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Early-age performance of lag screw shear connections for glulam-lightweight concrete composite beams

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HIGHLIGHTS

- Early-age performance of screw connections was experimentally investigated.
- Stiffness and strength of screw connections increase rapidly with time before 7 days.
- Properties of glulam and screw are decisive when concrete hardens to some degree.
- Models to predict the early-age performance of screw connections are proposed.

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ABSTRACT

Mechanical behavior of the shear connections has a significant influence on both the load-carrying capacity and the bending stiffness of timber-concrete composite (TCC) beams. All the studies reported so far have concentrated on the performance of TCC connections in mature concrete. The performance of shear connections for TCC beams at early concrete ages, however, has not been investigated yet. This information is essential to evaluate the structural behavior of TCC floors or bridges during construction. In this paper, a total of 18 push-out tests with concrete ages ranging from 12 h to 28 days are performed, to investigate the early-age performance of lag screw shear connections in the lightweight concrete. Development of concrete strength with time is also analyzed. At the concrete ages shorter than 7 days, both the stiffness and strength of the screw connectors increase evidently with time, which follows the same growth trend with the concrete strength. After a 7-day cure, screw shear connections reach almost 100% of both the 28-day serviceability slip modulus and shear strength. Material properties of the glulam and the screw fastener are decisive in the shear performance of connections when the concrete hardens to some degree. Based on the experimental results, the accuracy of the design methods proposed in Eurocode 5 is evaluated. In addition, by non-linear regression of the experiment data, expressions to predict the development of load-carrying capacity and serviceability slip modulus for screw shear connections before 28 days are established.

1. Introduction

Timber-concrete composite (TCC) beams represent a new type of structural element, in which an existing or a new timber beam is connected with a concrete slab by shear connectors. In TCC beams, both materials can be exploited as the concrete is mainly in compression and the timber joist is mostly in tension. The connection system transfers the shear forces at the interface between timber and concrete, which ensures a reliable composite action. TCC beams show many advantages over the traditional timber floors, including higher load-carrying capacity and stiffness, less susceptibility to vibration, improved acoustic performance, better fire resistance, etc [1–4].

The mechanical behavior of shear connections has a significant influence on both the load-carrying capacity and the bending stiffness of TCC beams. This has led to many investigations focusing on the development of shear connections with satisfactory performance, including notches, nails, studs, screws, dowels, nail plates, etc [2,5–13]. Steinber et al. [2] evaluated the mechanical behavior of five different connections, and the results showed that the vertical screw connectors achieved a very low shear stiffness, while the connection using inclined screws subjected to tension were more efficient. Khorsandnia et al. [11] reported the results of the

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push-out tests on three different types of shear connections, which included normal screw, SFS and bird-mouth notch. An analytical model was also derived for each type of connection based on the nonlinearity regression analysis of the experiment data. However, in consideration of the installation speed and construction cost, dowel-type shear connections, such as nails, screws and steel bars have obvious superiorities.

In recently years, there have been more experimental studies which aimed to identify the factors affecting the mechanical behavior of dowel-type connections. Dias et al. [14] reported that, the load-carrying capacity of dowel-type connections was greatly influenced by both the strength of the materials and the shape of the fastener. Moreover, Dias et al. [15] later demonstrated that the slip modulus of dowel-type connections was affected only by the timber properties, but not the strength of the concrete or the shape and yield strength of the fastener.

The use of lightweight concrete, compared with normal weight concrete, has the advantage of lower dead load, which reduces the seismic action and the loads imposed on the foundation [2,16,17]. Jorge et al. [16] investigated the mechanical behavior of screw-type connections using lightweight concrete, and it was proved that the use of lightweight concrete was compatible with the screw-type connections. Fragiacomo et al. [17] conducted push-out tests on a new type of head stud connector called Tecnaria. The load-slip behavior of this connection in both ordinary and lightweight concrete was investigated. Test results showed that the use of lightweight concrete instead of normal weight concrete had no significant influence on the performance of the connection system.

All the studies reported so far have concentrated on the performance of TCC connections in mature concrete. However, the performance of shear connectors for TCC beams at early concrete ages has not been investigated yet. This information is essential to evaluate the behavior of TCC floors or bridges during construction, as well as the development of composite bearing capacity and stiffness before the removal of supports.

In this paper, a total of 18 push-out tests with concrete ages ranging from 12 h to 28 days are performed, to investigate the early-age performance of screw shear connections in the lightweight concrete. The development of concrete strength with time is also analyzed. Based on the experimental results, the accuracy of the design methods proposed in Eurocode 5 [18] is evaluated. In addition, by non-linear regression on the experiment data, expressions to predict the development of load-carrying capacity and serviceability slip modulus for screw shear connections before 28 days are established.

2. Experimental program

2.1. Specimen configuration

A series of push-out tests was designed to obtain the load-slip response of the screw connectors in early-age concrete. Curing times were selected as 12 h, 24 h, 3 days, 7 days, 14 days, and 28 days after initial casting. For each test time, three push-out specimens were constructed.

Each test specimen consists of one glulam joist, and two 80 mm thick concrete slabs, as is shown in Fig. 1. Two lag screws with nominal diameter of 12 mm and length of 150 mm were installed on each side of the glulam member, with a transverse spacing of 70 mm symmetric about the centerline (see Fig. 1). The lag screws have the embedded depth inside the glulam 100 mm, and inside concrete 50 mm. Preparations of the glulam member included predrilling holes in the glulam for the screws, and pasting plastic foil both to avoid the water uptake and to reduce glulam-concrete friction during the tests.

2.2. Material properties

2.2.1. Glulam and screw fastener

The glulam used in this experiment was made of Douglas fir, with average density of 540 kg/m^3 and moisture content of 13.3%. In order to get an estimation of compressive strength, elasticity modulus and embedment strength of glulam, a few laboratory tests were performed. Details of physical and mechanical properties of glulam obtained from the tests are presented in Table 1. The embedment strength of glulam (parallel to grain) is tested according to CEN-EN 383 [19]. Steel lag screws are selected as the fastener in the connection system, and the nominal tensile strength of the screw fastener is 600 N/mm^2.

2.2.2. Lightweight concrete

Lightweight concrete with expanded shale, classed LC30, was used in this experiment. The mix design is given in Table 2. Before concrete mixing, the expanded shale aggregates need to be pre-wetted, leading to less water absorbed during mixing and therefore reducing the possibility of slump loss.

This paper focuses on the early-age performance of screw connectors in lightweight concrete. As a result, it is necessary to make clear the mechanical properties of lightweight concrete at an early age. For each concrete age, compression tests on three 150 mm cubes were performed nearly in the same time period with the push-out tests. Table 3 summarizes the ultimate compressive strength of the concrete test cubes at different times. Fig. 2 illustrates the relationship of the cubic compressive strength and the age of concrete. The cubic compressive strength of lightweight concrete increases rapidly before 7 days, after that it increases slowly. At very early ages (12 h, 24 h), binder failure between the aggregates occurs, which results in low strength, not exceeding 30% of the 28-day compressive strength. While for the test cubes after a 7-day cure, shear fracture of aggregates occurs on the failure surface, reaching more than 77% of the 28-day compressive strength.

The compressive strength of concrete at an age t is considered to be dependent on the type of cement, temperature and curing conditions [20]. For a mean temperature of 20 °C and curing according to EN 12390 [21], the mean compressive strength $f_{cm}(t)$ at various ages may be estimated as:

$$f_{cm}(t) = f_{cm,28} \cdot \exp\left\{ s\left[1 - \left(\frac{28}{t}\right)^{0.5}\right]\right\} \quad (1)$$

where t is the age of the concrete in days; $f_{cm,28}$ is the mean compressive strength at 28 days, in MPa; s is a coefficient which depends on strength class of the cement, and for the 42.5 N cement used in this test, s is equal to 0.25.

As shown in Fig. 2, Eq. (1) shows good agreement with the experimental results, and the coefficient of determination (R^2) was obtained as 0.995. Thus Eq. (1) can accurately predict the compressive strength development of lightweight concrete with expanded shale.

2.3. Push-out test setup and loading procedure

As shown in Fig. 3, the push-out specimens were loaded by a 20 tonnes universal testing machine, and the relative slip between concrete and glulam was measured with two displacement transducers installed at the central points of the test specimens. In addition, a thick steel plate was used to distribute the force applied on the top of the glulam member.

All the tests were performed in accordance with the procedure given in CEN-EN 26891 [22]. In this standard, the load-carrying capacity of shear connections is determined as the maximum load during the push-out tests before a slip of 15 mm. The serviceability slip modulus K_s, corresponding to the slope of the load-slip curve between 10% and 40% of the estimate failure load F_{est}, is used to represent the deformation resistance of shear connections.

3. Test results and discussion

3.1. General observations and failure modes

For the push-out specimens at the concrete ages of 12 h and 24 h, concrete strength of which was relatively low, apparent interfacial separation between the concrete and glulam was observed before 40% of the estimated failure load; a horizontal crack appeared at the position of the screws when the slip value was only about 2 mm. With the increase of load, this horizontal crack extended quickly in the diagonal direction towards the edges of the concrete slab (see Fig. 4(a)), and the relative slip increased sharply. When up to the maximum load, the screws leaned apparently in the forced direction (see Fig. 4(b)). After removing the screws from the glulam member, only small plastic deformation of the screws was observed, mainly on the part inside the glulam (see Fig. 4(d)).

When the concrete age was equal to or greater than 7 days, no damage occurred in the concrete slabs. Moreover, the concrete was stiff enough to keep the screw straight in the slab (see Fig. 4(c)). The flexural deformation of the screw fastener and compressive deformation of the glulam contributed to the majority of the