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TIMBER-CONCRETE COMPOSITE – A HIGH-EFFICIENT AND SUSTAINABLE CONSTRUCTION METHOD

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Timber-concrete composite (TCC) is a well-tried building method for construction of sustainable and robust floor systems with high load-bearing capacity. TCC sections consist of timber beams linked by shear connectors with a plain or reinforced concrete slab. Usually, by the shear connectors only flexible bond between the timber beams and the concrete slab may be provided. Nevertheless, TCC slabs have high flexural stiffness and appropriate load-bearing capacity enabling their application in residential and office buildings, and even in bridge construction. The paper reports state-of-the-art and recent developments in design and construction of TCC slabs. Especially, in the context of revaluation and strengthening of existing timber-beam ceilings it is a widely accepted technique today. But also, in design of new buildings, TCC slabs are an advantageous solution because of their reduced environmental impact in contrast to traditional reinforced concrete slabs. By many examples in recent design practice the high efficiency of TCC systems was proved.

Keywords: Composite members, Shear connectors, Flexible bond, Environmental impact.

1 INTRODUCTION

The application of two or more building materials in one composite member is a useful procedure that may advantageously affect structural behavior, building physics properties, and durability of the respective building members. Well-known examples are steel-concrete composite girders and columns, and steel, timber or reinforced concrete girders strengthened with glass fiber or carbon fiber reinforced plastics. Another, older solution is timber-concrete composite (TCC) where timber beams are linked by special shear connectors with a plain or reinforced concrete slab. The timber beams can be arranged with or without spacing (see Figure 1) and are arranged at the compression side of the composite section. Shear connectors are usually dowel-type steel fasteners (e.g. screws, nails, bolts), notches, and combinations of notches with steel fasteners. In few cases there was a glued connection between timber and concrete, see Figure 2. The development of easy-to-handle shear connectors with simultaneously high shear capacity was the subject of many investigations within the last years (Holschemacher and Kieslich 2021, Dias *et al.* 2018, Yeoh *et al.* 2011).

First applications of TCC slabs trace back to the early 20th century. One of the first documentations on TCC systems is the patent by Müller, published in the year 1922. Over many years the most important application of TCC has been the strengthening of existing timber beam ceilings by adding a concrete slab. After years of stagnation, TCC becomes more attractive in construction of new buildings, currently. Main reason is the lower environmental impact of TCC slabs in comparison to usually preferred reinforced concrete slabs (Holschemacher and Kieslich 2021).

Recent tendencies in the development of the TCC construction method are described in the following chapters.

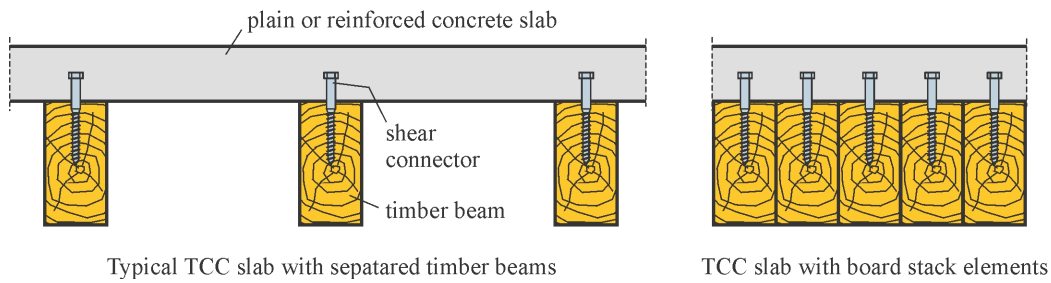

Figure 1. Typical structure of TCC slabs.

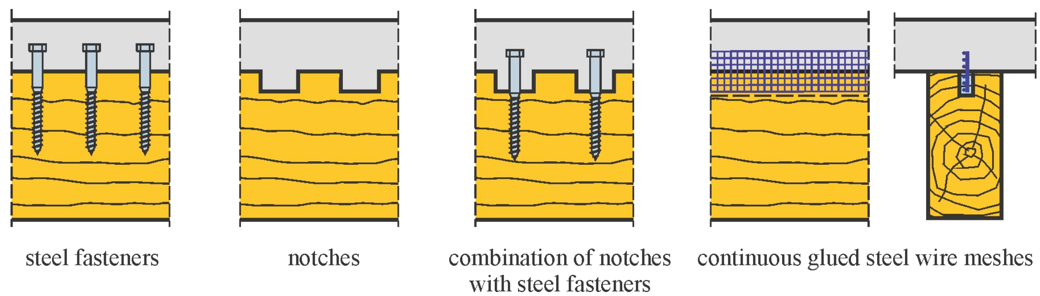

Figure 2. Typical shear connectors in TCC members.

2 STRUCTURAL BEHAVIOR

Caused by the bond between the sections' timber and concrete part, the stiffness of TCC members is much higher than the sum of the stiffness of their separate components. Thus, flexural stiffness and load-bearing resistance of TCC members are mainly influenced by mechanical properties of applied shear connectors. Caused by the limited stiffness and shear capacity of usually in construction practice applied shear connectors like steel fasteners, notches or their combination, normally only flexible bond can be realized. Therefore, a small slip between the bottom side of concrete slab and the topside of timber beams is not avoidable. Consequently, there exists a jump in the sections' strain distribution visible in the joint between concrete slab and timber beam, see Figure 3 (Holschemacher and Kieslich 2021, Yeoh *et al.* 2011).

TCC flexural members may be designed in different ways, e.g. solution of differential equation for flexible bond, strut-and-tie models, shear analogy method and Finite-element-method (Dias *et al.* 2018). For simple design situations as a single span system with uniformly distributed loads, the γ-method according to Eurocode 5 (2004), Annex B enables an easy but sufficient precise verification. When using the γ-method, the characteristic values of hardened concrete properties can be taken from Eurocode 2 (2004), those for timber from Eurocode 5 (2004).

The verification of mechanical properties of shear connectors is not included in codes, at time. Therefore, they must be defined in Technical Approvals on the basis of previously carried-out experimental investigations.

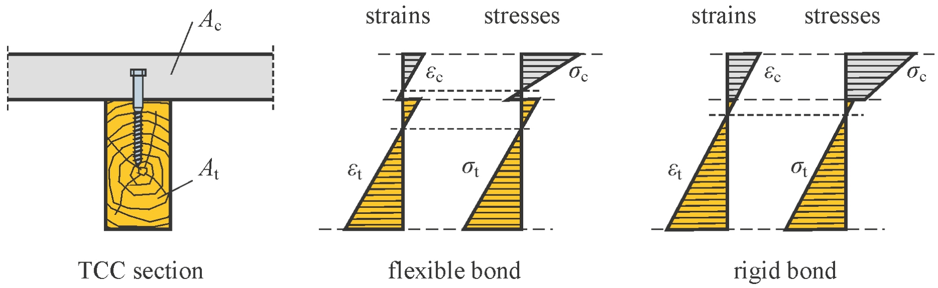

Figure 3. Strain and stress distribution for flexible bond in comparison to rigid bond.

Typical specimens for investigation of mechanical properties of shear connectors are shown in Figure 4 (Holschemacher *et al.* 2003). Based on the load F – deformation curves δ it is possible to find characteristic and design values of shear stiffness and ultimate load of the connection that may be used in the design of TCC members. Normative situation will change with the next revision of Eurocode 5. It is intended to include an approach for calculation of mechanical properties of simple shear connectors (Dias *et al.* 2018).

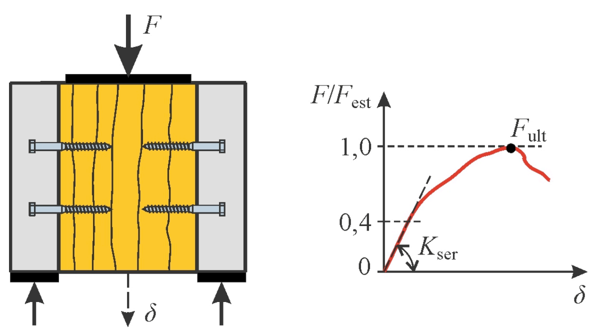

Figure 4. Experimental set-up for investigation of mechanical properties of shear connectors.

Creep and shrinkage of concrete, as well as shrinkage of timber result in a redistribution of stresses in TCC sections. Therefore, verification is needed at begin of loading (time t_0) and for completed time-dependent deformations (t_∞). An additional verification is needed because of the different temporal development of shrinkage and creep in concrete and timber around 2 – 3 years after begin of loading (Dias *et al.* 2018).

The influence of separate mechanical parameters on the flexural stiffness of a TCC section is demonstrated in Figure 5. For this, a TCC system was chosen consisting of timber beams measuring 10 cm/16 cm with a spacing of 80 cm, concrete slab with a height of 6 cm and shear connectors with a stiffness K_{con} = 20 MN/m. Moduli of elasticity were 11,000 MN/m^2 for timber, respectively 30,000 MN/m^2 for concrete. Stiffness of shear connectors, modulus of elasticity of concrete, height of concrete slab and timber beams were separately varied in a range usual for TCC members and resulting flexural stiffness of the TCC system was calculated.

It is obvious that the height of concrete slab is the most important influence parameter followed by the height of timber beams. Modulus of elasticity of concrete and stiffness of shear connectors are of essentially lower significance. However, in modern TCC structures it is attempted to reduce the height of the concrete slab to the minimum needed for load-bearing capacity, limitation of deformations, and fire resistance. One reason is the high dead load of concrete. Especially, in case of strengthening of existing timer beam ceilings the increased dead load as a result of the additional arrangement of the concrete slab is disadvantageous for supporting members like walls and foundations. The primary reason for reduced utilization of concrete in new buildings construction is the tendency to apply building materials from renewable resources such as wood. Nevertheless, concrete is a valuable and indispensible component in TCC section because of its contribution to the building physical properties, e.g. fire resistance and sound impact. Therefore, it is an optimization task to find the best possible depth of the concrete slab, whereby many different parameters must be considered.

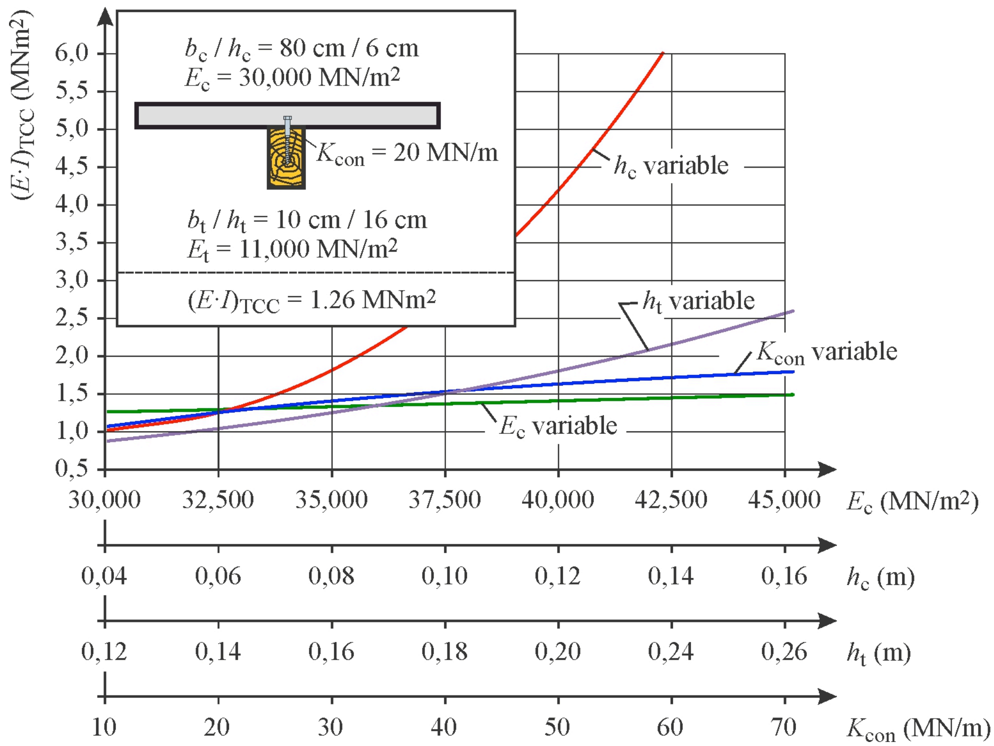

Figure 5. Influence of mechanical parameters on flexural stiffness of TCC sections.

3 OPTIMIZATION OF CONCRETE FOR TCC-APPLICATIONS

There are various requests that concrete slabs in TCC members have to meet. Main concrete stresses occur in parallel to the timber beam direction. Additionally, there are stresses caused by load distribution in lateral direction (Figure 6), single loads acting between the timber beams, lateral load sharing (Figure 7), and the function as member of the bracing system of the building. Possibility of lateral load sharing in TCC slabs is particularly useful when heavy loads are acting in the axis of only one of the timber beams. For verification of lateral load sharing effects, application of Finite-element models as well as girder grid systems have been approved.

The need of arrangement of reinforcement in the slab is often discussed. In parallel to timber beam axis concrete is almost complete under compression. A small tensile zone may be neglected by subtracting the height of the tensile zone from the total slab depth. In this case, tensile zone of concrete is considered as not load-bearing separating layer. Additionally, the influence of the separating layer on mechanical properties of shear connectors has to take into account. However, it is not reasonable to avoid reinforcement in the slab in normal design situations.

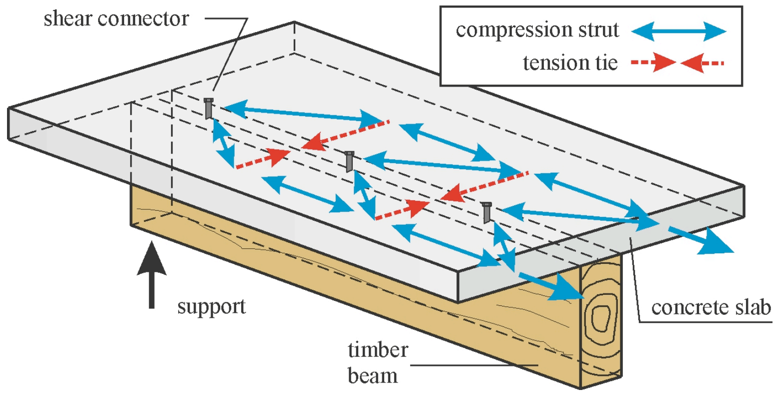

Figure 6. Lateral tensile stresses in the concrete slab.

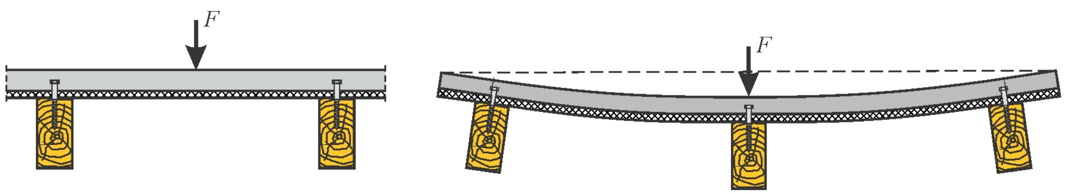

Figure 7. Influence of single loads.

Steel bar or steel mesh reinforcement needs a concrete cover and is mostly located in the middle part of the slab in close distance to neural axis. Under this condition steel strain is low and steel stress is far of yield strength. Useful alterative solutions are application of steel fiber reinforced concrete and/or textile fabrics resulting in a significant reduction of the concrete slab height because concrete cover may be essentially reduced.

For decrease of dead load of the slab, the application of lightweight aggregate concrete is recommended. Another issue is the fresh concrete properties. Utilization of self-consolidating concrete (SCC) enables a very easy casting procedure at site and has proved in many cases. SCC slabs have a very smooth and flat surface leading to decreased efforts in the following screed construction.

Regarding the building physical characteristics, the concrete slab is the most important part of TCC members. In most cases it is easy possible to achieve fire resistance class REI 60 without any special measures. It is to state that fire resistance of TCC slab is between reinforced concrete slabs and timber beam ceilings. Only in meeting high fire resistance requests there is a benefit with reinforced concrete slabs (Frangi *et al.* 2010).

4 ENVIRONMENTAL IMPACT

Environmental issues are becoming more and more important in civil engineering. It is assumed that cement production is accountable for about 8% of total CO_2 emissions (Andrew 2018). In this context it is to check if TCC slabs have advantages in comparison to comparable reinforced concrete slabs. A recent study based on the model ‘cradle to grave’ showed that the global warming potential (GWP) of TCC slabs amounts only 60% compared with reinforced concrete slabs of same span and same imposed loading. The determined GWP for TCC slabs was close to

50 kg CO_2-eq/m^2 (Hoffmann *et al.* 2021). That is an important argument for increasing application of TCC in construction practice.

5 APPLICATIONS

The main application of TCC in reconstruction of existing buildings is strengthening of timber beam ceilings. Usage of TCC results in many benefits in this context. In most cases, the bottom side of the timber beam ceiling may be unchanged when strengthening with TCC technique. This is a huge advantage, e.g. if historical buildings are revaluated (Holschemacher and Quapp 2018).

Application of TCC for erection of new structures has been strongly increased for the last 10 years. This tendency has been accelerated by the development of more efficient shear connectors and the lower environmental impact of TCC. Nowadays, even multi-storey buildings and bridges are constructed with TCC applications.

6 SUMMARY

TCC slabs are a serious competition to reinforced concrete slabs. TCC slabs provide good load-bearing behavior combined with reasonable building physical properties. They have clear advantages in their lower environmental impact. The only disadvantage may be the higher construction height in comparison to reinforced concrete slabs with similar effective length and imposed loading. Based on their beneficial properties it is to expect that application of TCC will strongly increase in future.

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