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Insight into mechanics of externally indeterminate hardwood–concrete composite beams

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HIGHLIGHTS

- Tests on externally indeterminate hardwood LVL–concrete composite beams.
- Use of a special test to assess connection behaviour in cracked concrete.
- Comparing behaviours using fully or partially threaded screw connectors.
- Checks on internal consistency of slip, strain, deflection and load data sets.

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ABSTRACT

This paper presents tests on beech LVL–concrete slab composite connections and externally indeterminate beams using connectors comprising fully threaded (FT), small-headed screws or partially threaded (PT), large-headed screws in X-formation. A test was devised to quantify connection characteristics in fully cracked concrete (applicable to hog zones of the beams). Relative to the FT-based connections, the PT-based connections were of greater strength, nonlinearity and flexibility in compression concrete, and weaker, less stiff but more ductile in tension concrete. One composite beam exhibited 22% redistribution of support reaction at 88% of the failure load. Failure occurred primarily at the connections, which then gradually led to fracture of the LVL as a secondary mode of failure.

1. Introduction

Timber–concrete composite (TCC) floors comprise concrete slabs acting in structural unison with timber joists or panels via shear connectors. Parisi and Piazza [1] describe the emergence of such floors in historic buildings, when thin concrete toppings are cast over and connected to the original timber joists, leading to stiffer and stronger floors. Since the advent of engineered timber components such as glulam joists, TCCs are also being used in the dual role of floors and diaphragms in tall timber buildings. Examples of this are the glulam joist–concrete slab composite floors of the eight-storey Life Cycle Tower One building, constructed in Dornbirn, Austria, in 2012.

TCCs are structurally efficient because they exploit the complementary tension- and compression-resisting properties of timber and concrete respectively. Such floors are much lighter (giving cheaper foundations) than reinforced concrete floors, because the high stiffness-to-weight and strength-to-weight timber members need act compositely with only thin concrete slabs in order to satisfy deflection, vibration, load-carrying and other code-specified criteria. Consumption of both cement (a key CO_2 emitter during production) and timber is thus relatively modest in these floors. This, and the fact that responsibly-sourced timber is a renewable construction material, equips TCCs with a desirably low carbon footprint. The thin but effective concrete slabs also mean that TCCs generously exceed all-timber floors in thermal mass and in fire/acoustic insulation between storeys.

Owing to their internal slip-based indeterminacy and to the nonlinear constitutive behaviours of the concrete, the timber and the connections, even the short-term load responses of single span, simply supported TCCs are complex. Multiple experimental and predictive studies, including [2–10], have led to significant insight into these load responses. Frangi and Fontana [8], and later Zhang and Gauvreau [9], illustrated the analysis simplifications which arise at the ultimate limit state if the slab-to-joist connections are sufficiently ductile. Zona et al. [10] used probabilistic analysis with finite element modelling to show how uncertainties in

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material and connection properties influence prediction-test correlations for TCCs. Previously, using results from tests on floor specimens each comprising multiple timber joists nailed to floorboards, Foschi [11] concluded that the variability in floor strength was significantly less than the variability in bending strength of individual joists.

The above and other studies have been reviewed in the context of design of timber–concrete floors in [12–14], where the pivotal role of the connections in securing desirable structural performance is highlighted. Both mechanical and chemical connections have been researched. Mechanical examples include [15–20] vertical nails, inclined screws, perforated steel plates, glued-in rebars, and notches cut into the timber, all with normal concrete. A chemical connection fabricated by pouring wet concrete onto wet adhesive, itself freshly smeared onto the timber, and allowing the whole to cure, was investigated [21] for normal concrete. These studies show that notched and bonded connections exhibit excellent slip stiffness, also that notched connections possess excellent strength, and that inclined screw connections possess good stiffness, strength and ductility. Mechanical connectors in lightweight concrete have also been studied [22,23], with the latter case [23] including use of cork to lower concrete density.

In the above cases the concrete has cured around connectors pre-fastened to the joists. Alternatively (e.g. [24]), prefabricated slabs can be connected to the joists *after* the slabs have cured. This facilitates in-situ construction and eliminates self-equilibrating forces in the TCC system (especially on the connections) from shrinkage of the concrete. Alongside these largely experimental studies, attempts (e.g. [25]) have been made to predict the strengths of TCC connections.

Due largely to the mechano-sorptive behaviour (material property changes due to variation in moisture content over time) of timber [26], along with creep of the concrete, TCCs can exhibit a significant long-term load response. This has been the subject of various studies, including [27].

Softwood (commonly spruce) glulam, of typically 40 mm thick laminations, features often in the above studies. Relative to the original timbers, glulam has fewer defects (e.g. knots), so improving consistency in material properties. Laminated veneer lumber (LVL) comprises laminations of only about 4 mm thickness, which further enhances consistency in material properties. Failure of a knot within such a thin lamination might perturb the LVL section's performance only marginally. Production of glulam and (significantly more so) of LVL is very efficient in use of original material. Moreover the use of hardwoods (such as beech), which possess moduli and strengths superior to softwoods, can lead to shallower, narrower timber joists and thinner concrete slabs in design. This in turn enables reduced storey heights in buildings and improves the sustainability of TCC floors.

Modern developments in rotary cutting machinery mean that very thin laminations can now be produced by successively peeling layers off original *hardwood* rounds, see Fig. 1. Thus beech LVL joists and panels are very recent innovations, and so research into their use in TCCs is currently limited. One of few studies to date in the field is that by Boccadoro and Frangi [28], who tested single span, simply supported TCC slabs comprising beech LVL panels connected to concrete toppings via notches cut into the timber. These composite slabs were found to carry high loads, with failure modes influenced by notch geometry [28]. Dias et al. [18] found that TCC connections based on chestnut (another hardwood) were up to 14% stronger than their softwood counterparts, while studies such as that by Yeoh et al. [29,30] have focused on softwood LVL–concrete composites.

Alongside the innovation of hardwood LVL production, recent advances in transportation and in joist–joist connection technology now dictate that longer timber joists can be taken to and connected on site. This in turn presents an unrivalled opportunity to create multi-span continuous TCC members. Continuity enhances structural efficiency and so can be exploited to further reduce material consumption, which in turn beneficially lowers the carbon footprint of TCC construction. In order to maximise these benefits, understanding is needed of any changes to TCC member behaviour (beyond the single span, simply supported case) brought about by the *external* indeterminacy in the longitudinal direction, by concrete cracking in hog zones and by changes in connection behaviour between sag (largely compression concrete) and hog (cracked concrete) zones.

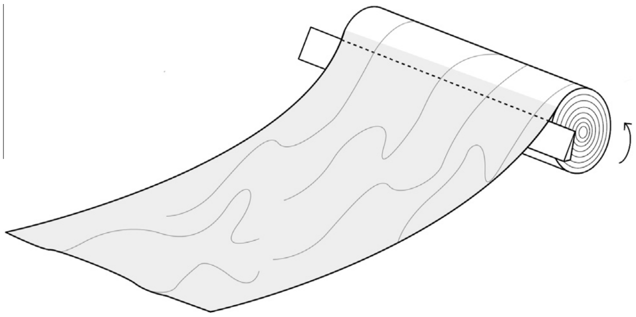

Fig. 1. Rotary cutting of roundwood to form thin laminations.

Now Brunner and Lehmann recently [31] reported tests on two-span continuous glulam beams without concrete slabs. Also, Dias et al. [32] and, separately, Kieslich and Holschemacher [33] presented tests on softwood TCC members which were *transversely* indeterminate externally, owing to the presence of multiple longitudinal joists spaced at regular intervals transversely under the slab. As a complement to these studies, the present paper reports tests on TCC members with the following novelties, namely:

- Supports which render the TCC members *externally* indeterminate in the *longitudinal* direction.
- Beech (a hardwood) LVL joists (rather than panels) to act compositely with the concrete slabs.
- Alternative use of fully threaded and partially threaded screws as the slab-joist shear connectors.
- Development of a special longitudinal shear test for the screw connections in *tension* concrete.

The fully-threaded screws possessed small heads and so were expected to transfer force into the concrete slabs via the threads, while in the concrete the partially-threaded screws had unthreaded shanks, but large heads through which much of the force transfer into the concrete was expected to occur. Hence the two screw types were expected to lead to different connection behaviours. Also, the inter-span continuity of the present specimens introduced hog moments and so cracked concrete in zones over internal supports. In these zones the connections were still needed to transfer force into the slab's tension steel reinforcement. This situation was absent from previous studies, where only sag moments and so largely compression concrete were pertinent. It is for this reason that the novelty of a test to quantify screw connection behaviour in cracked concrete is listed above.

In what follows, these new tests are described, the key results are discussed and conclusions are drawn. In presenting the results, attempts are made to investigate the internal consistency of the output test data. This is accomplished by applying various combinations of constitutive behaviour, equilibrium and compatibility to different subsets of the test data to arrive, for example, at the same section stress resultants via different routes, and then assessing the levels of correlation between these independently calculated stress resultants.