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A NEW BUILDING STRUCTURAL SYSTEM USING TIMBER-CONCRETE-COMPOSITE MEMBERS

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ABSTRACT: This paper presents a novel system for the construction of building structures based on the use of timber-concrete-composite pieces (floors, beams and columns). Beams and floors are composed of a prefabricated lower glued laminated timber (GLT) flange glued to one or more plywood ribs that are linked to an upper concrete slab poured in situ using an efficient timber-concrete connection of holes made on the ribs.

An extensive experimental campaign was carried out to validate the solution: shear tests of wood-wood and wood-plywood glue line; delamination tests of wood-wood and wood-plywood glued planes; shear tests of the timber-concrete connection with different configurations; finally, full scale four-point bending tests of simple supported beams and three-point bending tests of pieces in an overhanging configuration.

In order to know the performance of the system, sizing curves using the Gamma Method were developed. Results indicates a light, slender and high stiffness structural solution very suitable to be used in building construction.

KEYWORDS: Timber-concrete-composite, structural building systems, timber flooring, mixed beams, shear connection

1 INTRODUCTION

The advantages of the timber-concrete structural solutions are well known and are referenced in many papers [1-3]. A suitable design of timber-concrete composite (TCC) sections allows to take advantage of the properties of both materials to achieve a more efficient structural solution than only-timber structures with lower self-weight than only-concrete solutions.

The behaviour and performance of these systems fundamentally depends on the efficiency of the shear connection between both materials. This efficiency is based on achieving a high strength against shear forces with low slip of the connection; thus achieving a high composite effect and a ductile behavior. The state of the art includes different timber-concrete connection systems such as steel fasteners and plates, glued solutions, or the mechanical transmission of forces through the use of notches, grooves or slots in the wood [4-7]. These connections show very different characteristics in strength, stiffness and ductility of the joint.

This paper describes a complete solution for the construction of building structures using perforated plywood or laminated veneer lumber (LVL) as timber-concrete connection. The paper contains a summary of the different experimental campaigns carried out to validate the behaviour of the system. This includes not only the experimental analysis of the connection but also bending full-scale tests of simply supported beams and pieces in a an overhanging configuration. Results obtained allow to conclude the high strength and stiffness behaviour of the system proposed.

2 DESCRIPTION OF THE SYSTEM

The system is based on the use of prefabricated timber pieces complemented with concrete poured in situ [4]. The system is composed of the following elements:

Floors. The floor is formed by prefabricated T or π shaped pieces composed by a lower flange of glued laminated timber (GLT) glued to one or more perforated plywood or LVL ribs (Figure 1). The connection between this pieces and the upper concrete slab is made using the holes filled by the in situ poured concrete.

Beams. The beam solution is very similar to flooring pieces. A π-shaped piece composed by a lower GLT flange glued to two perforated plywood or LVL ribs which ends are machined to conform the connection to the columns. The use of reinforcement bars makes it possible

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to create an efficient semi-rigid connection with the columns.

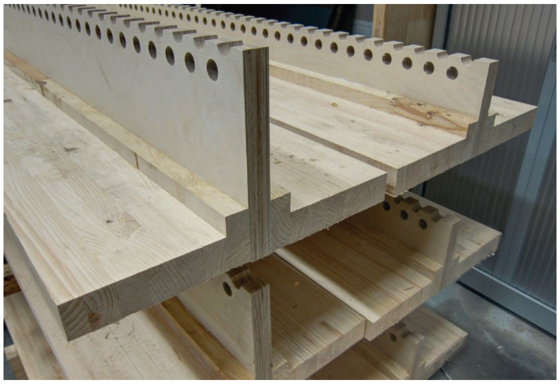

Figure 1: *Prefabricated T-shaped flooring pieces with different heights*

Columns. The columns are composed of a perforated plywood box section that satisfied two objectives: formwork of the concrete and support the flooring structure during the period in which the concrete is not sufficiently strong.

Figure 2 shows a computer-generated image of the complete system using cardboard blocks as infill formwork during the concrete pouring.

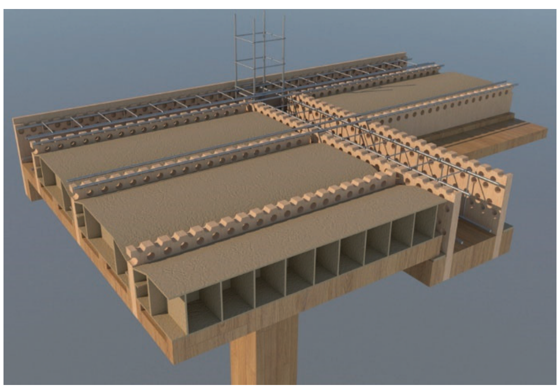

Figure 2: *Image of the complete system*

3 TEST CAMPAIGN

In order to validate the solution five test campaigns were carried out.

3.1 SHEAR TEST IN THE GLUE LINE

96 glue lines (72 wood-wood and 24 wood-plywood) of 8 samples of 390x50x50 mm, consisted of 7 *Picea abies* wood layers, strength class GL28h, and 2 birch plywood layers glued at both ends, were tested according to the UNE-EN 14080:2013 (Figure 3).

The results showed the efficacy of the connection in terms of strength with an average value of shear resistance of 9.63 N/mm^2 for wood-wood glue line and 7.16 N/mm^2 for wood-plywood glue line [8].

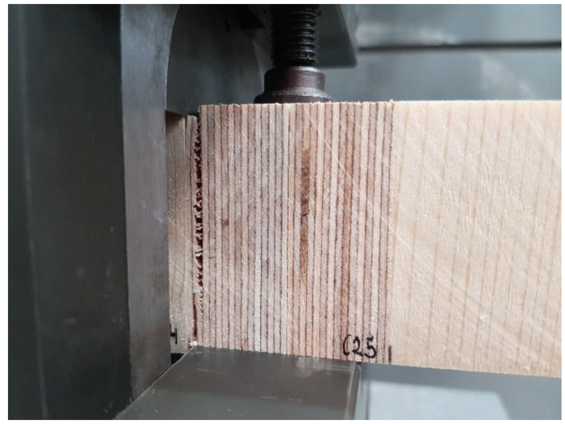

Figure 3: *Shear test in the glue line*

3.2 DELAMINATION TEST IN THE GLUE LINE

32 glue lines (24 wood-wood and 8 wood-plywood) of 8 samples of 195x75x77 mm were tested according to the UNE-EN14080:2013 (Figure 4). In 79.2% of wood-wood lines and in 62.5% of wood-plywood lines no delamination occurs. In the other lines average delamination was of 8%. Consequently, the results guaranteed the integrity of the glue lines [8].

Figure 4: *Delamination test in the glue line*

3.3 SHEAR TEST OF TIMBER-CONCRETE CONNECTION

An experimental analysis of the shear connection was carried out using push-out shear test according to EN 26891:1992 (Figure 5).

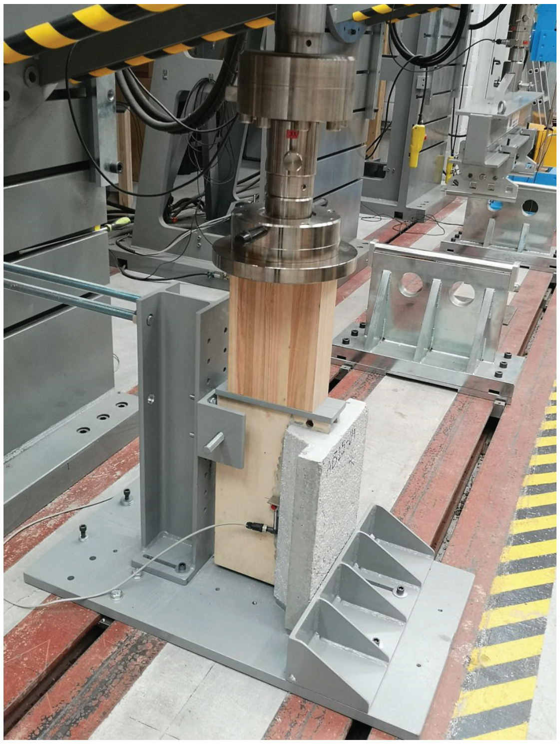

Figure 5: *Push-out shear test of timber-concrete connection*

Twelve samples of 480x300x300 mm were tested in a first campaign. Six of specimens were constituted with two 15 mm thick birch plywood boards joined to a 50–120 mm thick concrete slab. In the other six specimens the thickness of the boards was increased to 21 mm. 3 reinforcement bars of 8 mm, B500S steel grade, were placed in concrete slab crossing the upper file of holes of the board.

A second campaign was carried out with 45 samples of nine types of specimens in which different parameters were analysed: configuration of boards (one of 42 mm thick or two of 21 mm thick each one), holes disposition and diameter (2 rows, 20 mm diameter and 50 mm spacing or 1.5 rows, 30 mm diameter and 62 mm spacing), and use or not of B500S grade steel reinforcement bars.

Tests results show a very high stiffness and consequently a favourable composite action with k_{ser} values from 283.5 to 887.7 kN/mm per unit length depending of different configurations analysed [8, 9]. Moreover, load-slip curves for each tested showed a ductile failure that is a very positive characteristic in TCC solutions (Figure 6).

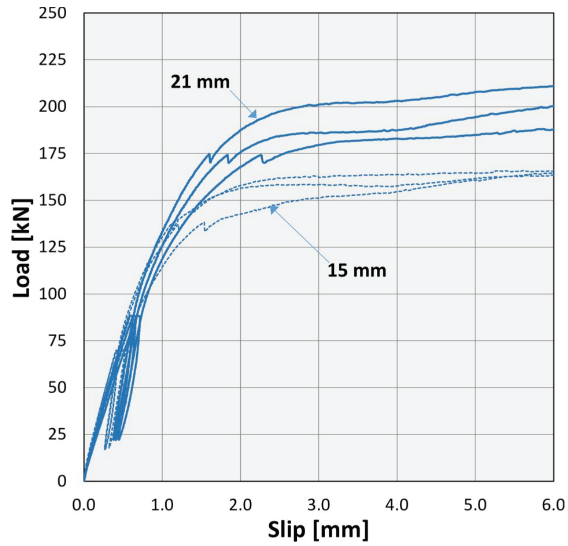

Figure 6: *Load-slip curves of specimens with two birch plywood boards of 15 mm and 21 mm thick.*

3.4 FULL SCALE FOUR-POINT BENDING TESTS OF SIMPLE SUPPORTED TCC BEAMS

Based on the results obtained in the shear test connection analyzing different parameters, the solution of a single 40 mm thick board with 1.5 rows of 30 mm diameter roles and 62 mm spacing has been chosen. This configuration combines efficiency and simplicity.

Full scale four-point bending tests of nine simple supported TCC beams according to standard EN 408:2010+A1:2012 were carried out with 3 different configurations: 3 samples of 6 m span and a height of 25 cm; 3 of 7.2 m and 30 cm; 3 of 8.4 m and 35 cm. In all cases the slenderness ratio was L/24 (been L the span of the beam).

The specimens consist of an inverted T-shaped piece formed with a 600x60 mm glulam flange made with *Picea abies* GL24h and a 40 mm thick birch plywood board with 30 mm diameter perforations. This board is joined to an upper concrete slab of 600x50 mm with polyolefin macrofibres added. Compression test of concrete specimens provided a mean strength value of 39.9 N/mm^2 at 28 days. 8 mm diameter and 120 mm long rebars were inserted through every three perforations of the boards (Figure 7). Additionally, a 200x200 mm ϕ6 mm steel mesh was placed to control cracking caused by shrinkage of concrete. Light cardboard blocks were designed to acting as lighten infill and formwork during the concrete pouring.

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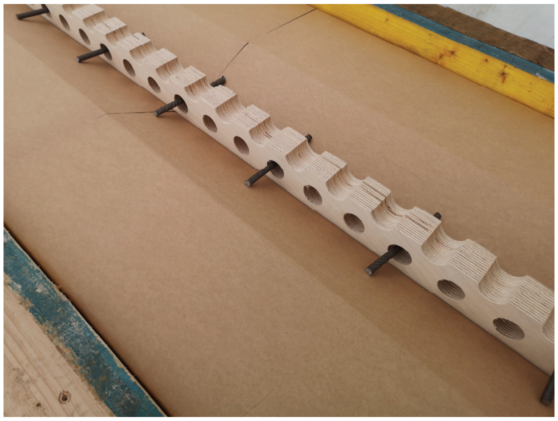

Figure 7: Specimen with carboard bloks and rebars positioned previously the concrete pouring of 50 mm thick upper slab. In the photograph, the steel mesh has not yet been placed.

Figure 8: Bending test of a 7.20 m span specimen

The lowest ultimate load value obtained in the tests corresponds to a total equivalent surface load of 39.04 kN/m^2, which represents a value 7.8 times higher than the total load of floors for residential use (self-weight+light partitions and finishes+ variable load=5.0 kN/m^2) [10].

Failure occurs suddenly, affecting the glulam flange of the central part of the beam in areas of knots or finger joints and extending due to longitudinal shear failure up to the beam supports (Figure 9).

The most unfavorable relative deflection obtained for service load of all samples tested was L/1069 for a total service load of 5.00 kN/m^2 and L/573 for a load of 9 kN/m^2 (been L the span of the beam), that would correspond to a building for public use. Therefore, the results indicate a high bending stiffness of the pieces and the effectiveness of the composite action despite the high slenderness of the pieces (L/24) and the unfavorable configuration that represents, from the point of view of the deformations, the simply supported beams condition [10].

Figure 9: Longitudinal failure of the glulam flange

3.5 FULL SCALE THREE-POINT BENDING TESTS OF TCC PIECES IN A AN OVERHANGING CONFIGURATION

One of the outstanding advantages of the developed system is that it allows the construction of floors and beams with pieces serving several spans or in an overhanging configuration. This results in a more efficient use of materials thanks to a more favorable distribution of bending moments and better behaviour in service at the deformation level. Three–point bending tests were carried out of eight specimens to evaluate the behavior against negative bending. 3 with a height of 250 mm an a overhanging span of 1.5 m; 3 with a height of 300 mm an a overhanging span of 1.8 m and 2 with a height of 350 mm an a overhanging span of 2.1 m. A slenderness ratio of L/6 was adopted in all cases.

Figure 10: Specimen with the steel mesh and the rebars positioned in the area of negative bending moments.

The specimens tested have the same section and material characteristics as those already described for the four-point bending tests, with the only difference being that there is a reinforcement in the area of negative bending moments made up of two 12 mm diameter rebars (Figure 10).

Figure 11: *Test of 1.80 m overhanging span specimen*

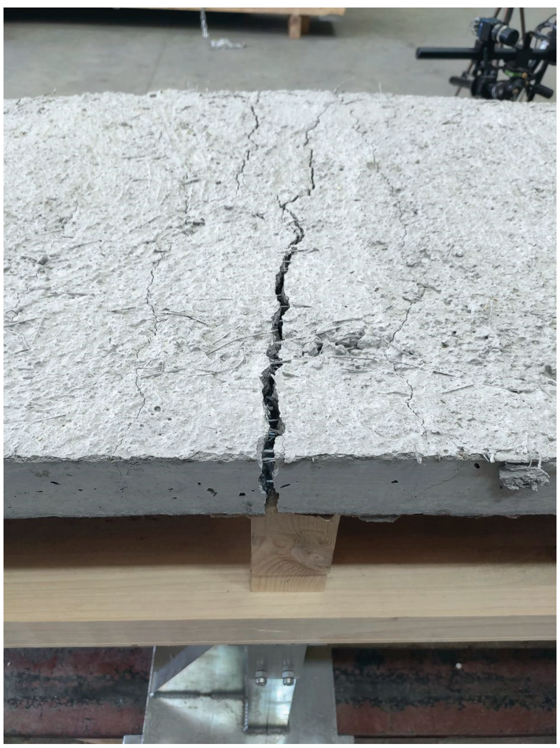

Figure 12: *Cracking process in the concrete upper slab*

Two types of failure modes have been observed in the tests: tensile failure of plywood rib in three of the specimens and shear failure at the glulam joint between flange and plywood rib in the remaining five pieces. In all cases, when load is approaching to the ultimate load value, an important cracking process of concrete slab occurs (Figure 11).

The lowest value of ultimate load obtained for all specimens tested was 8.03 times the design load considered for residential buildings (5.0 kN/m^2). Attending to service state limitations, a relative deflection of 1/358 of overhanging span was obtained for a design load of 5.0 kN/m^2.

Both results obtained, ultimate load and relative deflection, indicates a very favourable behaviour of the structural system proposed.

4 SYSTEM PERFORMANCE

With the aim to know the performance of the floor system preliminary sizing curves were developed using the Gamma Method, usually recommended for the analysis of TCC structures [11]. These curves are no final sizing solutions but simply establish the appropriate range of use of the floor system developed and its possibilities [8].

Gamma Method is highly accurate for simply supported beams but its error increases significantly in pinned-clamped beams and clamped-clamped beams as Girhammar pointed in [12]. However, the error can be significantly reduced by applying the Gamma Method but using effective beam length la distance between points of zero moment.

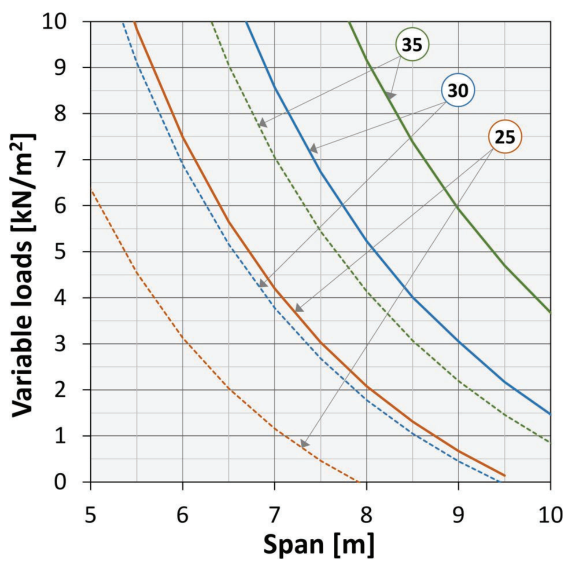

Figure 13: *Floor sizing curves.*
Symply supported pieces. Permanent load 2.5 kN/m^2.
Deformation: L/300-continuous line; L/500-dashed line

Figure 13 shows the most unfavorable case at the dimensioning level of the floor, since it corresponds to simply supported pieces. Creep deformation was considered with the total permanent load and a 30% of the variable load. The results indicate that for residential use and a deflection limit of L/500, a floor with a slenderness of L/24 has adequate sizing for a permanent service load of 2.5 kN/m^2 and an additional variable load slightly

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higher than 3.0 kN/m^2. This range of slenderness increases to L/30 and L/35 for extreme and internal spans, respectively.

These results indicate the efficient use of mechanical qualities of the materials of the system thanks to the high composite action and, consequently, its suitability for the execution of building structures.

5 CONCLUSIONS

Timber-concrete-composite system developed show very interesting properties for the construction of building structures: low self-weight of 1.80 kN/m^2, high stiffness, slender flooring solutions, semi-rigid connections between elements and an easy construction process.

The system is based on an efficient timber-concrete connection characterized by the use of boards perforated in their entire length crossed by the in-situ poured concrete. Shear test results show a very favourable combination of high stiffness and efficient composite action with a ductile failure, desirable characteristic in TCC solutions.

Full-scale four and three-point bending test results indicate a very strength and stiff behaviour of the system proposed.

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