Chapter

Timber-Concrete Composite Structural Elements

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Abstract

Timber-concrete composites are interesting engineered wood products usually used for structural elements, which are mainly subjected to bending load; from simple floor systems to long-span bridges. This way, the advantage can be taken of timber tensile strength and concrete compression strength. The chapter begins with an introduction of various types of timber-concrete composite structural elements regarding type of the element, connection type and types of timber and concrete. Next, specific characteristics and advantages of timber-concrete composite structural elements are thoroughly discussed from viewpoints of engineering, architecture, builders and ecology. Furthermore, basic mechanical principles of timber-concrete composite structural elements are presented and some design methods are briefly described. Finally, worldwide inclusion of timber-concrete composite structures in currently applicable standards is discussed.

Keywords: timber-concrete composite, floor systems, mechanical principles, advantages, design methods, standards

1. Introduction

Timber-concrete composite (TCC) structural elements are usually horizontal elements, which carry the load in one direction (so called one-way spanning elements) subjected to uniaxial bending. Timber and concrete part of TCC element are connected with one of several types of connectors in order to achieve composite action [1]. Since concrete has almost negligible tensile strength, timber is commonly on the lower side of the element, where tensile stresses are expected, and concrete is on the upper side, where compressive stresses occur. While there are also some reversed TCC structural elements with concrete on the bottom side [2] and even some TCC wall systems [3], this chapter focuses on most typical application of TCC structural elements described above.

A development of TCC structural elements began around 100 years ago in Germany, aiming at renovation and strengthening of existing timber floors. Paul Müller patented TCC floor system, made of upright timber boards with concrete topping in 1922. Another patent was received by Otto Schaub in 1939 for TCC slab made of timber ribs and concrete slab, connected with Z- or H-shaped steel connectors [1]. While in Europe TCC elements were firstly used as floor systems only, TCC bridges of short and medium span were developed in 1930s in America, as a result of shortage of steel for concrete reinforcement. Construction of TCC bridges spread to Australia and New Zealand in 1950s, where they were probably built by US army. In Europe, TCC bridges did not appear until 1990s [4].

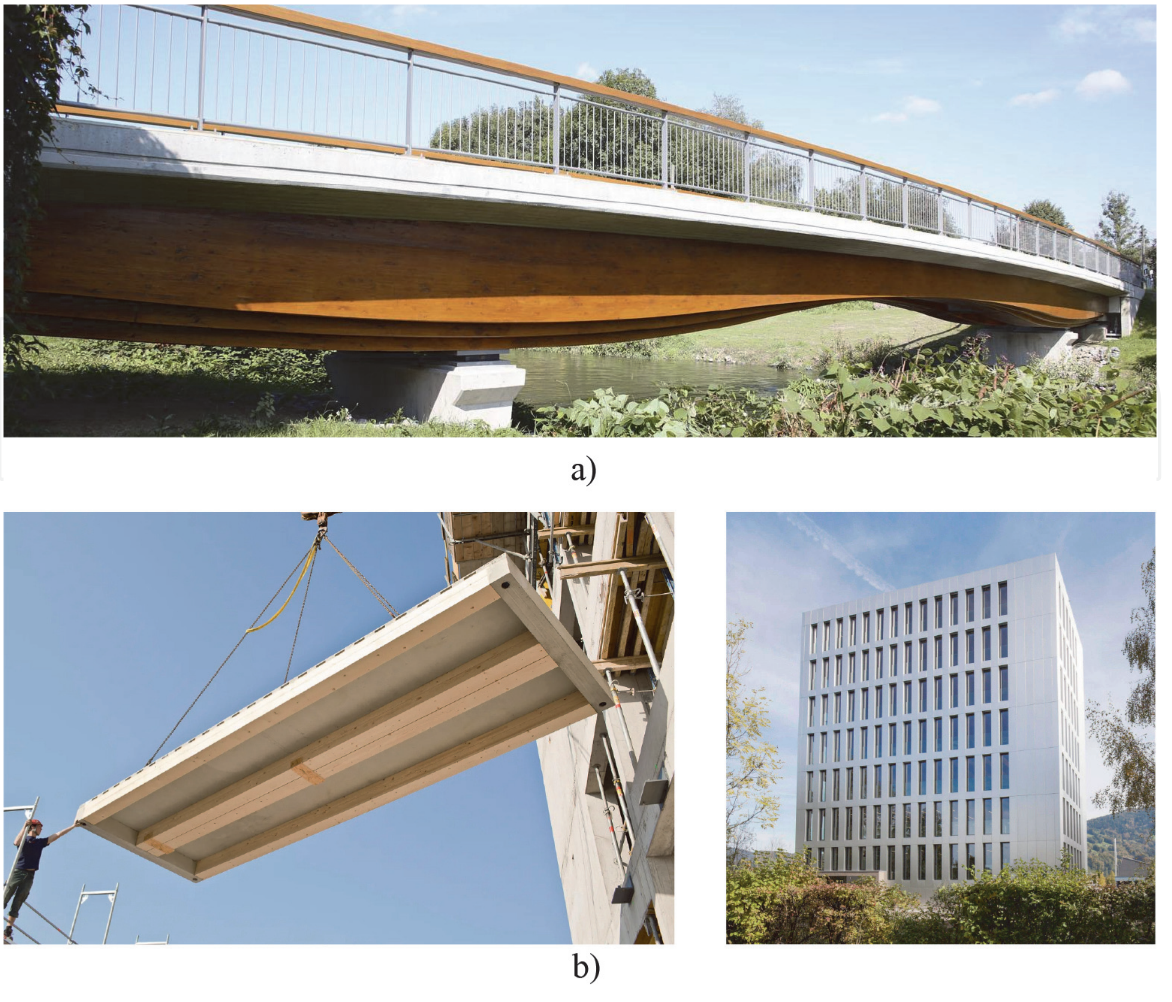

Figure 1.
Examples of structures with TCC structural elements. (a) Bridge over river Agger, Germany [5]. (b) LifeCycle Tower One, Austria: prefabricated TCC slab during construction (left) and finished building (right) [6].

Nowadays, however, TCC structural elements are getting more and more popular worldwide. They are used both in restoration and renovation of existing, often historical structures as well as for new buildings and bridges. **Figure 1** shows TCC bridge over river Agger in Germany, which was built in 2014 [5], and 8-story building called LifeCycle Tower One in Austria, which has TCC horizontal structural elements and was built in 2012 [6].

In this chapter, various types of TCC floor systems are presented and described regarding type of the element and connection type, as well as types of timber and concrete. Next, specific characteristics and advantages of TCC structural elements in comparison with fully concrete or fully timber floor systems are thoroughly discussed from viewpoints of engineering, architecture, construction process and ecology. Furthermore, basic mechanical principles of TCC structural elements are presented, together with most often used simplified methods for their design. The chapter concludes with discussion on worldwide inclusion of TCC structures in currently applicable standards.

2. Variety of designs

TCC structural elements are very diverse. While there are only two main types of geometry of TCC floors (beam and slab type), there are a lot of different types of connections between timber and concrete with considerably different behaviour.

Also, there are several possibilities for type of concrete and even more for type of timber.

2.1 Beam type and slab type TCC floor systems

TCC structural elements are usually slab-like elements (floors in buildings and decks of bridges) and can be either of uniform thickness or ribbed, depending on several factors such as aesthetics, height limit and availability of materials. At the same time, TCC structural elements are almost always one-way-spanning elements, and can be modelled as beams, loaded with uniaxial bending. Therefore, there can be some confusion with the terms: is it a TCC beam or is it a TCC slab? Hereinafter, the following terms will be used: beam type of TCC floors and slab type of TCC floors. Beam type cross-section consists of a timber web and a concrete flange, i.e. timber part is much narrower than the concrete part. Consequently, the neutral axis of the entire TCC cross-section is located in the web. On the other hand, concrete and timber parts of slab type have equal widths and neutral axis is often in the concrete part. Besides the difference in appearance of both types, presented in **Figure 2**, there is also the difference in location of the neutral axis, which influences the portion of the concrete where tensile cracking can occur, and consequently influences appropriate design methods.

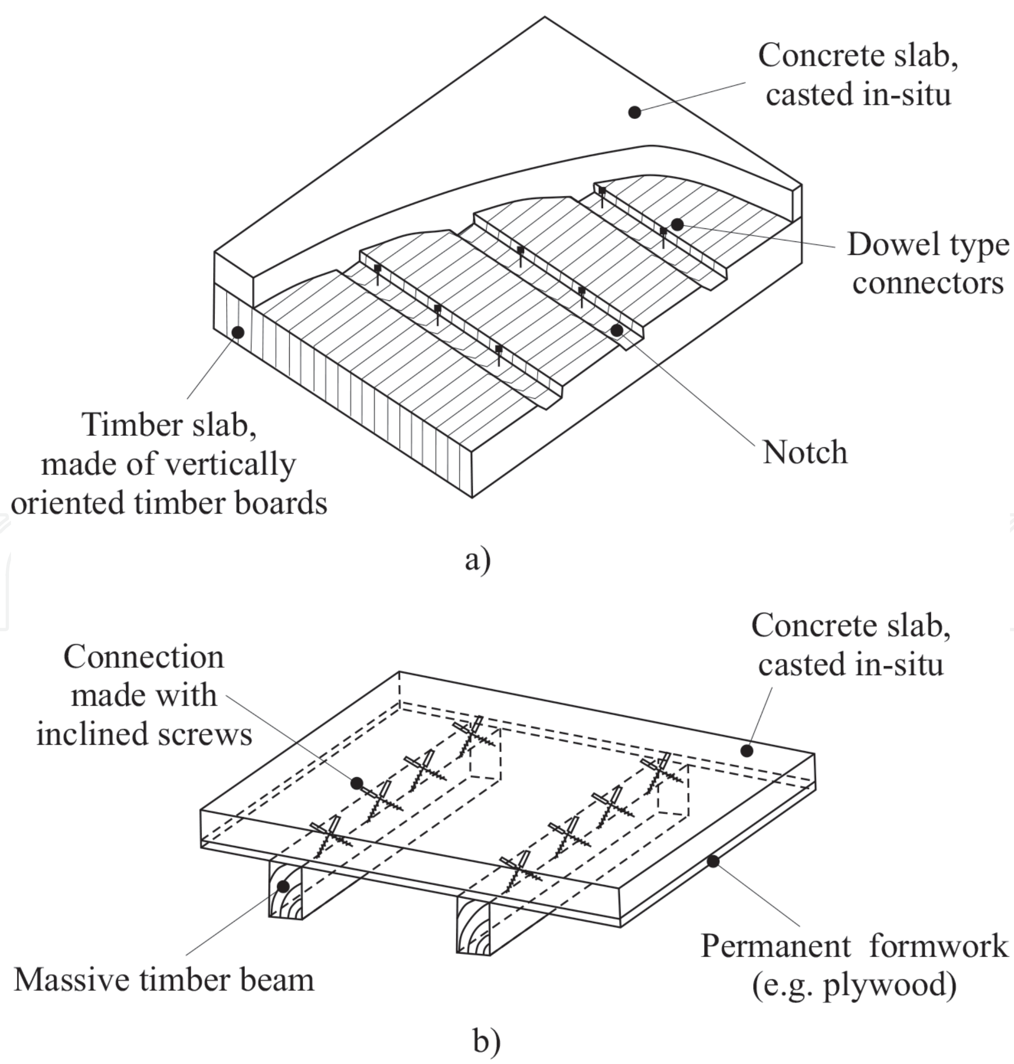

Figure 2.
Examples of slab type and beam type of TCC floor systems. (a) An example of slab type of TCC floors. (b) An example of beam type of TCC floors.

2.2 Materials

Timber part of TCC cross-section can be made from massive timber (beams or boards) or engineered wood products such as laminated veneer lumber (LVL), cross-laminated timber (CLT), glued laminated timber (Glulam), … Especially with slab type of TCC floors there is also a matter of orientation of timber components; boards, plates and lamellas of LVL beams can be orientated either horizontally (placed one on top of another) or vertically (placed next to each other) [7]. Furthermore, while beam type of TCC floor usually has web made of one timber beam, there can also be two connected timber beams next to each other [8]. Such solution is necessary in case of certain type of connectors (e.g. nailplates), but can also be used in other cases.

Concrete in TCC structural elements is usually normal-weight concrete, reinforced only with small amount of steel reinforcement in order to prevent cracking of concrete due to its shrinkage. However, some research was conducted regarding the use of light-weight concrete with the aim of achieving smaller self-weight of TCC element (e.g., [9]). Furthermore, steel-fibre-reinforced concrete (SFRC) in TCC structural elements has proven to reduce possibility of explosive spalling of concrete in fire conditions [10].

The lower side of concrete part of TCC cross-section could be bare, or it can be covered with permanent formwork made of thin timber layer (e.g. plywood).

2.3 Timber-concrete connection

Timber-concrete connection has major influence on behaviour of TCC structural element. The perfect connection has enough strength for transfer of shear forces between the two materials, enough stiffness to allow only limited slip and enough ductility to avoid brittle failure of the connection. Additional, non-mechanical properties of the connection, such as cost and handiness, can also influence the choice on the connection type [1]. However, the perfect connection is nearly impossible to achieve in practice. Several connection systems have been developed, each with its own advantages:

- *Dowel type fasteners* include dowels, screws, inclined screws, nails and other metallic connectors. With exception of inclined screws, dowel type fasteners represent a connection system with the lowest stiffness and the largest ductility [11].

- *Notched connections*, where notches can be of various shapes (rectangular, circular, with vertical sides or with inclined sides, …), are among the most brittle connections. Ductility of notched connection is greatly improved with addition of steel fastener (dowel or screw) into the indentation [11].

- When strength of *glued connections* is exceeded, they experience brittle failure. Their advantage is that they are very stiff and enable almost full composite action. Also, they ensure uniform distribution of shear forces and can be used for connection of timber with prefabricated concrete slab [1].

- *Connections with nailplates* have various designs of plates; one of the possibilities is a plate with lower part designed as a nailplate, positioned between two timber beams, and with the upper part designed as a perforated plate [8].

- *Friction based connections* are based on a system with upright positioned timber boards of altering heights, and are mainly used in Switzerland [1].

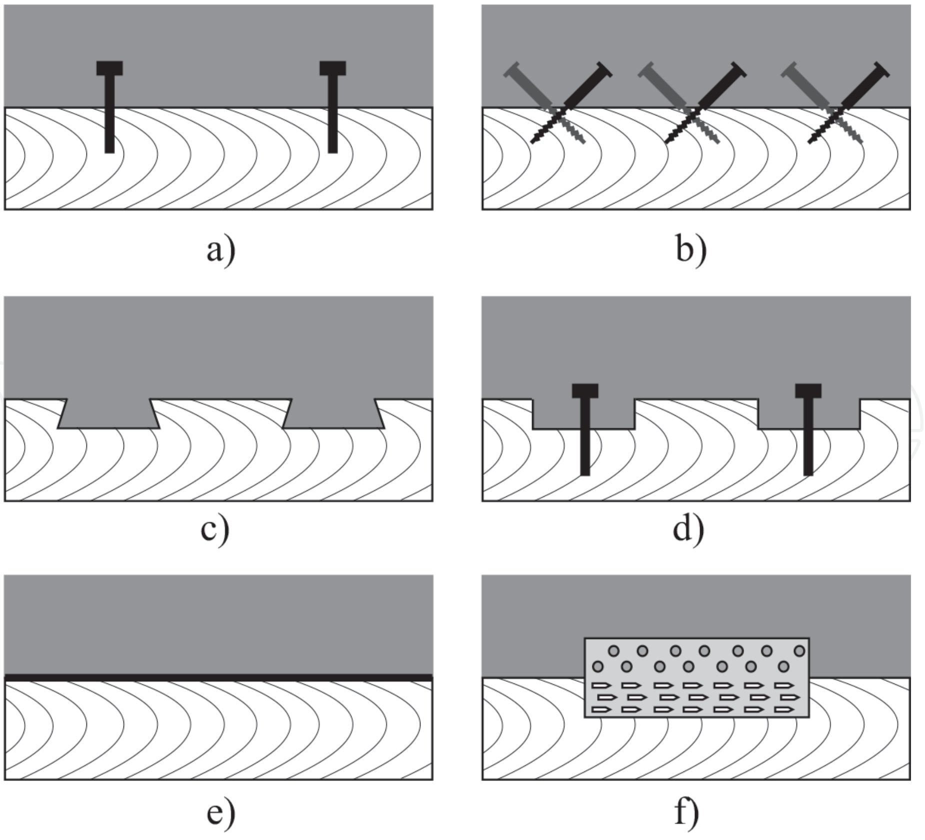

Figure 3.
Connection types. (a) Connection with dowels. (b) Connection with inclined screws at 45° in two rows. (c) Notched connection with inclined sides. (d) Notched connection with vertical sides and dowels. (e) Glued connection. (f) Connection with nailplates.

Some of the connection types are schematically presented in **Figure 3**. An interested reader can also find graphical comparison of stiffness and ductility of various connection systems (with respect to their normalised strength) in [11]. Additionally, more variations of connections can be found e.g. in [12].

In one-way-spanning simply supported floors, which is most often the case for TCC floors, the greatest shear force in the connection occur close to the supports, while it can be negligible in the middle of the span. The failure of one connector near the supports would lead to an additional load in the remaining connectors, which could result in more brittle failure of the TCC element [11]. In order to avoid that, the spacing between separate connectors near the supports is sometimes reduced, while at the midspan the spacing can be increased [13].

3. Characteristics of TCC structural elements

Due to their composite nature, TCC structural elements have pretty specific characteristics, some of them represent advantages over fully timber elements and other over fully concrete elements.

3.1 Aesthetics and convenience

From architectural point of view, timber, as a natural structural material, is often preferred over concrete. Therefore, timber parts of TCC structural elements are usually left to be visible due to aesthetic reasons. Furthermore, visible timber parts are desired when TCC structural elements are used in restoration of historical buildings.

In comparison with fully concrete structural elements of similar mechanical performance, TCC structural elements have lower self-weight. Among other benefits, this contributes to easier transport of materials to the construction site, as well as to smaller seismic forces on the finished structure.

Moreover, TCC structural elements can be prefabricated, either as a whole element or timber and concrete part separately. This can expedite the process of construction on site and the use of resources can be more controlled in a workshop, which result in smaller amount of waste.

3.2 Strength, stiffness and ductility

Strength of a structural element governs maximum load that the element can withstand without failure. In comparison with traditional timber-only floor systems, TCC floor systems (with properly connected timber and concrete parts) achieve up to three times higher load carrying capacity and up to six times greater bending stiffness [12]. Concrete on the upper side contributes to compressive load capacity of the TCC element, and timber on the lower side contributes to its tensile load capacity.

Bending stiffness of structural element is a resistance of an element against bending deformations, i.e. it determines how large deflections will occur under certain bending load. Greater bending stiffness of TCC elements, which means smaller deflection, is achieved due to elastic modulus of the concrete being several times higher than elastic modulus of the timber. In-plane rigidity of TCC floors is also improved when compared to timber floors. In fact, TCC floor systems can act as horizontal bracing of the structure and thus improve its seismic response, if both timber and concrete part of TCC element are connected to the walls [12].

Ductile structural elements can sustain large plastic deformations before failure. Properly designed and executed connection between timber and concrete can lead to improved ductility in comparison with fully concrete or fully timber floors. In order to achieve that, the connection must be sufficiently strong and rigid [1]. However, if the connection is too strong and stiff, a brittle tensile failure of the timber may occur prior to plastification of the connectors [12].

The bending stiffness of TCC structural element (which depends on the stiffness of the connection) influences distribution of deformation and stresses over TCC cross-section, and consequently importantly influences verification of ultimate limit states (ULS) as well as of serviceability limit states (SLS) [1]. As both timber and concrete are rheologically active materials, initial and long term response of TCC structural elements must be checked. Calculation of strength and stiffness of TCC elements is discussed in Section 5.

3.3 Sound insulation and vibrations

Normal-weight concrete has density around 2400 kg/m^3, which is three to five times higher than hardwood and around five to eight times higher than softwood (depending on the quality class of timber) [14]. As a result, TCC floor systems provide better insulation for air-transmitted sound than fully timber systems. Furthermore, in comparison with fully concrete systems, TCC floor systems provide improved insulation for impact noise, due to increased damping characteristics [12].

As already mentioned, TCC structural elements can achieve longer spans than fully timber floors, due to higher strength and bending stiffness. However, a research on one TCC slab type floor system has shown that an increase of height of concrete part with the aim of achieving higher load capacity and consequently longer span has its limit. When this limit span is exceeded, vibration performance becomes the controlling design parameter. The reason is in reduced natural frequency of TCC element as a result of increased self-weight of the element due to increased concrete height [15]. Because of low natural frequency, TCC floor systems could be categorised as susceptible to resonance [16]. Nevertheless, the viscous damping ratio of TCC systems is higher than that of fully timber systems. Consequently, "springiness" felt by the users when jumping or walking on the floors is reduced and users are less annoyed [12]. It was experimentally confirmed, that the achieved values of occupancy annoyance for TCC floors are way below the annoyance limit proposed in Eurocodes [16].

3.4 Fire conditions

Behaviour of TCC structural elements in fire conditions is an important factor in their design. First of all, there are certain phenomena, inherent to each of the two materials, which occur at exposure to high temperatures. In timber, being a combustible material, pyrolysis occurs at elevated temperatures, resulting in reduction of material properties and eventually (at approximately 300°C) in charring of material [17]. The charred layer of the timber part of TCC cross-section have negligible strength and stiffness and is for design purposes considered as mechanically completely ineffective layer. However, char works as a thermal insulation and therefore protects the remaining cross-section. On the other hand, mechanical properties of concrete are reduced when temperature exceeds 400°C [18]. Concrete part of TCC cross-section is usually quite thin slab, reinforced with small amount of steel reinforcement (aimed only at prevention of concrete cracking as a result of shrinkage). It has been shown that thin concrete slabs are more likely to experience explosive spalling than thicker ones [2]. Another research has shown that explosive spalling in beam type of TCC floor can be avoided with the use of concrete reinforced with steel fibres (SFRC) [10].

Geometry of the TCC cross-section changes during fire duration due to charring of timber and spalling of concrete. Additionally, height of the timber part can be reduced in case of laminated timber (LVL, CLT ...) if separate lamellas fall off [13]. This can occur either due to charring and result in lesser thermal insulation of the remaining cross-section or earlier due to failure of glued connection between lamellas, which causes additional reduction of otherwise effective cross-section.

Elevated temperatures influence behaviour of the connection between timber and concrete as well. Reduction factors for both strength and stiffness of the connection depend on: (i) type of the connection, (ii) initial timber cover i.e. distance between initial boundary of the cross-section exposed to fire and the connectors and (iii) development of elevated temperatures and related charring progress. It appears that lateral timber cover in beam type of TCC floors is more important for protection of the connection than bottom timber cover [19].

An obvious, yet important difference presents itself between beam type and slab type of TCC floor systems in fire conditions. With beam type, there are three sides of timber part (lower and both lateral sides) directly exposed to fire and charring progress. Additionally, almost entire lower side of the concrete slab is either immediately exposed or initially protected with thin layer of permanent formwork only. On the other hand, only lower side of timber slab in slab type of TCC floor system is directly exposed, therefore, heat transfer and charring process can be considered one-dimensional [7].

A different approach to TCC floor systems, so-called reverse TCC system, has concrete slab below timber beams and timber deck. An important function of concrete slab in such systems is fire protection of the timber part. The research has shown that very thin concrete slabs already provides efficient thermal insulation and thickness of the slab is actually governed by required cover depth of steel reinforcement and by prevention of explosive spalling of concrete [2].

Thus far, behaviour of TCC structural elements in fire has been extensively experimentally investigated [20] and both analytical simplified methods and numerical methods for fire safe design have been developed, see for example [19, 21, 22], respectively. However, the variety of designs and complexity of behaviour of TCC structural elements in fire conditions calls for further research.

3.5 Ecology aspect

Design of buildings with TCC structural elements can contribute to more ecological and sustainable built environment in several ways.

Firstly, TCC floor systems were developed and are still being used for strengthening of existing timber floors with added concrete layer or as their replacement. Consequently, the lifetime of renovated building is prolonged and thus its sustainability is improved.

Furthermore, in comparison with reinforced concrete structural elements with similar structural performance, TCC elements contain less concrete and, clearly, more timber. This brings the following ecological advantages:

- Unlike concrete, timber is a *renewable natural resource*.

- Carbon footprint is defined as sum of greenhouse gas emissions caused by organisation, event, product or individual expressed as carbon dioxide equivalent. Several studies have shown that timber-based buildings generally have *lower carbon footprint* and lower energy consumption during their life cycle (i.e. *lower embodied energy*) than concrete buildings with comparable heating and cooling requirements [23]. Research on cradle-to-gate environmental performance has also confirmed very low values of carbon footprint and embodied energy for prefabricated TCC wall element [3].

- Timber part of TCC element represents *storage for carbon*, which was captured there during tree growth. In order to avoid release of the captured carbon in the atmosphere and consequential increase of carbon footprint it is important to apply available carbon capture and storage (CCS) technologies for timber incineration at the end of its lifetime [23].

Since concrete, which is obviously less friendly to the environment than timber, importantly influences structural performance of TCC element, the question remains: "What geometry of TCC cross-section is optimal for satisfying both structural and environmental needs?" It was shown for a specific slab type of TCC floors, that for achieving longer spans than 7 m it is better to increase height of timber part, while keeping concrete thickness in specified range [15]. However, due to many different designs of TCC structural elements that is not always the case.

4. Mechanical principles

TCC structural elements are most often simply supported one-way-spanning floors (either slab type or beam type), subjected to vertical external load resulting in positive bending moment only. Each of the two parts of the TCC cross-section (i.e. timber part and concrete part) is usually rectangular. Mechanical principles in this section are presented accordingly.

Due to positive bending moment, tensile normal stresses occur on the lower half of each part of the TCC cross-section and compressive normal stresses occur on their upper halves. The connection between timber and concrete restricts horizontal slip on the contact and transfers shear force, which is in equilibrium with internal normal force in each part of the cross-section. The magnitude of the shear force and inherent magnitude of the constant normal stresses in each part of the cross-section are determined by the stiffness of the connection. Therefore, stiffness of the connection between timber and concrete has important influence on total stress distribution over cross-section. Theoretically, there are three possibilities: perfectly rigid connection, semi-rigid connection and without connection [22]. *Perfectly rigid connection* means that there is no horizontal slip between timber and concrete parts. Shear force is fully transferred, which enables full composite action of TCC cross-section. Such connection is desired because it results in the greatest bearing capacity of the TCC cross-section with the smallest possible total normal stresses as well as the smallest deflections of the element. However, perfectly rigid connections are practically impossible to achieve in reality, with exception of glued connections. On the other hand, timber and concrete parts *without connection* (i.e. with un-prevented slip between both parts) work completely separately. There is no shear force

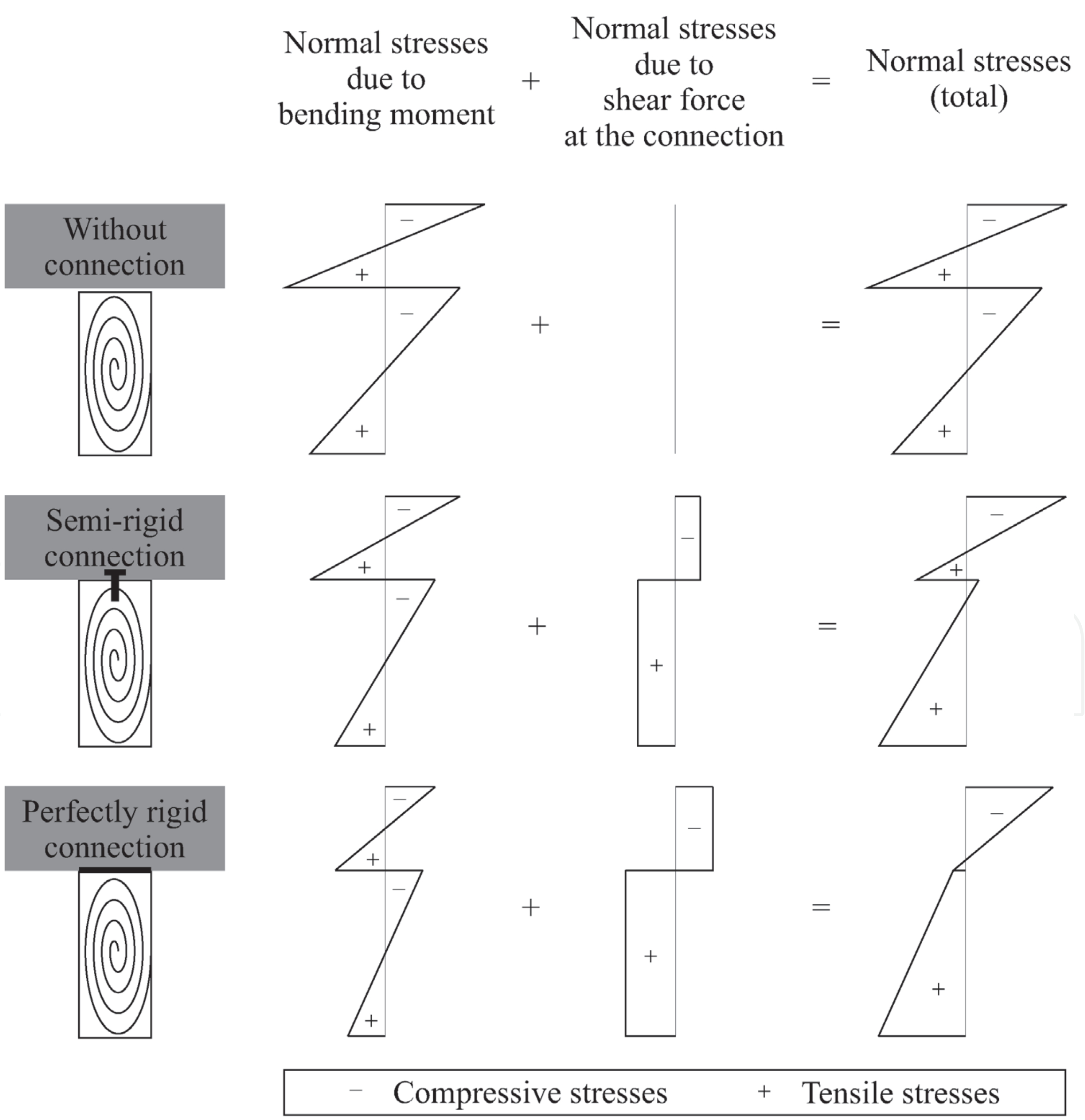

Figure 4.
Stress distributions over TCC cross-section for perfectly rigid connection, semi-rigid connection and without connection.

transferred and consequently there is no composite action between the two parts which causes the lowest bearing capacity of the TCC cross-section with the largest possible total normal stresses and deflections of the element. In reality, the connections between timber and concrete part of TCC element are *semi-rigid*; somewhere in-between the two aforementioned extreme options. Stress distributions over TCC cross-section for each of the three possibilities are depicted in **Figure 4**.

Failure of TCC structural element occur when any of its components fails; either the outermost fibres of timber part fail in tension, or the outermost fibres of concrete part fail in compression, or the connection fails due to exceeded shear capacity. Type of the connection determines its failure mode. For example, for notched type of the connection with dowels, shear failure of the dowel occur together with local compressive failure of timber (parallel to fibres) [22]. On the other hand, screwed connection with inclined screws (usually at 45°) in two rows work as a virtual truss with screws representing tensile and compressive diagonals; at the failure, tensily loaded screws fail due to withdrawal from timber part, while screws in compression experience buckling [19].

5. Currently available simplified design methods

Behaviour of TCC structural element is quite complex, mostly due to non-linear response of semi-rigid timber-concrete connection. Therefore, currently available analytical design methods introduce several simplifications.

Majority of simplified design methods for TCC structural elements (see e.g., [19, 24]) is based on so-called gamma method [25], developed in 1956, with one of its formulations being presented also in EN 1995-1-1, Appendix B [26]. The method introduces gamma coefficient (γ), which describes slip stiffness of the connection and depends on type of the connectors (their slip modulus) and on spacing of the connectors. Provided that geometry and material properties of the connected parts (i.e. timber and concrete part) are known, effective bending stiffness of TCC cross-section can be calculated. With that, stress distribution over cross-section can be determined.

Another approach includes a crude simplification and completely disregards slip in the connection. Thus, Bernoulli hypothesis can be applied and stress distribution over TCC cross-section in ULS (due to exceeded tensile or compressive bearing capacity) can be determined, see e.g., [21, 27]). The advantage of this method in comparison with the gamma method is in possibility to consider cracking of concrete as a result of exceeded tensile strength. Cracked concrete cannot contribute to effective stiffness of the cross-section; as the height of the cracked part depends on stress distribution, the effective bending stiffness according to gamma method could not be determined.

There are also some simplified methods available for fire safe design of TCC structural elements. These methods are often basically the same as the methods for design at normal temperatures, but upgraded to include charring of timber and reduction of material properties due to elevated temperatures. Usually (but not always), simplified methods for reduction of geometry and material properties, which are already established and described in standards for timber or for concrete, are applied [17, 18].

6. Recommendations for construction workers

While there are several proprietary TCC systems on the market [1], with detailed instructions for builders, Ceccotti [12] gives some general recommendations for construction of TCC structures. Mostly, he warns against water presence (use of wet timber should be avoided, timber should be protected from moisture when casting the concrete and connectors should be protected against corrosion). Regarding concrete, he advices to reinforce thicker layers of concrete, to use mixture with lower water/cement ratio and to leave propping in place longer than it is usual for fully concrete elements. Furthermore, he advices to avoid timber species, which could adversely react with cement (such as larch due to high-sugar-content extracts).

7. Inclusion of TCC structural elements in standards around the world

TCC structural elements are currently still very scarcely considered in design standards and guidelines worldwide. Most often, some information, which apply to timber-concrete connections, can be found in other standards (e.g. in standard for timber structures). There are also few specifications for timber-concrete bearing systems in some standards concerning bridges [1].

In *Europe*, where structural design is covered by Eurocode standards, some guidelines about general connections and even some more specific clauses regarding timber-concrete connections can currently be found in Eurocode 5, parts EN 1995-1-1 and EN 1995–2. A simplified method for calculation of moment resistance of mechanically jointed beams, known also as gamma method, is given in appendix B of EN 1995-1-1 and most of currently available methods for design of TCC structural elements are based on this method. However, as part of second generation of Eurocodes novel part of Eurocode 5, EN 1995-1-3, which will cover wholesome design of TCC structures, is in preparation and it is expected to be published soon [28].

According to information from European commission [29] there are several *Asian* and *African* countries that have already adopted Eurocodes or are currently in process of adoption and thus the same conclusions regarding inclusion of TCC structures in standards can be made for them as per European countries. Those countries are: Russia, Kazakhstan, Malaysia, Vietnam, Turkey, Madagascar, Angola, Ethiopia and Kenya. Additionally, China, India, South Africa and majority of Middle East countries have expressed interest in adopting Eurocodes [29].

Standards, which include some specifications for TCC design in *North America* and in *South America*, consider design of bridges [1]. In USA, there are AASHO and AASTHO codes, which date back to 1949 and 1983, respectively. In Canada, there is a Canadian Highway Bridge Design Code, which specifically allows two types of notched connections between timber and concrete. Guidelines for TCC floors can be found in recently published Design Guide for Timber-Concrete Composite Floors in Canada [30]. Greenland, on the other hand, has adopted Eurocode standards [29]. In Brazil, bridge design code has been published in 2006, which includes specifications for TCC bridges and analytical method based on shell theory. Otherwise, Eurocodes are being used in Brazil.

Oceania has its own design guide, namely Australia and New Zealand design guidelines, which is based on Eurocode 5. Some modifications have been made, though, in order to satisfy Australian and New Zealand rules for timber structures. Here, spans up to 8 m are allowed and two configurations of notched connections with screws are prescribed [1].

8. Conclusions

Increasing popularity of TCC structural elements over last decades is connected to many advantages of TCC systems over more established fully concrete and fully timber systems. In comparison with fully concrete elements, TCC elements have improved aesthetic and ecological component, reduced self-weight, as well as improved sound insulation for impact noise. Main advantages of TCC elements over fully timber elements are increased load-carrying capacity and stiffness, improved insulation for air-transmitted sound and decreased annoyance of users because of vibrations. Connection between timber and concrete is a very important component of TCC system; its strength and slip stiffness ensure composite action of timber and concrete part and, if the connection is properly designed, increased ductility of TCC structural element can be achieved.

TCC structural elements come in variety of designs; in particular, there is many different types of connectors, each with its own characteristic behaviour. If properties of the connection (shear strength, slip modulus, spacing, ...) are known, bending resistance of TCC element can be determined with one of existing simplified methods for design of TCC structures.

Design of TCC structural elements is scarcely represented in currently applicable standards. Lately, however, some design guidelines specifically for TCC floor systems were published in Canada. Furthermore, new part of Eurocodes, which will thoroughly consider design of TCC structural elements is already in preparation. Nevertheless, experimental research as well as development of more accurate design methods are still continuing, due to many different designs of TCC structural elements and their complex behaviour.

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Conflict of interest

The authors declare no conflict of interest.

Abbreviations

CCS	carbon capture and storage
CLT	cross-laminated timber
Glulam	glued laminated timber
LVL	laminated veneer lumber
SLS	serviceability limit state
SFRC	steel-fibre-reinforced concrete
TCC	timber-concrete composite
ULS	ultimate limit state

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