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GLUED TIMBER CONCRETE COMPOSITE WALLS USING ULTRA-HIGH-PERFORMANCE CONCRETE

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Abstract. This paper gives a short introduction of the development of cross laminated timber (CLT) concrete composite walls with a glued connection. In the composite walls, prefabricated ultra-high-performance concrete (UHPC) lamellas replace timber lamellas at the core layer of the CLT elements. To check the feasibility of gluing timber to UHPC small-scale shear, delamination and bonding tests were performed and showed promising results. The load bearing behaviour was analysed with centrically and eccentrically loaded tests on wall segments. Analytic modelling of the wall experiments using an effective bending stiffness, based on shear analogy method, showed a good correlation to the experimental results.

Keywords: Adhesive bond, cross laminated timber, timber concrete composite, ultra-high-performance concrete.

1. Introduction

Cities are forced to grow, due to an increasing urbanization and population growth in general [1]. Growth occurs vertically, horizontally or in both directions [2]. Vertical growing cities need more high-rise buildings to accommodate the rising number of people. Because of sustainability aspects and numerous technical innovations at the turn of the millennium, timber multi-storey buildings came into focus [3]. Currently, there are visionary timber high rise projects with building height up to 300 m [4].

The increasing building height leads to high forces in vertically load bearing members in the lower floors. This causes a mass consumption of material and space in timber-only high-rise buildings, due to a relative low compression strength and youngs modulus of timber compared to ultra-high-performance concrete. Compared to the sustainable construction material timber, ultra-high-performance concrete may be regarded as not-sustainable, because of its high content on non-renewable material and its energy consumption for processing.

Aim is the sustainable use of ultra-high-performance concrete (UHPC) through its targeted use for vertically load bearing members. Therefore, timber and ultra-high-performance concrete are combined in walls. The wall cross section is comprised of a slender UHPC core, encapsulated within timber, as shown in figure 1. Applied normal forces concentrate on the concrete core. The surrounding timber prevents the slender concrete core from buckling and bears compression and tensile forces, caused by bending moments due to eccentricities or external loads.

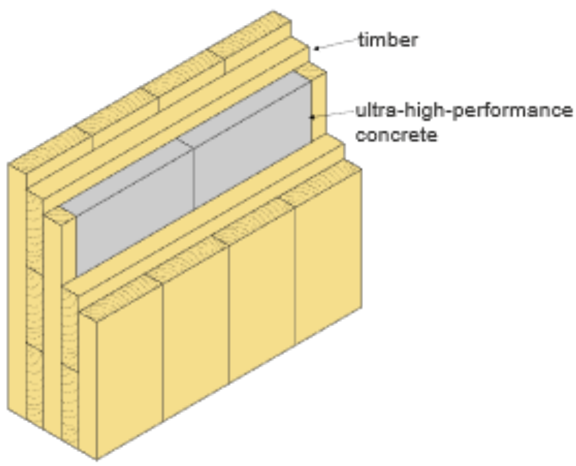

Figure 1. Wall with hybrid cross section comprised of timber and UHPC [5]

The walls are economically produced in the industrialized environment of the cross laminated timber (CLT) production. Three steps are necessary. First, a precast concrete plant prefabricates lamellas. In the regular production process of a CLT plant, the manufacturer inserts the prefabricated concrete lamellas into the raw CLT panels at previously defined places. After pressing the panels, wall elements are formed out with joinery machines, automatic cutting machines or machining centres.

To ensure statically monolithic acting walls and to enable this production process, a glued connection between timber and concrete using standard glues in

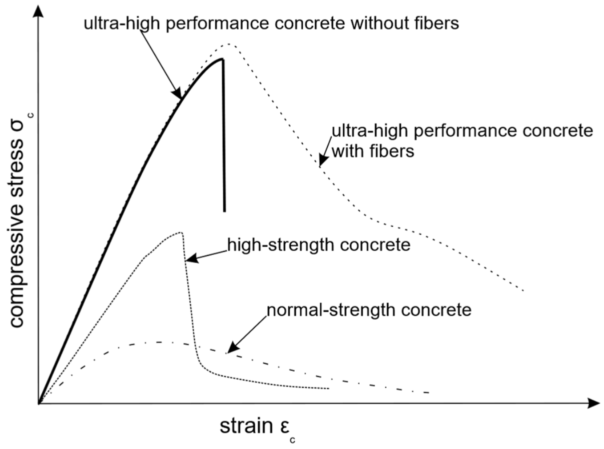

Figure 2. Typical stress-strain relationship of different types of concrete according to [7]

CLT production is inevitable.

2. Fundamentals

2.1. Ultra-high-performance Concrete

Ultra-high-performance concrete is characterized by its, for concrete, high compressive strength, up to 200 N/mm^2, and a young's modulus between 45.000 and 55.000 N/mm^2, which is shown in figure 2. The high compressive strength comes along with a brittle failure when no steel fibres are added to the concrete. A certain degree of ductility can be achieved by adding steel fibres [6].

The high compressive strength of UHPC is achieved through its optimised packing density of the aggregate. Therefore, almost no pores exist in UHPC. This leads to a very dense surface of UHPC compared to normal strength concrete and the possibility to easily glue UHPC. [8]

2.2. Cross Laminated Timber

Cross Laminated Timber is a quasi-rigid composite, plate-like engineered timber product, which is commonly composed of an uneven number of layers, each made of boards placed side-by-side, which are arranged crosswise to each other at an angle of 90°C [9]. The layers are normally glued together using polyurethane (PU) or melamine-urea-formaldehyde resin (MUF) adhesives [10]. The thickness of CLT elements is commonly between 51 mm and 300 mm, whereas the single layer thickness generally varies between 20 mm and 40 mm. Common lengths of CLT elements is around 18 m with a width up to 3,0 m [9]. Figure 3 gives an overview of the CLT production process and figure 4 displays a simplified technical drawing of a CLT element.

CLT bears in-plane and out-of-plane loads through its crosswise layering. The load bearing behaviour is influenced by the cross wise layering and for stability and deformation calculations the shear deformation must be considered [11].

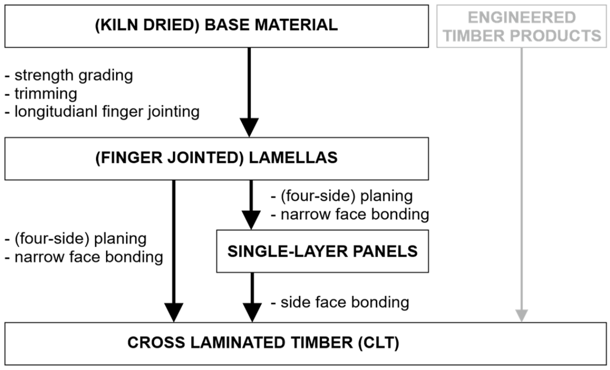

Figure 3. Production process of cross laminated timber according to [9].

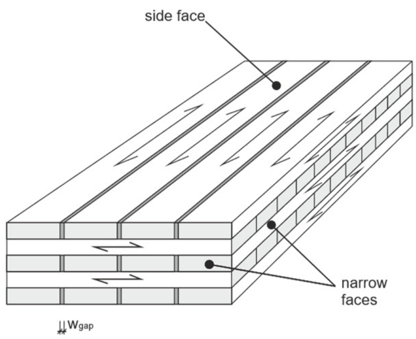

Figure 4. Simplified technical drawing of a CLT element according to [9].

2.3. Timber Concrete Composite

A well-known timber concrete composite (TCC) member is the TCC slab. In this composite element the concrete is positioned in the compressive zone, whereas the timber is placed in the tensile zone. The two elements are connected with special connectors to form one statically acting cross section. The effectiveness of the TCC element is mainly characterized by its connection. The usage of systems with high composite action can reduce beam depth and allow for longer span length [12].

Adhesives are a very effective connector for TCC elements and lead to a quasi-rigid connection which increases the member stiffness and strength. In addition, the shear forces are distributed uniformly over the entire surface and local concentrations are avoided. [13] In the past, lots of research on glued connections has been performed, e.g. [14–17], most of these research projects have the use of epoxy resin as adhesive in common.

3. Small scale experiments

3.1. General

In the beginning of the project numerous small-scale experiments were performed to determine the possibility to glue timber to UHPC using standard glues for CLT production. This was an iterative process, as the information obtained served as basis for

Figure 5. Experimental test setup for shear experiments [5].

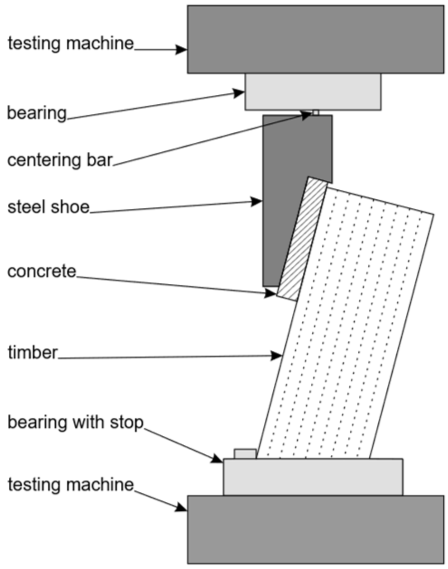

Figure 6. Technical drawing of experimental test setup of inclined bond tests [5].

the following experiments. These small-scale experiments were shear, delamination and bond experiments, which will be discussed in this section.

3.2. Shear

First, small-scale shear experiments on bonded timber concrete composite specimen were performed to find combinations of concrete, concrete surface treatments and adhesives with a promising behaviour. The three-layered specimen consisted of a concrete layer, placed in the middle, and two layers of spruce, which were free of any defects. Per specimen two shear joints existed and shearing off took place parallel to the grain. Three different types of concrete (C1, C2 and C3) were tested with and without steelfibres. C1 and C2 were commercially available compounds and C3 was a laboratory mixture. The used concrete surfaces were a) smooth, directly out of the formwork, b) ground and c) sandblasted. Five adhesives were used: a one-component polyurethane adhesive, a melamine-urea-formaldehyde resin, a phenol resorcinol resin, a two-component polyurethane resin and an epoxy resin. The adhesive application was 400 g/m^2 and the pressure at bonding was about $0,75 \pm 0,1$ N/mm^2 for all specimen. The test setup is displayed in figure 5. A combination of concrete, concrete surface treatment and adhesive was characterized as promising if it achieved high shear strength and timber fracture in the experiment.

Considering only standard CLT production adhesives, suitable results could be achieved independently from the used concrete type, with a ground concrete surface in combination with the one-component polyurethane adhesive. Specimen glued using the melamine-urea-formaldehyde resin failed in the glue line, which was characterized through a low shear strength and a maximum timber fracture of 20%.

3.3. Delamination

Although this research project concentrated on the short-term load bearing behaviour of CLT walls with glued in lamellas from UHPC, durability keystroke tests with glued specimen were performed. The test procedure included storing the specimen in boiling water for six hours, the storage in 20 °C cold water for one hour and afterwards drying in an oven for approximately 16 hours. This induces shear- and tensile stresses on the glue line due to the swelling and shrinkage behaviour of the timber. If the glued connection is insufficient there will be a gap opening of the glue line. According to DIN EN 16351 [18] the maximum tolerated failure of a single glue line is 40% of its length and 10% of glue line length may be opened for the sum of all glue line lengths.

Based on the shear experiments, delamination tests with promising combinations were performed. Here, both steel-fibre reinforced concrete types C1 and C2, a smooth and ground surface, the one-component polyurethane adhesive, the two-component polyurethane resin, and the epoxy resin were used to form the specimens. The manufacturing procedure of the specimen was identical as for the shear tests. For each series two specimen were produced.

3.4. Bond

To verify the assumption of a rigid connection inclined shear tests with three different bond lengths,

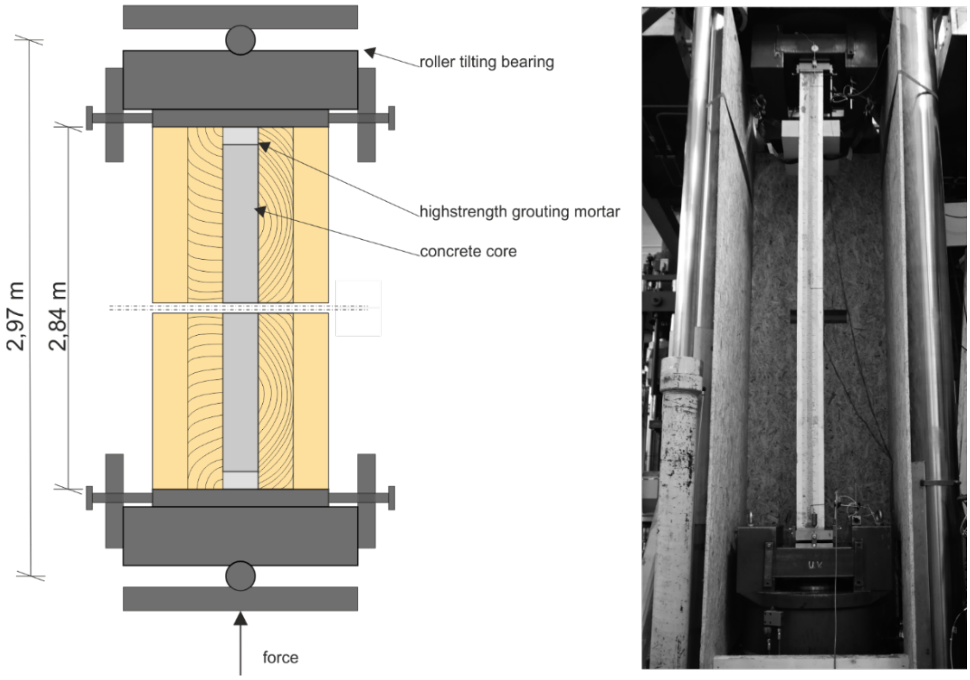

Figure 7. Schematic (left) and real (right) experimental test setup for full scale tests [5].

14 cm, 28 cm and 45 cm, were performed. A technical drawing of the experimental test setup is displayed in figure 6. The specimens were comprised of concrete type C1 lamellas with smooth and ground surface, glued to spruce glulam GL24C using the one-component polyurethane adhesive. Bonding parameters were identical to the shear and delamination tests.

All experiments showed a brittle failure when reaching the maximum force. With increasing bond length, the average shear force leading to failure increased. The average failure shear force for the 14 cm bond length with the ground concrete surface was 77,1 kN and increased up to 217,1 kN for the 45 cm long bond length. No difference could be seen in the behaviour of the smooth or ground concrete surface. The maximum measured relative slip between concrete and timber, recorded with an optical measuring system, in the middle of the bond length was approx. 0,25 mm for all experiments. In most cases the failure occurred in the timber part. Only in two experiments, with the 14 cm long bond length, the failure occurred in the glue line.

4. Full scale tests

4.1. Methodology

To analyse the load bearing behaviour of the composite walls, centrically and eccentrically loaded, experiments at scale 1:1 have been performed. Figure 7 displays the test setup. For every eccentricity, 0 mm, 10 mm and 20 mm, three wall segments were tested. The tested wall segments were 0,5 m in depth, 2,84 m high and had a thickness of 15 cm. Two roller tilting bearings were used to test a pendulum rod with a buckling length of 2,97 m. The five layered wall segments with a complete concrete core, every layer was 30 mm thick, were produced in a CLT production facility. The adhesive application of a one-component polyurethane was production based 170 g/m^2 and the bonding pressure was 0,08 N/mm^2, because the elements were pressed in a vacuum bed. The used timber was spruce with a strength class of C24, the concrete had a mean compressive strength of $f_{\mathrm{ck,\,cyl}} = 132,5\mathrm{N/mm}^2$ and a mean young's modulus of 46.774 N/mm^2. These values were determined according to DIN EN 12390-13 [19] and DIN EN 12390-3 [20]. The tests were conducted displacement controlled with a speed of 0,12 mm/min. Laser distance sensors controlled the horizontal displacement of the wall segments during the experiments. Strain gauges recorded the strain on the outermost timber fibres and in the middle of the cross section on the concrete. The strain gauges were placed in the centre, at the bottom and the top of the wall.

4.2. Results

Figure 8 displays the force-horizontal deflection in the vertical wall centre and the force-piston stroke diagram for the centrically loaded experiments. All three experiments showed similar behaviour and the maximum force varied between 1331 kN for V_D_30_00_3 and 1693 kN for V_D_30_00_2. With increasing load, the horizontal deflection increases slowly until the critical point is reached and the walls buckle. This is indicated by a rapid increasement of the horizontal deflection, accompanied with a decreasing load. After the specimen were removed out of the testing machine material failure could visibly not be detected.

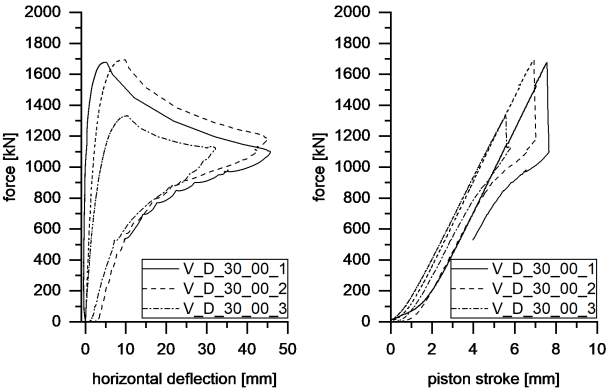

Figure 8. Force-horizontal deflection and force-piston stroke diagram for centrically loaded experiments [5].

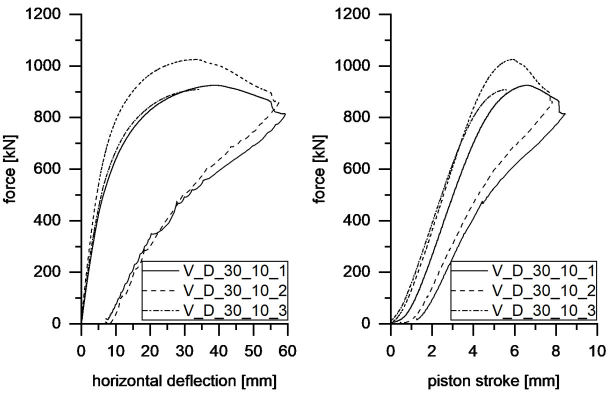

Figure 9. Force-horizontal deflection and force-piston stroke diagram for 10ămm eccentrically loaded experiments [5].

The force-horizontal deflection diagram of the 10 mm eccentric loaded experiments is shown in figure 9. The three specimens showed a similar behaviour upon reaching the maximum force, which varied between 908 kN and 1025 kN. The horizontal deflection at the maximum load is close to 30 mm. Experiments V_D_30_10_1 and V_D_30_10_2 showed a ductile behaviour, whereas V_D_30_10_3 failed brittle. Material damage could clearly be seen on the compressive side of the wall segments in the outer most timber lamella.

The recorded strains in the wall centre showed a similar behaviour for all experiments. Figure 10 shows a typical force-strain diagram, explicitly for experiment V_D_30_10_1. The concrete middle layer suffers only compressive strain, whereas the outermost timber fibres are either under compressive- or tensile strain.

4.3. Analysis

To calculate the maximum buckling force for the centrically loaded experiments, Euler's formula using an effective bending stiffness, accounting for the additional shear deformation, according to [11], was used. The eccentric experiments were analytically modelled

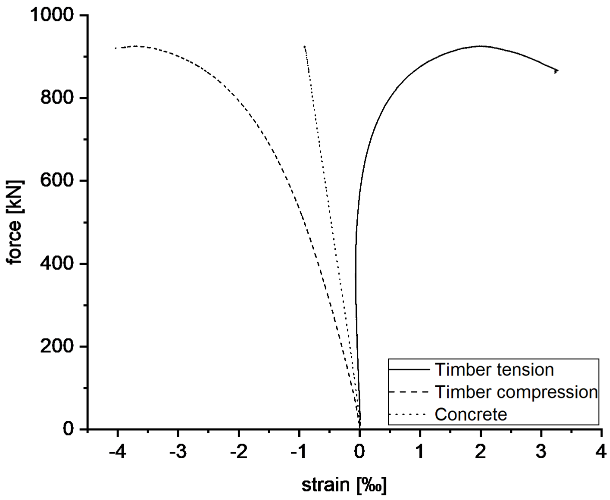

Figure 10. Development of strains at the vertical wall centre for timber and concrete for experiment V_D_30_10_1. [5].

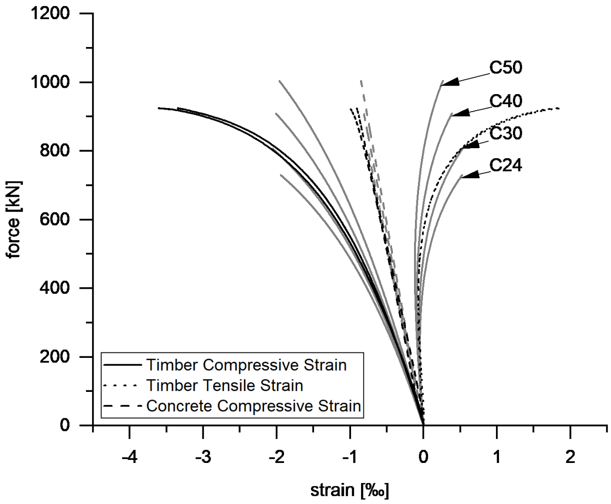

Figure 11. Development of strains at the vertical wall centre for timber and concrete calculated (gray) and experiment (black). [5].

with the differential equation for second order problems, also using an effective bending stiffness.

Due to the scattering of the elastic timber properties the mean stiffness values and the characteristic material strength of nominal timber strength class C24 according to DIN EN 338 [21], and for concrete the determined young's modulus and compressive strength were used for the calculations.

The calculated buckling forces were lower than the ones achieved in the experiments. Figures 11 and 12 compare the calculated strain distribution and horizontal deflection for different timber strength grades in the vertical wall centre with ones obtained in an experiment. The curves fit well. Because a linear elastic material model was used to model the experiments, the declining branch in the experiment cannot be considered.

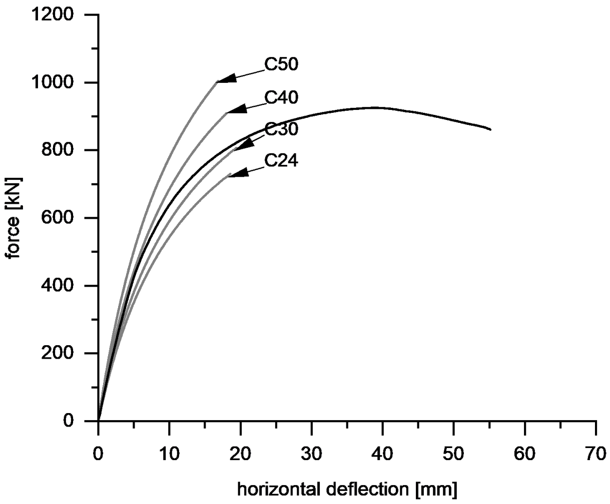

Figure 12. Force-horizontal deflection calculated (gray) and experiment (black). [5].

5. Conclusions

The completed test program showed that it is possible to bond timber to UHPC using standard glues for CLT production regarding short-term behaviour. The tests on wall segments verified, that the cross section can be considered as monolithic and the elements can be calculated using an effective bending stiffness. The maximum load capacity depends on the slenderness of the walls and the eccentricities. Compared to homogenous CLT walls, the hybrid walls tested with a 10 mm eccentricity, show a 25% higher load bearing capacity, calculated with characteristic values for material strength.

Acknowledgements

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