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Time-dependent behaviour of timber–concrete composite floors with prefabricated concrete slabs

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ABSTRACT

This paper presents the results of long-term experimental tests performed on prefabricated timber–concrete composite beams intended for use in a proposed floor system, in which the concrete slab is prefabricated off-site and connected to the timber beam using one of two novel connection systems (either steel tubes inserted into the concrete slab and coach screws, or metal plates embedded in the concrete slab and nailed to the timber beams). In the experimental programme two beam specimens representing strips of composite floor were subjected to sustained (quasi-permanent service) loading for almost a year in an indoor, unheated and unconditioned environment. Throughout the test, mid-span deflection, relative slips at various connector locations, strains in the concrete slab and timber beam, and the ambient relative humidity and temperature, were continuously monitored. Both specimens showed only minor increases in deflection, slips and strains over time, demonstrating excellent overall long-term behaviour. The findings are consistent with a major advantage of prefabrication in this context; the concrete cures and can thus freely shrink before the slab is connected to the timber beam, thereby minimising stresses and deflection in the composite beam. Results of accompanying numerical analyses are also presented. A rigorous uniaxial finite element model was first validated against experimental results, and then used to predict the total deflection at the end of the 50-year service life of the specimens tested and of other specimens with different connection system not tested. The total deflection was found to be in the range of 3.5–4 times the elastic deflection due to the quasi-permanent load condition (excluding the self-weight of the beam). This value was always lower than the acceptable limit of span length over 200, with better predicted performance from stiffer connection systems such as notches cut in timber and glued-in dowels.

1. Introduction

Timber–concrete composite beams are constructed from a concrete flange connected to a timber web. This technique has been extensively used in Europe to upgrade existing wooden floors [1] and, in some cases, to rejuvenate deteriorated short-span wooden bridges. They are also being used in the construction of various office, residential, commercial and industrial buildings [2–8]. In a timber–concrete composite beam, the concrete provides high compression resistance and some bending resistance, while the timber provides capacity to withstand bending and tension. This structure offers many advantages over timber-only or reinforced concrete floors. The concrete slab diminishes live load deflections and susceptibility to vibrations of the floor system (due to its greater stiffness), and provides greater fire resistance and thermal mass than timber-only floors, but the composite floor is lighter than a reinforced concrete floor and, therefore, less dead load is transmitted to the gravity load resisting system and to the foundations.

To make the composite system a convenient alternative to traditional timber, steel–concrete and reinforced concrete floor solutions, it is essential to use an appropriate type of connection to ensure economic design and to obtain an effective interlayer connection (i.e. one that ensures a high degree of composite action, and thus high stiffness of the composite system) [9]. Hence, diverse mechanical connectors have been proposed and tested, e.g. continuous steel meshes epoxy-glued into the timber [2,10], notches cut into the timber [3,5,11–13], smooth metal bars, screws [14–17], nails or spikes. Recent Swedish studies on timber frame systems suggest that industrialised timber frame housing construction has the potential to reduce costs by up to 25–30% of the total construction outlay [18], largely through simplification of the construction processes, rather than simply by minimising material costs, although industrialisation can also reduce wastage. Therefore, several research projects are currently focused on developing

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semi- [7] or fully-prefabricated [10,19–21] timber–concrete composite panels capable of competing with more traditional steel–concrete composite and precast concrete floor systems.

Timber–concrete composite systems, in which fresh (“wet”) concrete is cast on top of timber beams/wooden decking with mounted connectors, have been extensively investigated. However, this traditional “wet” production process has some disadvantages, notably: (i) the time needed for the concrete to harden; (ii) the lower stiffness and higher creep of the system while the concrete hardens; (iii) the higher cost of cast-in situ concrete; and (iv) potential quality control problems.

These drawbacks of the ‘wet’ systems can be eliminated by prefabricating a concrete slab with shear connectors already inserted, and connecting it to the timber beams on the building site [19–21]. A significant advantage of this novel, prefabricated system is that some of the concrete shrinkage occurs before the slab is connected to the timber beam. Consequently, the increases in deflection and flexural stresses in the composite beam due to the timber beam restraining shrinkage of the concrete can be markedly reduced. Furthermore, by casting the concrete slab separately, there is no need to use a plastic membrane or to paint the top layer of the wood with a water-proof painting to eliminate the moisture flow between the two materials during concrete curing. Additional advantages of prefabrication include reductions in construction costs, improvements in quality, saving of resources, and simplification of waste recycling due to moving most of the work from the building site to the fabrication plant. Several novel connectors have been tested for use with this system. However, the development of new, mechanically effective connectors is pointless if the construction of the system is too intricate and/or too time consuming. Therefore, particular attention has been paid to developing connection systems that are simple to produce and assemble in order to accelerate the construction process.

An important issue in timber–concrete composite floors is the performance in the long-term, as very often their design is governed by serviceability considerations such as vibration and deflection control. Little relevant, published information is available due to the complexity and expense of long-term testing, e.g. long-term control and monitoring equipment must be dedicated and is subject to being disturbed over that time. The most important phenomena to assess in long-term testing include the combined effects of loading and moisture changes. Timber under loading exhibits much greater creep deformations over time when subjected to variations in moisture than under constant humidity conditions, and the effect of changes in moisture on the deformation (the so-called ‘mechano-sorptive’ effect) is generally more significant than the effect of time [22–24]. The mechano-sorptive behaviour of the connection system should also be considered [25–27]. In addition, thermal variations in timber and concrete should not be neglected since they induce both stress and strain distributions in the composite structure. The creep and shrinkage of the concrete must also be taken into consideration. These phenomena may cause excessive deflections in timber–concrete composite structures at the serviceability limit state, particularly for medium to long-span beams. Thus, accurate evaluation of the time-dependent behaviour is very important when designing such structures, and testing is the best way to obtain basic information. Although there is a need for further information from long-term tests, a number of such tests have been performed on various (mainly ‘wet’) timber–concrete composite beams. Noteworthy are the 5-year tests carried out at EMPA (Switzerland) on composite beams with proprietary inclined screwed (SFS) connectors [26], in Florence (Italy) on composite beams with glued-in rebars [28], and at the University of Canterbury (New Zealand) on composite beams with Laminated Veneer Lumber and either notches cut into the LVL or metal plates pressed into the LVL [29]. Further long-term (about 2-year duration) tests were performed in Brescia (Italy) on composite beams with double gang-nails welded together as shear connectors [30], in Germany on a semi-prestressed composite panel with continuous glued steel connections [2], in Portugal on composite beams with lightweight concrete slab [31], and in Colorado on wood–concrete composite decks made of dimensional lumber [32,33] and recycled utility poles [34] with shear key connection details. Full-scale composite floors were also tested over time for shorter durations in the UK [17] and in Germany [13]. All these tests showed that there is a significant increase in deflection during the first couple of years, particularly for composite beams in outdoor conditions. In some cases the deflection limit of one over two-hundreds of the span length was exceeded. The tests also showed some seasonal fluctuations of deflection which make it difficult to extrapolate the experimental results to the end of the service life.

In order to extrapolate the results of the few long-term experimental tests available to the end of the service life, and to extend such results to composite systems with different geometrical and mechanical properties, some numerical models which account in a rigorous way for all the time-dependent phenomena of concrete, timber and connection discussed above were developed. These models are either based on the finite difference method [35] or on the finite element method. In the latter case, uniaxial beam elements [36,37] were implemented in a custom-made software. Alternatively, the composite beam was schematized with three-dimensional solid elements in a general purpose software package such as Abaqus [33]. Reasonably accurate solutions were obtained for the trend in time of the deflection by comparison with the results of experimental tests. Due to their complexity, however, the models cannot be used readily in common practice, therefore some approximate analytical solutions have also been proposed for design purposes [35,38,39].

This paper presents the outcomes of a long-term experimental test, part of a pilot research project conducted at Luleå University of Technology, Sweden, on timber–concrete composite beams with prefabricated concrete slabs. The overall research programme included four series of experimental tests: (i) direct shear tests to failure on seven different types of shear connectors, published in a previous paper [19]; (ii) full-scale bending tests to failure of composite beam specimens, discussed in another paper [20]; (iii) long-term tests under sustained loading, presented in this paper; and (iv) dynamic (vibration) tests, which are presented in another paper [40]. The purpose of the long-term tests was to investigate the time-dependent behaviour of the prefabricated timber–concrete composite systems at the serviceability limit state. Two 4.8 m long timber–concrete composite beam specimens, representative of floor strips, were constructed and tested under sustained loading for nearly 1 year. After validation on the experimental results, a rigorous uniaxial finite element model [36] is used to predict the deflection at the end of the 50-year service life of the experimentally-tested specimens. The same model is also employed to predict the deflection of composite beams with prefabricated concrete slabs characterised by different connection details that due to the lack of needed funds could not be tested. The predicted deflections are then compared with design limits adopted in common practice.

2. Construction of the specimens

Two 4.8 m long timber–concrete composite beam specimens, designated Specimens 1 and 2, representative of floor strips, were constructed and tested under sustained loading. Both consisted of a $60 \times 800 \times 4800$ mm prefabricated concrete slab (strength class C20/25 according to Eurocode 2 [41]) and one