State of the art on Timber Concrete Composite floor

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Synopsis: Interest in timber-concrete composite (TCC) floors has increased over the last 20-30 years. Since the 1990's, TCC solution is seen as a viable and effective alternative to conventional reinforced concrete and/or traditional timber floors in multistorey buildings. In TCC technology, a timber beam, either solid wood, glued laminated or laminated veneer lumber (LVL), is connected to a concrete slab using a connection system that resists shear forces and impedes slip between the members of the composite section. The strength, stiffness, location and number of connectors play a crucial role for the composite action and determine the structural and serviceability performance of the floor system.

This paper discusses the state of the art of TCC structures. It presents a comprehensive review of the literature about the development and structural behaviour of TCC structures. The review addresses construction aspects and shear connection concepts. It evaluates experimental tests, finite element and numerical models. It discusses the influence of concrete elements. As recommendations, the best types of shear connection for cast in-situ and prefabricated TCC floors are put forward and assessed for criteria such as strength, stiffness, ductility and ease of manufacturing. Furthermore the most relevant numerical models are introduced. These models can be used to further the experimental results in parameters such as connections, configurations, geometrical and material properties.

Keywords: timber concrete composite, TCC, connection, short term test, FEM, prefabrication, lightweight concrete, high performance concrete, composite action, shear connection.

1. Introduction

Timber Concrete Composite (TCC) floors have been recognised as viable and effective alternatives to reinforced concrete and/or traditional timber floors. In TCC technology, a timber beam is connected to a concrete slab using a connectors, generally mechanical fasteners or shear keys, capable of transferring shear forces and impeding slip Yeoh et al.(1) .

The development and initial implementation of TCC structures was initiated by the shortage of steel in Europe during the 1920's to 1950's van der Linden (2) . Interest in TCC structures has increased again in the last 20-30 years in United States, New Zealand, Australia, Switzerland, Austria, and Scandinavian countries, where TCC solution have been used for the construction of bridges, upgrading of existing (heritage) timber floors and construction of new buildings – typically public and/or multi-storey structures Natterer et al. (3) .

One of the first investigations on full scale TCC beams was conducted at the University of Illinois, USA, between 1938 and 1942 by Richart and Williams (5) . Their research included flexural testing 32 composite beams. At the same time McCullough (6) completed bending tests on 22 full size TCC specimens for the development of cost-effective short-span highway bridges (also known as Oregon tests in the USA). From 1932 and 1952, McCullough (6) constructed and tested many short span TCC decks.

In European countries, such as Germany and Italy, TCC technology is introduced as a way for renovation and upgrading old timber (heritage) buildings, constructed in the late 19th and beginning 20th centuries, whose traditional timber floors do not comply with acoustic and fire safety requirements of the current design codes and practices Holschemacher et al. (7) and Ceccotti (8) .

Application of TCC solutions in timber multi-storey residential and commercial building received particular attention in the 1980's and 1990's. One investigation Natterer et al. (3) proposed vertical nailed planks topped a concrete slab that is connected with shear keys and stud type fasteners. Other researches for solutions applicable for floors in new multi-storey buildings have been conducted by Natterer et al. (3) and Lukaszewska (4) and Bathon et al. (9).

2. Advantages of TCC solutions

The main advantages of TCC are summarized as follows:

(1) TCC is lighter than reinforced concrete floors thus prefabrication off site and rapid erection of timber component is possible. Furthermore the lower part of the section in concrete slab is cracked and ineffective. The cracks of tensile region in reinforced concrete may cause moisture penetration and corrosion of the steel mesh Gutkowski et al. (10) , Ceccotti (11) and Yeoh et al. (1) ;

(2) TCC with well connected inter-layers exhibits triple load carrying capacity and also up to six time enhancement in flexural stiffness comparing to common timber floors Ceccotti (11) ;

(3) TCC is more efficient than conventional reinforced concrete system in term of carried load per unit self-weight. However it is less efficient than fully timber floors but it costs less Ceccotti (11) ;

(4) TCC represents large in-plane rigidity which helps floor to keep their shape during earthquake. Furthermore lower weight of TCC leads to reduction of gravity load on foundation, mass and hence seismic action Ceccotti (11) ;

(5) TCC has relatively high value of damping about 2% viscous damping ratio whilst usual timber floors have only about 1%. This characteristic provides users with more comfortable feeling Ceccotti (11) ;

(6) TCC has appropriate sound insulation characteristic. Based on enhanced mass in TCC than fully timber floors it exhibits better air-transmitted noises insulation. Furthermore as a consequence of higher damping ratio TCC shows better impact noise insulation rather than reinforced concrete floor Ceccotti (11) ;

(7) TCC exhibits better fire safety performance regarding presence of concrete layer with higher resistance against fire propagation than fully timber floor Ceccotti (11) ;

(8) TCC with timber sheets presents permanent formwork for the upper concrete. Also it results in timber as a decorative ceiling lining Yeoh et al. (1) ;

(9) TCC consists of timber as carbon-neutral material hence it has low embodied energy and also reduced CO2 emissions Yeoh et al. (1) ;

(10) TCC exhibits an enhancement in thermal mass rather than fully timber floors therefore, the energy consumption for heating and cooling is reduced; Yeoh et al. (1)

3. Construction methods

TCC floor can be constructed in three different methods as follows:

(1) Wet method as common way of pouring concrete on installed timber joint addressed in most of researches;

(2) Semi-prefabrication method (cast in-situ);

(3) Prefabrication off-site (dry-dry method) such as TCC panels prefabricated off-site and connected to the adjacent panels on site and concrete slab prefabricated off-site (Figure 1) connected with timber joists and adjacent slabs on site Lukaszewska (4) and Yeoh (12) .

3.1 Semi prefabrication

The semi-prefabricated solution proposed by Yeoh (12) consists of two separate parts (1) the M section wooden panel and (2) cast-in-situ concrete slab with the steel mesh to prevent the shrinkage(Figure 1).

“M” section panel floor with the width of 2400 mm consists of single 400 × 63 mm LVL joist on the outer edges and a double LVL joist in the centre including plywood sheets as permanent form work. The specimen with span of 8 to 10 m requires six to eight connectors along the joint aiming to provide adequate composite action.

The lightweight panel with the weight of about 1 kN facilitates a lightweight off-site prefabricated component. Such semi pre-fabricated element can transport, crane and connect to main frame with designed joist hangers. Furthermore casting monolithic concrete slab on it results in better in-plane strength and stiffness. In addition there is no need for additional connections between adjacent panels Yeoh (13) and Yeoh et al. (14) .

3.2 Prefabrication

Application of TCC with prefabricated concrete slab can overcome the disadvantages of TCC with cast in situ concrete as follows:

(1) presence of concrete as a wet component in the typically dry construction of timber;

(2) time interval for the setting of concrete;

(3) low stiffness and high creep of concrete in curing period which needs propping of beams to sustain the full self-weight of the concrete slab Yeoh (13) ;

(4) the high cost of cast-in-situ concrete slabs as a consequent of fresh concrete transportation, propping, extra self-weight of the floor due to application of formwork increases Lukaszewska (4) ;

(5) significant increases in initial deflection and flexural stresses regarding connection of timber joint to the concrete slab with a non fully developed shrinkage Lukaszewska et al. (15) ;

(6) potential problems of quality control Lukaszewska (4) .

In Lulea University, Sweden Lukaszewska (4) developed some level of prefabrication in terms of ‘‘dry’’ connections Lukaszewska et al. (15) . In this novel composite system, the timber joint has been connected to prefabricated concrete slab with the embedded mechanical connectors i.e. coach screws, metal plates (glued or nailed), dowels and toothed metal plates(Figure 3 (a)) Lukaszewska (4) . It has been concluded that prefabrication system has represented equally well as “wet” common system and as the connection solution the coach screw plus notch has exhibited better structural performance.

As the design point of view two major differences are recognized between the prefabricated and the cast-in-situ construction methods of TCC: (1) higher value of MOE in prefabricated concrete rather than cast in situ concrete; (2) markedly lower value of shrinkage, creep and swelling in prefabricated concrete TCC rather than cast in situ concrete Lukaszewska et al. (15) .

In Germany a fully prefabricated TCC panel has been introduced by Bathon and Clouston (16). This prefabricated system can compete with reinforced concrete and steel-concrete composite floors (Figure 3 (d)) Yeoh et al. (1) and Bathon and Clouston (16) .

In Finland, two TCC prefabricated systems with nail plates connectors were developed for multi-storey buildings. The first system was a cast in-situ floor whilst the second prefabricated floor represented concrete casted upside down in factory without framework Yeoh et al. (1) .

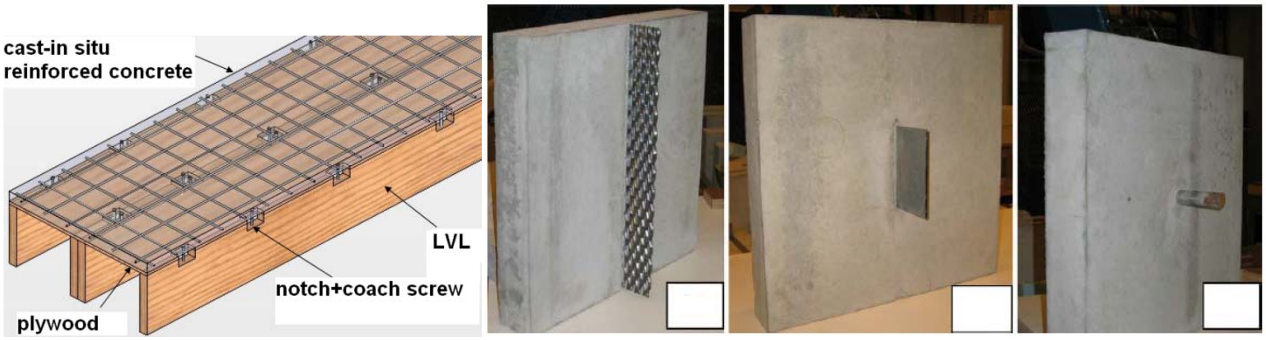

Figure 1 Semi-prefabricated TCC on left Yeoh(12) and prefabricated slab on right Lukaszewska(4).

4. Connection solutions

Effectiveness of shear connection solutions are evaluated in terms of their strength, stiffness and failure mode using shear test. The strength refers to maximum load capacity whilst the failure mode exhibits ductile behavior of connection. In addition the stiffness of connection indicates the resistance to slip at interface of timber and concrete.

The idea behind TCC is to use the capabilities of both timber and concrete materials efficiently. Hence, the Concrete component resists compression force whilst the timber member carries tension and flexural forces.

Furthermore, Since both concrete and timber exhibit quite brittle behaviour in tension and compression respectively, plasticization of shear connection is highlighted as the only source of ductility van der Linden (2) and Ceccotti et al. (17) .

There are two lower (none) and upper bounds (full) of composite action. The lower bound refers to layers which are not connected together and work quite independently whilst the upper bound represents a rigid connection without relative slip. Furthermore, most of commonly used shear connections exhibit a partial composite action with some relative slip at interlayer. Furthermore, most TCC structures exhibit partial (not full) composite action and this adds to the complexity of the system Clouston et al. (18) . TCC floor with larger composite efficiency reduce the beam depth and in contrary the medium to long span floors (7 to 15 m) are achieved Yeoh (12) . Gutkowski et al. (19) proposed Equation 1 to evaluate the composite efficiency of TCC beam.

$$E = \frac{D_N\text{-}D_I}{D_N\text{-}D_C} \tag{1}$$

where, D_N is the theoretical fully non-composite deflection, D_C the theoretical fully composite deflection and D_I is the measured deflection for partially composite action of the specimen Gutkowski et al. (19) .

The shear connections can be classified into different groups such as glued/non-glued , prestressed/non-prestressed , discrete/continuous and vertical/inclined Yeoh et al.(1) . Generally the shear connections are classified into four groups as: (a) dowel-type, (b) tubular-type,(c) notches(shear keys)with an anchoring device (post-tensioned bolt or lag screw) and (d) (dis)continuous glued-in-wood plate Clouston et al.(18) .

4.1 Mechanical connections

The research by Ahmadi and Saka (20) identified the feasibility of TCC floor constructed from high strength nails in residential and commercial building. In this investigation ten types of high strength nail were tested using push out, bending, and long-term tests on full scale specimens. In addition a FE model was implemented to verify the results of experimental tests. Comparing of non-composite and partially composite TCC, proposed partially composite beams exhibited two times higher load carrying capacity and one-fifth of deflection than non-composite system. It was concluded that application of appropriate connections in TCC structures increases the stiffness and load carrying capacity of floor. Hence, at least a 50% saving in the cost of the timber joists comparing with non-composite floors is achieved Ahmadi and Saka (20) .

In 1992 a major R&D project commenced at Delf University and University of Karlsruhe aiming to study the load bearing capacities of TCC floors. A number of shear connections such as inclined SFS screws, with an interlayer of particleboard, 90 angled nailplates (Figure 3 (b)), reinforcement bar with a concrete notch and grooved connections have been tested using push-out and bending tests on full scale specimens.

It was found that TCC beams exhibited a plastic behaviour before ultimate collapse contrary to timber beam with brittle failure in tension zone. Ductility of connectors resulted in occurrence of the plastic hinges in outer connectors, hence the load redistributed to the adjacent connectors until they behaved as plastic hinge. The dominant failure mode of TCC beams was combined bending and tensile failure of the timber component van der Linden (2) and Lukaszewska (4) .

Ceccotti (8) also presented an overview of most commonly used shear connections to achieve composite action between the concrete and the timber members. The selected shear connectors have been tested using push-out tests and classified according to their stiffness as follows: elements connected by nails, screws or dowel shaped fasteners (a) with the lowest stiffness; the rigidity can be increased by surface connectors (b); or by cutting the notches along the timber joint (c); or as continuous glued to timber connector which presents highest stiffness with full composite action and neglected slip (d) Ceccotti (11) .

Piazza and Ballerini (21) identified the mechanical properties of TCC specimens constructed from eight different types of connection and subjected to push-out and bending tests. Furthermore, some numerical analyses were done to verify the influence of the connection systems on the mechanical behaviour of the composite beams.

Two types of glued-in connections such as 16 mm diameter bent dowels and concrete stocky dowels coupled with 16 mm diameter steel ribbed dowels (Figure 3 (c)) have been tested using bending tests on full scale TCC beams. These connectors exhibited a quite linear response up to 50% of the failure load followed by a post-elastic hardening branch. The composite efficiency of 70% and 85% was obtained by hardening branch of bent dowels and concrete dowels respectively. The bending strength of bent and concrete stocky dowels applied in TCC were measured about 2.0 and 2.5 times larger than that of timber beams, respectively. Lukaszewska (4) and Piazza and Ballerini (21) .

Bathon and Graf (22) has introduced the continuous glued-in metal plate at FH Wiesbaden – University of Applied Sciences, Germany. In this novel connection, the steel mesh embedded in a concrete slab was inserted into a continuous slot in the timber beam and bonded by an adhesive (Figure 3 (d)). It was found that this continuous connection exhibited a rigid stiffness in elastic branch followed by a ductile post peak. Furthermore, TCC beams with continuous connectors presented a near full composite action with 97% effective stiffness and 99% strength of that of a fully composite beam Bathon and Clouston (16) Clouston et al.(23) . Elsewhere Clouston et al. (17) has applied the same continuous connectors for use with U.S. manufactured products.

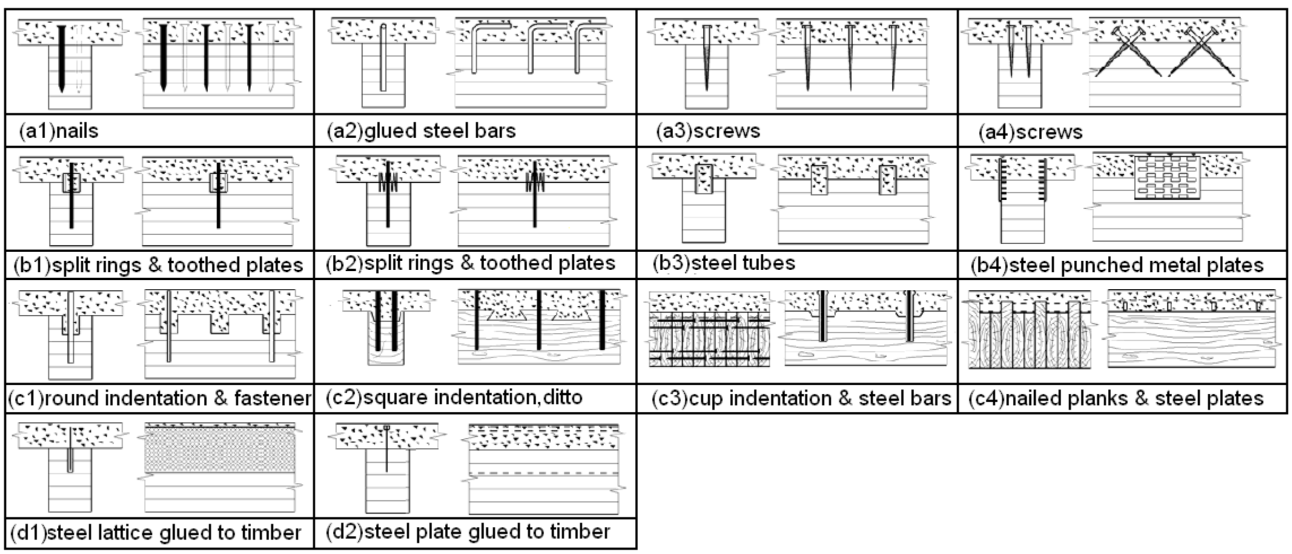

Figure 2 Overview of TCC connections Ceccotti (11) and Lukaszewska (4).

Extensive experimental and numerical investigations on mechanical properties of TCC joints have been undertaken by Dias(24) at University of Coimbra, Portugal. TCC joints constructed from dowel type fasteners and glued to timber notches (Figure 3 (e)) were subjected to eight series of short-term and long-term shear tests. The differences in test series were about the material properties of timber or concrete, diameters of fasteners and presence of interlayer.

In addition numerical investigations were implemented to simulate and predict various mechanical properties of TCC floor. It was concluded that the ultimate load capacity of joints depends upon material properties of timber, connections and concrete whilst the stiffness of joint is influenced by material properties of timber.

Furthermore, the glued technology and notch joints exhibited the highest stiffness whilst the mechanical fasteners i.e. nails and dowels were identified by lowest stiffness Dias (24) .

Deam et al. (25) at the University of Canterbury, New Zealand investigated on the feasibility of composite structure consisted of laminated veneer lumber (LVL) beam, concrete slab and shear connections -aiming to identify the most cost effective connection systems.

A number of shear connections such as round and rectangular concrete plugs with and without steel pipe or screws reinforcement, SFS screws, coach screws with different diameters, sheet brace anchors, and framing brackets (Figure 3 (f)) have been tested using push-out tests on full scale specimens Deam et al. (25).

Deam et al. (25) summarized the main conclusions of the experimental program as follows:

(1) The concrete plugs reinforced with a screw or steel pipe exhibited the best stiffness, strength, and post-peak behaviour. The screw reinforcement enhanced the strength and post-peak behaviour;

(2) The strength and stiffness of these connection systems depended upon the bearing area , hence a rectangular plug exhibited higher composite action rather than a smaller round plug;

(3) The rectangular concrete plug reinforced by a coach screw spaced 500 mm along the beam was found as a capable solution with highest stiffness and ductility for 8 m span floor; Deam et al. (25)

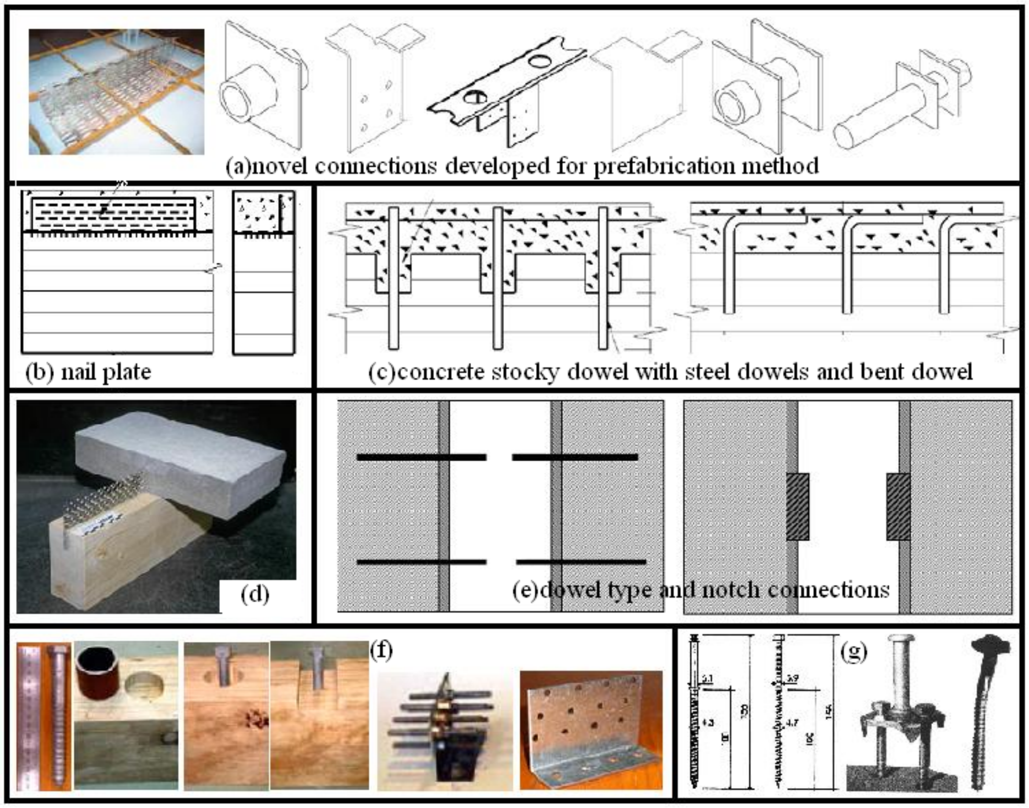

Figure 3 Different connection systems (a) Lukaszewska (4),(b) van der Linden (2),(c) Piazza and Ballerini (21),(d) Bathon and Graf (22),(e) Dias (24),(f) Deam et al. (25) and (g) Steinberg et al. (41).

4.2 Adhesives connections

However the mechanical connections are commonly used in TCC floor but an adhesive connection is also possible. Application of adhesive material in interface of timber and concrete has been addressed and investigated in many researches such as: Pincus (26) and Pincus (27) , Brunner et al. (28) , Brunner and Schnüriger (29) , Schober and Rautenstrauch (30) , Ceccotti et al. (17) , Negrao et al. (31) and Negrao et al. (32).The main drawbacks of mechanical fastener such as: limited stiffness of the connectors, extensive drillings and mountings, force concentration may be overcome by application of adhesive bound as a slip-free and force distributed connection Negrao et al. (32) .

Pincus(26) investigated on feasibility of an epoxy resin compound in TCC. It was found that pouring immediately fresh concrete on still wet adhesive has resulted in an efficient rigid connection with negligible slip before final failure. Furthermore, application of nail fastener in bounded TCC increased the shear capacity of joint up to 50% Lukaszewska (4) .

Esewhere Brunner et al. (28) and Brunner and Schnüriger (29) studied the possible displacement of the adhesive when the fresh concrete was poured onto the wet adhesive. In this delicate process important factors such as: concrete type, falling height and adhesive stiffening time were investigated and optimised. Negrao et al. (32) concluded four major reasons of limited investigations on adhesive solution as follows:

(1) The brittle failure of bonded layers;

(2) delimination damage due to different hygroscopic behaviour of timber, adhesive and concrete;

(3) the fire behaviour.

5. Design and codes

The connection between timber and concrete is not fully rigid and there is some relative slip. Therefore, the assumption of plane section remaining plain and the transformed section method are not applicable in design of TCC Clouston and Schreyer (33) .

the "Gamma method" in Eurocode 5 part 1 CEN(34) annex B CEN(12) has recognised as the specific design provision of TCC Yeoh et al. (1) . The Gamma method has implemented an elastic analysis for the short-term (instantaneous) verifications whilst a simplified method called "Effective Modulus Method" has been proposed to consider the effect of creep for the long-term verifications of Gamma method. Stiffness or slip modulus of the connection is one of the key parameter in design of a TCC beam.

In Gamma method two slip moduli of K0.4 and K0.6 represent the non-linear behaviour of connection systems in the serviceability limit state (SLS) and ultimate limit state (ULS) Ceccotti (11) .

Usually the design parameters of shear connectors such as the stiffness and the load capacity are obtained using shear tests but Eurocode 5 provides the guidelines to evaluate the design parameters of dowel-type fasteners inserted perpendicular to the shear plane Lukaszewska (4) and CEN (34) .

6. Short term shear test

Effectiveness of shear connection solutions are evaluated in terms of their strength, stiffness and failure mode using shear test. Herein the maximum load carrying capacity and slip at interface of composite materials are measured precisely then plotting load-slip curve, the slip modulus or stiffness of connection can be obtained Kuhlmann and Michelfelder (33) .

Short term shear test are implemented in two ways as follows:

(1) symmetrical with two sides concrete slabs connected to timber beam at middle;

(2) asymmetrical (also called push out)in which one concrete slab connected to the timber beam.

Comparing symmetrical and asymmetrical tests, the asymmetrical specimens are lighter and cheaper. Furthermore, in asymmetrical test overturning moment of the axial forces with eccentricity increases the compression force at interface, hence higher compression force results in larger mechanical properties van der Linden (2).

7. Short term bending test

Short term bending test is implemented to measure the composite efficiency, load bearing capacity and failure mode of floor Yeoh et al. (1) . In bending test vertical load is gradually increased to failure and in each loadstep corresponding mid-span deflection is measured and consequently the load- deflection curve at mid-span is plotted Clouston et al. (18) .

8. Numerical models

The numerical model consists of analytical equations and finite element models (FEM). Non-linear FEM analysis is powerful tool to predict the behaviour of TCC construction Dias et al. (36) Lukaszewska et al. (37).

Kuhlmann and Michelfelder (35) and Kuhlmann and Aldi (38) in University of Stuttgart modelled grooved connection subjected to shear test. However the numerical simulation exhibited a good agreement with experimental failure mechanism but the stiffness and the ultimate load capacity of connector were overestimated by the simulation. Lack of softening in timber material model probably caused this deviation in load carrying capacity Kuhlmann and Michelfelder(35) and Kuhlmann and Aldi(38) .

Dias et al. (36) implemented a 3D non-linear FEM models to predict mechanical properties of dowel type fasteners. Whilst an Isotropic model was used to model Steel and concrete materials, timber was modelled by an orthotropic model. In addition the interaction between materials was modelled by contact elements with friction. Comparing the experimental and numerical results, it was concluded that the initial stiffness and maximum load capacity were overestimated by the numerical models. The assumption of a yielding strength equal to the embedding strength of timber might cause the overestimated load carrying capacity. Furthermore the perfect linear elastic behaviour probably resulted in higher linear stiffness Dias et al. (36) .

Elsewhere, Lukaszewska (4) used FEM to extend the outcomes of the experimental tests to composite beams with four connectors such as: u shape steel plate welded to a long punched metal, lag screwed into steel tubes, long punched metal plate and inserted steel tubes (Figure 3 (a).

The results of nonlinear FE modelling were very similar to the results of experimental tests particularly in short term. Therefore it can be concluded that FE models are useful to extend the experimental results of composite floor with different geometrical and mechanical properties Lukaszewska et al. (37) .

9. Influence of concrete properties

However normal concrete has been used in most of investigations on TCC floor but there are few researches about the effect of concrete properties on structural behaviour of TCC Kieslich and Holschemacher(39) . Based on the application of admixtures and additives mix design of concrete has been modified into innovative high performance concretes such as: Light Weight Concrete (LWC), Fibre Reinforced Concrete (FRC) and Self Compacting Concrete (SCC) Kieslich and Holschemacher(39) .

Comparing LWC and normal concrete, LWC causes larger shrinkage strains and lower MOE in TCC floor. Hence, deflection is expected to be increased.

On the other hand the nominal reduced creep coefficient and lower dead load of LWC may result in lower values of deflection. Therefore the question about reliability of replacing normal concrete with LWC cannot be answered directly Jorge et al. (40) .

Steinberg et al. (41) tested 5 different types of shear connection (Figure 3 (g)) using push-out tests on full scale specimens casted by LWC with the density of 1.6 KN/m3. Application of LWC slab reduced the deadload of TCC floor about 15%. Hence, it is appropriate for renovation and upgrading of existing timber floors.

It was concluded that the MOE of LWC reduced the composite efficiency and effective bending stiffness of floor. Therefore, the spacing of connectors in LWC must be less than normal weight concrete. The design depends upon the compromise between the lower spacing of the connectors (higher cost) and the reduction in permanent load of lightweight concrete Steinberg et al. (41) .

TCC specimens with LWC slab exhibited failure in concrete while in most of TCC investigations using normal concrete the predominant failure mode occurred as shearing off or withdrawal of the connector. The failure in connection allows that altering dimensions of the screws governs the failure. Furthermore the application of light weight concrete in TCC requires an evaluation of the anchorage potential of the connectors in concrete Steinberg et al. (41) .

Grantham et al. (42) investigated on application of LWC made from recycled sewage sludge in upgrading of timber floor. Existing timber floor casted by LWC with a density of 1760 kg/m3 has been tested using full-scale long-term and collapse test. It was concluded that LWC exhibited a favourable lower self weight and high strength. On the other hand LWC represented a larger sensitivity to rheological phenomena compared to normal weight concrete Yeoh(12) .

Fragiacomo et al. (43) tested Tecnaria connectors using push-out tests on 18 specimens constructed by LWC and normal concrete at University of Trieste. It was found that application of LWC rather than normal concrete did not affect the stiffness Yeoh et al. (1) and Fragiacomo et al. (43).

Jorge et al. (40) implemented push out test on specimens constructed by SFS screws and LWC. A strength reduction of 30% and 50% for the specimen without interlayer were observed whilst in case of presence of interlayer the reductions were smaller. This is promising for renovation and strengthening purposes that the floor board acts as interlayer.

However the application of LWC in TCC beams reduced the strength, but the stiffness is maintained approximately constant. The stiffness is more relevant to design than load capacity. Therefore the difference between lightweight and normal concrete seem to be negligible in short term Jorge et al. (40) .

Holschemacher et al. (7) at Leipzig University of Applied Science investigated on application of Steel Fibres Reinforce Concrete (SFRC) in TCC. In the investigation 160 mm normal screws were applied in 3 test series such as: (1) plain concrete with concrete key (2) SFRC with concrete key and (3) SFRC -aiming to study the effect of shear key and SFRC rather than steel mesh reinforced concrete.

Comparing normal concrete and SFRC, application of SFRC with concrete key increased the ultimate load capacity 30% whilst the initial slip was reduced about 60%. Steel fibres did not need any concrete cover therefore the thickness of concrete slab was reduced about 3.5 cm. It was concluded that application of steel fibres has no important effect on strength and MOE of TCC joints. Furthermore the crack initiation and development in concrete was delayed and the stresses distributed more uniformly Holschemacher et al. (7) . As a drawback steel fibres may wear out the concrete pump and pump-line Kieslich and Holschemacher(39) .

Kieslich and Holschemacher(39) proposed the application of innovative high performance concretes such as: Self Compacting Concrete (SCC), Fibre Reinforced Concrete (FRC), Lightweight Concrete (LWC), High Strength Concrete (HSC) or combinations of them in TCC -aiming to study easy workable mixture with lower dead load and shrinkage strain.

LWC with porous lightweight aggregates was applied in TCC to reduce dead load of floor. The effect of the MOE of concrete on the effective stiffness (EI) of TCC beam versus the level of connection (γ) was investigated. It was found that the LWC slab with higher value of MOE and same thickness increased the effective stiffness (EI) of TCC. The proposed values of the MOE for concrete were obtained from the German standard DIN1045(44) whilst the real value strongly depends upon the type and MOE of aggregates. The main drawback of the LWC is the characteristic of sucking some part of the concrete's water which has to be considered in mixing ratio Kieslich and Holschemacher(39) .
Compressive strength, post-cracking behaviour and dry density are more interested as main hardened concrete properties whilst workability, compatibility and pumpability are known as fresh concrete properties Kieslich and Holschemacher(39) .

Based on good workability and flowability Kieslich and Holschemacher(39) proposed SCC for renovation of old building with complex formworks, high reinforcement ratios and little space for compacting measures. SCC exhibits a sensitive behaviour to the variability of the source materials and has higher amounts of finest grain such as cement, fly ash and limestone flour. Furthermore it shows higher shrinkage, hydration heat and an extra compressive strength which results in higher minimum reinforcement.

The higher compressive strength of cement matrix rather than the lightweight aggregates causes high brittleness in LWC. In contrast to LWC, the cement matrix of normal concrete exhibits a lower compressive strength rather than the aggregates Kieslich and Holschemacher (39) .

Kieslich and Holschemacher (39) proposed a mix of Poly venyl alcohol-Fibres (PVA) into Dry Lightweight Concrete (DLWC) –aiming to modify high brittleness. The important concerns about the combined high performance concrete are summarised as follows: (1) problematic Pump ability using porous light weight aggregates and (2) uniform distribution of fibres in concrete. Five different mixtures of two types of fibres with the dry density of 1600 kg/m³ were tested using bending test. It was concluded that increasing fibre content using both fibres load bearing capacity improves Kieslich and Holschemacher (39) .

Leborgne and Gutkowski (45) studied the negative effect of poor consolidation, moisture loss, transverse shrinkage cracks of the concrete and swelling of the wood on composite action of TCC floor. Moisture absorption from the concrete into wood was reduced by painting the specimens with water proofing paint and as a consequence the swelling of the wood was mitigated. Furthermore a self-levelling concrete was utilized with a design compressive strength of 34.5 MPa and a slump of 279.4 mm to modify consolidation.

Two types of Nylon and Type I steel fibres admixtures were tested using ultimate bending test on12 full size specimens constructed with Hilty shear key connectors and notches. The dominant failure mode was observed as a combination of bending and tension failure at mid span. The composite efficiency of specimens did not vary significantly. The average composite efficiency of 12 specimens was 83.4% LeBorgne and Gutkowski (45) .

10. Conclusions

Interest in TCC floors as a viable and effective alternative to conventional reinforced concrete and/or traditional timber floors in multistory buildings has increased over the last 20-30 years.

This paper has discussed the state of the art of TCC structures. It has presented a comprehensive review of the literature about the development and structural behaviour of TCC structures. The history behind and various advantages of TCC have been introduced.

In addition three different construction methods of TCC such as (1) wet method; (2) Semi-prefabrication method (cast in-situ) and (3) Prefabrication off-site (dry-dry method) have been discussed. Furthermore through the most important literature different shear connection solutions i.e. mechanical fasteners, continuous steel mesh, notches and adhesive bond have been quoted.

As the specific design provision, the Gamma method proposed in Eurocede 5 part 1 annex B has been introduced. Furthermore various FE models developed around the world to extend the experimental results and parametric study have been reviewed briefly.

Finally applications of innovative high performance concretes such as Light Weight Concrete (LWC), Fibre Reinforced Concrete (FRC) and Self Compacting Concrete (SCC) in TCC have been identified.

It is conclude that further investigations on economical shear connections with high mechanical properties and prefabrication process with application of light weight concrete can introduce TCC to construction industry as a competitive alternative flooring system.

11. Acknowledgement

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