (Fig. 7), Germany, United States (Ritter, 1990; Weaver et al., 2004), France (Flach and Frenette, 2004), Portugal, Switzerland (Meyer, 2005), Australia (Yttrup and Nolan, 2009), New Zealand, Brazil (Junior, 2008) and also in China (Fu et al., 2014). These bridges have used either rectangular section glulam beams or recycled utility poles.

Fig. 7 TCC bridge in Oulu, Finland (Nordic Timber Council, 2002). (a) Elevation. (b) Details.

An interesting TCC bridge was designed by Schaffitzel + Miebach GmbH in 2014 (Fig. 8) in Germany. The shape of the glulam beams follows the bending moment and creates a very harmonic side view. Moreover, the bridge is under monitoring to demonstrate the durability of well-protected timber bridges. The first results of the average timber moisture content, around 16% of mass, indicate that structural protective measures can guarantee acceptable timber moisture contents (Koch et al., 2017). In the following, three TCC bridges will be described in full detail.

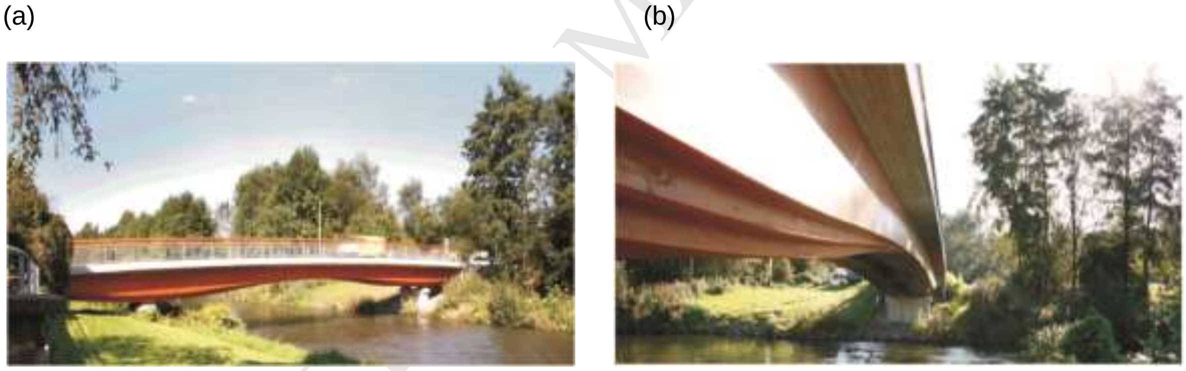

Fig. 8 TCC-Bridge over the Agger in Lohmar Schiffarth (Schaffitzel Holzindustrie, 2018). (a) Elevation. (b) Details.

4.1 Use of recycled utility poles for short-span TCC bridges

Currently, there is a need for improvement to the transportation system of United States as about 27% of the nation’s bridges are deemed structurally or functionally deficient. A possibility investigated at Colorado State University (CSU) consists in the use of reclaimed utility poles for the wood layer of a composite wood-concrete longitudinal deck bridge. As more utility wires are being buried or roadways widened, utility poles that are in good condition are being removed and are available at a very low or no cost. The traditional formworks are only needed on the sides of the bridge deck. Shoring is also unnecessary as the poles provide sufficient support as the concrete layer cures (Gutkowski et al., 2011; LeBorgne, 2007; Miller, 2009).

To overcome the dead load deflection of the beam due to the weight of the concrete and utility poles, it is critical to have camber in the beam since shoring is not practical for bridges. The camber on the underside of the wood-concrete composite beam is natural and comes from the tapered shape of the utility poles and their placement as shown in Fig. 9. To create camber, the tops of the logs are placed level relative to each other so that a natural arching occurs on the underside of the utility poles. However, since the utility poles are different diameters at the ends, the smaller log need to be shimmed so that its top is level with the larger utility pole as shown in Fig. 10.

The interlayer connection is achieved by cutting the notches and reinforcing them with a threaded rod (Fig. 11), which extend all the way through a pre-drilled hole in the utility pole. The rod has a washer on top with a plastic cap (see the red caps in Fig. 12) which protects the washers from the concrete layer once it has been placed. A waterproof paint was applied to the utility poles to keep the swelling of the wood due to the bleeding of the fresh concrete from occurring. After placing the anti-cracking reinforcement (Fig. 12), concrete was placed and left to cure (Fig. 13). 28 days from the concrete placement, the top of the red protective plastic cap was removed and the nut torqued to 34 N•m so as to tighten the rods and reduce the small gaps at the timber-concrete interface due to concrete shrinkage within the notch. Such gaps would significantly reduce the slip modulus of the connection due to the absence of contact between the concrete and the timber within the notch. The nut and the steel plate at the bottom of the rod allow retightening of the rod from underneath the poles, if needed, during the service life of the bridge. It should be noted that only six notches 70 mm deep and 230 mm long were found to be necessary for a 7500 mm span composite bridge. The mean diameter of the poles, which were made of ponderosa pine and douglas fir, was 275 mm, and the depth of the concrete slab above the poles was 170 mm.

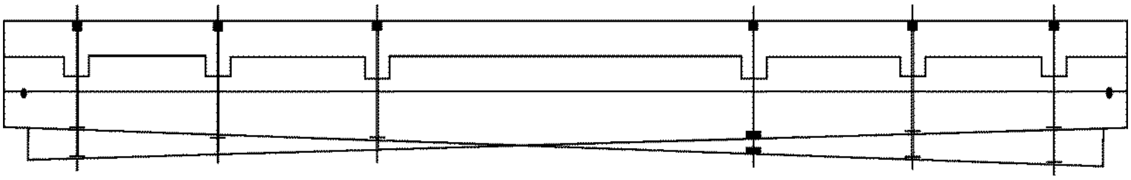

Fig. 9 Elevation of the TCC beam specimens tested at Colorado State University (LeBorgne, 2007).

Fig. 10 Detail of the support with the shim underneath the smaller diameter pole (LeBorgne, 2007).

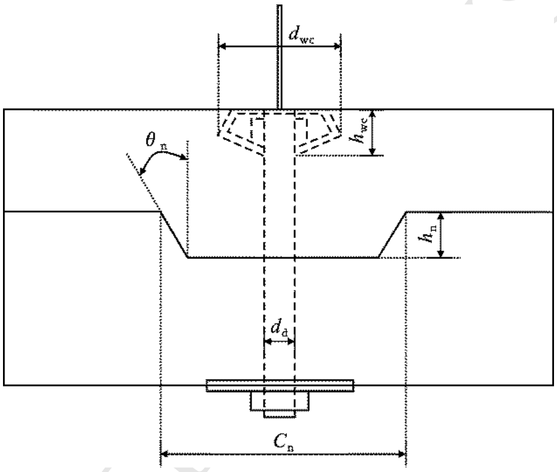

Fig. 11 Notched connection detail (LeBorgne, 2007).

Fig. 12 Beam specimen before concrete placement (LeBorgne, 2007).

Fig. 13 Beam specimen after concrete curing (LeBorgne, 2007).

Monotonic load tests performed on the beam specimens proved the high composite efficiency achieved at serviceability and ultimate limit states (about 97%, i.e., nearly rigid) and the large design point loads (66 kN and 47 kN on a beam specimen with two utility poles made from douglas fir and ponderosa pine, respectively). Specimens subjected to sustained load were monitored for almost two years showing a significant increase in deflection which, however, did not impair the strength capacity. No significant reduction in stiffness was found in specimens subjected to repeated loading tests. This solution can represent an excellent alternative for short span bridge decks used in rural areas, where either recycled utility poles or round wood can be used for the timber deck.

4.2 A TCC bridge with triangular notches reinforced with glued rebars

A TCC bridge was designed and constructed in Portugal (Dias et al., 2011). The bridge had to be designed to accommodate one traffic lane and carry normal traffic loads. Despite being a secondary road, however, it was likely that overloaded trucks carrying logs or sand will use it. The minimum span length of 15 m was chosen so as to minimize the risk of flooding of the river underneath. A timber solution was required for the bridge. The first choice was a stress-laminated timber deck, where the deck is made of timber planks on the edge prestressed across the grain to increase the friction between them. Such a choice, however, was considered not suitable due to the span length of more than 10 m. It was then decided to use a TCC solution.

The TCC bridge was made by a 500 cm × 20 cm concrete slab over four equally spaced GL28 straight 126 cm × 24 cm glulam beams (Fig. 14). The beams were fastened to the concrete slab using 20 triangular notches cut in the timber and reinforced with three inclined rebars glued to the timber (Figs.

15-17). The glulam beams were left unpropped during the concrete placement (Fig. 18). The final result is displayed in Fig. 19. The bridge is part of the National Forest Road Network and was designed in accordance with the Portuguese Load and Safety for Buildings and Bridges Regulation for the heaviest truck specified. Two load sets were considered: (1) transversal, uniformly distributed load of 50 kN/m and area load of 4 kN/m^2, and (2) 600 kN truck per traffic lane (equally divided by three axle loadings of 200 kN). Since this was the first TCC bridge erected in Portugal, it was decided to closely monitor it over time. In four years of inspections, the timber members have not shown any sign of degradation, expressed by cracks or discoloration induced by moisture variations. It should be noted the important role played by the concrete slab in protecting the timber beams from direct contact with water. In this respect, the overhangs of the concrete slab on both sides are crucial to keep the water off the timber.

Fig. 14 Cross-section of the TCC bridge (courtesy of A.M.P.G. Dias).

Fig. 15 Ends of glulam beams with triangular notches (courtesy of A.M.P.G. Dias).

Fig. 16 Glulam beams with notches and holes for inclined rebars (courtesy of A.M.P.G. Dias).

Fig. 17 Detail of the notch connection with inclined rebars (courtesy of A.M.P.G. Dias).

Fig. 18 Concrete placement (courtesy of A.M.P.G. Dias).

Fig. 19 TCC bridge after construction (courtesy of A.M.P.G. Dias).

4.3 First TCC bridge in Germany

The first TCC bridge was erected in Germany at Wippra (IB-MIEBACH, 2018). This bridge follows extensive research undertaken at the University of Weimar (Döhrer and Rautenstrauch, 2006; Simon, 2008) and at the University of Stuttgart (Kuhlmann and Aldi, 2009), which include fatigue tests of connections under millions of cycles aimed to draw the S-N lines, creep tests under sustained load, and tests to failure of beams and pushout specimens.

The bridge has a span length of 15 m and is made of two GL32h glulam solid sections 1260 mm wide and 700 mm deep made up by seven 180 mm × 700 mm glulam beams. A 25 cm concrete slab overhanging the glulam sections (Fig. 20) is placed atop the glulam and connected to them through 30 mm deep rectangular notches cut in the timber. A 30 mm thick steel plate is inserted in the notch and connected to the concrete slab through head studs welded to the steel plate (Fig. 21). Some screws also connect the steel plates to the timber to resist any possible uplift. The shear forces are therefore transferred from the concrete to the steel plates via the head studs, and then to the timber via bearing at the steel-timber vertical interface of the notch. The TCC bridge was designed according to the German code for heavy traffic load. A photo of the bridge after construction during the load testing is displayed in Fig. 22. The overall cost of the bridge was 330,000 € (around 4000 € per square meter).

Fig. 20 TCC bridge from underside (courtesy of P. Aldi).

Fig. 21 Glulam sections with connectors before concrete placement (courtesy of P. Aldi).

Fig. 22 TCC bridge built at Wippra, Germany, during the loading test (courtesy of P. Aldi).

5 Conclusions

Extensive research has been conducted on timber-concrete composite (TCC) structures. This research has highlighted the potential of the composite construction not only for the upgrading of existing floors but also for new short span bridges. Potential advantages over all-timber bridges include larger load-bearing capacity and stiffness due to the higher modulus of elasticity of concrete with respect to timber, less susceptibility to vibrations, better redistribution of vehicle loads across the bridge, increased durability since the concrete slab protects the timber from direct contact with water due to the rain and wind, and protection of the timber part from wheel impact. Compared to reinforced concrete bridges, TCC bridges are lightweight as timber weighs only one-fourth of the concrete and has about the same strength in both compression and tension, not necessitating any additional steel reinforcement, are more sustainable as timber segregates carbon dioxide from the atmosphere and has less embodied energy, and are aesthetically pleasing.

The choice of the connection system between concrete slab and timber beam is crucial to make the TCC competitive with more traditional precast reinforced concrete and steel-concrete composite bridges. The research carried out worldwide has indicated the notched connection as one of the most convenient systems to fasten the concrete slab to the timber. In this connection, either rectangular or triangular notches are cut in the timber and reinforced by coach screws, epoxied rods, or threaded rods to increase the shear resistance and improve the post-peak behavior. The notched connection is very stiff and strong, resulting in the possibility to use few connectors and, eventually, in an inexpensive type of connection. Since almost all connection systems are flexible, the design of TCC beams is carried out by using the elastic approximate solution for a composite beam with a flexible connection.

Three examples of TCC bridges are discussed in the paper. A first possibility, suitable for short-span rural bridges spanning up to 8 m, makes use of either recycled utility poles or round wood for the timber layer. The concrete slab is fastened to the timber layer through six notches cut in the timber and reinforced with threaded rods, which are tightened after 28 days from the concrete placement to reduce the gaps at the timber-concrete interface within the notch due to concrete shrinkage. High degree of composite action (nearly as in the case of fully rigid connection) was achieved despite the low number of notches used.

Another possibility for heavy loaded bridges is to connect glulam timber beams with a concrete slab using, again, notches cut in the timber. In Portugal, triangular notches reinforced with inclined glued rebars were used, whilst in Germany, a concrete-steel-timber connection was used where a thick metal plate was inserted into a rectangular notch cut in the timber and connected to the concrete through welded head studs. In both cases, the concrete slab overhung the lateral glulam beams so as to provide effective protection of the timber from the rain.

All three examples of TCC bridges described above represent effective possibilities to replace contemporary precast concrete and steel-concrete composite bridges with more sustainable and aesthetically pleasing solutions. The main drawback is the possible higher cost due to the expensiveness of timber in countries such as Italy and China where this material is imported from abroad.

More research aimed to optimize the fabrication of the connection detail, for example by off-site prefabrication of components such as timber beams with connectors already mounted, and to encourage production of locally grown timber is thought to be a possible way to resolve the aforementioned issue and to promote a more extensive use of this technology.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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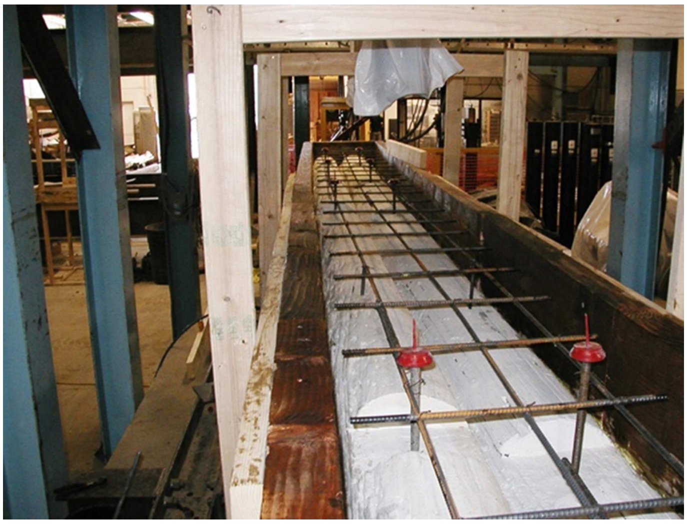

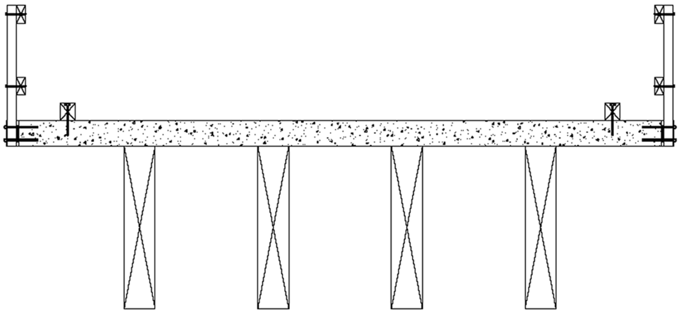

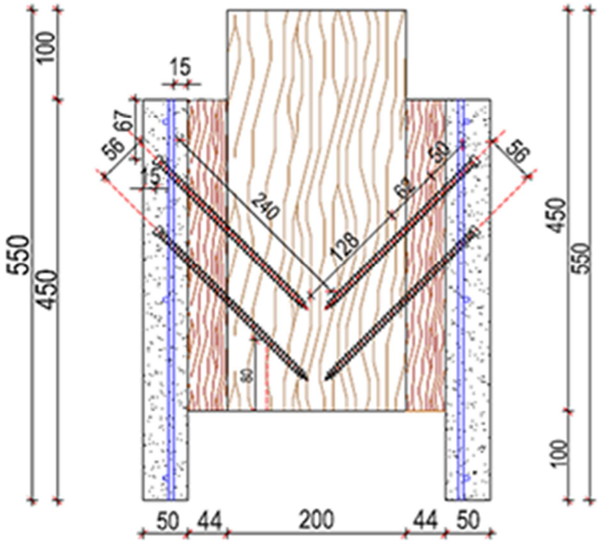
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