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Bolt shear connectors in grout pockets: Finite element modelling and parametric study

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HIGHLIGHTS

- Continuum FE modelling of bolt shear connector in grout pocket (BCGP) is conducted.
- Load-slip, stiffness, strength and failure modes of BCGP connections are determined.
- Parametric study is conducted on stiffness and peak load-carrying capacity of BCGP.
- Formulae for stiffness and strength of the joints with BCGP connection are derived.

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ABSTRACT

Recent laboratory experiments have demonstrated the superior performance (high stiffness, load-carrying capacity and ductility) of bolt shear connectors embedded in the pockets of cementitious grout compared to conventional fasteners (e.g. screws) for developing composite action between steel beams and timber slabs. Accordingly, this paper investigates the structural behaviour of steel-timber composite (STC) joints with bolt connectors embedded in grout pockets (BCGP) using 3-D continuum-based finite element (FE) models. Following validation of the FE models against available push-out test data, they are used to conduct a parametric study that elucidates the influences of the compressive strength of the grout, the yield strength and size of the bolt shear connectors, the size of the grout pockets and the thickness of the steel profile flange on the load-slip behaviour, service stiffness, peak load-carrying capacity and failure modes of STC joints with BCGP. Simple formulae for the stiffness and load-carrying capacity of the STC joints with BCGP are derived from linear regression of the results of the parametric study.

1. Introduction

Over the past few years several types of steel-to-timber connections comprising of mechanical fasteners (e.g. screws and bolts), glue and/or a combination of them have been developed and tested [1–7]. However, conventional methods which rely mainly on the dowel action provided by screws and/or bolts are not very efficient for transferring the horizontal shear force between the timber slab (panels) and the steel girders in innovative steel-timber composite (STC) floors [1–4]. Accordingly, STC connections with bolt shear connectors embedded in cementitious grout pockets have been proposed recently by Hassanieh et al. [4,8] and superior stiffness, load-carrying capacity, ductility and composite efficiency of the bolt connectors in grout pockets (BCGP) compared to conventional dowel connectors such as screws and bolts have been demonstrated through push-out and 4-point bending tests. The stiffness and load carrying capacity of the BCGP connections were over 100% higher than conventional screw and bolt connections with the same screw/bolt diameter size [4,8]. In particular, the significantly higher stiffness of BCGP connections compared to screw and/or bolt connectors can improve the efficiency of STC system, because stiffness of the connections is a key governing design parameter in composite timber structures. The BCGP connection comprises two main components: bolts installed on top flange of the steel beams using a pair of nuts (above and below the beam flange), and cementitious grout which fills the pockets or void confined by timber floor panel and steel flange (Fig. 1). After placing the bolt (with the top nut installed) in the hole drilled in the top flange of the steel profile, the bottom nut can be tightened to a shank tension that can mobilise a friction grip mechanism. Apart from their superior structural performance, the BCGPs facilitate

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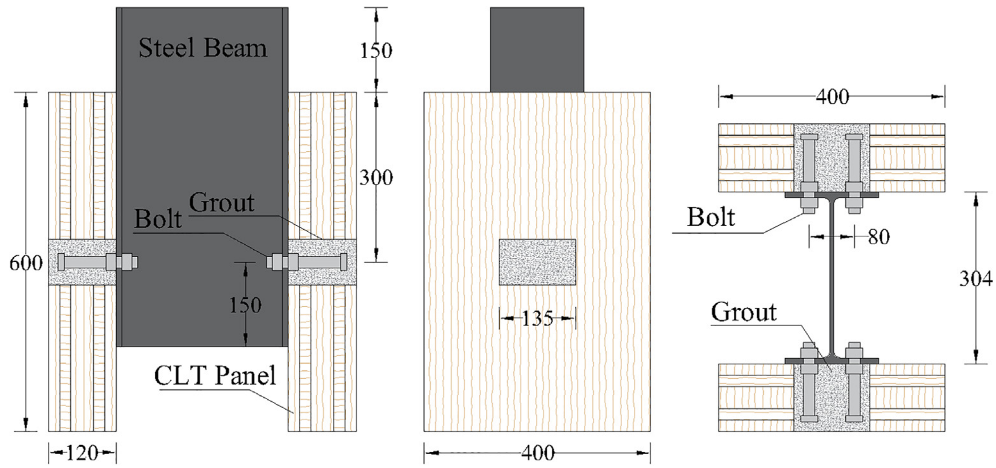

Fig. 1. Outline of the STC push-out specimens with BCGP connections.

construction of the STC floors by minimising the above-head works required for installing a large number of conventional fasteners (screws and/or bolts) while allowing for easy dismantling of the composite floors at the end of structure's service life [4]. In the BCGP connections, bolt connectors can be installed and tightened before placing the CLT panels on the steel beams and the pockets will be filled easily from the top which can facility construction process compared to conventional screw/bolt connections which must be installed from the bottom. In addition, no tolerance for predrilled holes in BCGP connections is required due to fact that bolts can be installed, tightened and pre-tensioned before mounting the CLT panels on the steel beams.

The application of bolt shear connectors embedded in grout pockets for the construction and repair of precast prefabricated reinforced concrete and steel-concrete composite structures and bridge decks has been reported extensively in the literature [9–12]. Moreover, there is a large body of research on the potential applications of adhesives (epoxy-based, polyurethane-based etc.) for timber connections and joints [13–17]. However, the use of cementitious grout (or cement-based adhesives) in hybrid timber connections is relatively new and the acceptable performance and versatility of cementitious grout in hybrid timber joints have been demonstrated in only a few recent studies [18–20]. More specifically, Kaestner and Rautenstrauch [18] investigated the behaviour of grouted connections in timber-concrete composite beams, while Schober et al. [19] studied the performance of a timber truss with grouted joints. Furthermore, Negrão et al. [20] replaced the corner connection of a small scale timber frame with a concrete joint and demonstrated the acceptable performance of such hybrid concrete-timber joints by laboratory experiments and numerical simulations. An overview of hybrid connections for timber structures with potential application of concrete type adhesives has been provided by Schober and Tannert [21].

In addition to laboratory experiments, attempts have been made to use numerical models and particularly finite element (FE) analysis to simulate behaviour of hybrid steel-timber, timber-concrete and timber-timber connections/members under different loading conditions [4,22]. The FE models used for the analysis of hybrid timber elements can be classified into three categories, i.e. 1-D beam, 2-D (plane-stress and/or axisymmetric) and 3-D continuum-based FE models. The adequacy of discrete 1-D frame elements in conjunction with non-linear springs or links for predicting global short- and long-term behaviour of hybrid timber beams has been demonstrated through multiple studies [23–25]. Furthermore, 1-D beam on elastic and inelastic foundation FE models have been used successfully to capture the behaviour of dowel-type fasteners in timber connections [2,22,26]. While 1-D FE models are a good compromise between accuracy and computational efficiency for predicting the global behaviour of timber structures, only 2-D FE [3,27,28] and especially the 3-D continuum-based FE models [29–32] can provide the versatility required for representing the highly non-linear behaviour of hybrid timber connections at the local level. However, non-linear 3-D continuum-based FE modelling of hybrid timber connections has been hindered due to a dearth of reliable and robust constitutive laws that can efficiently describe the complex failure modes and anisotropic behaviour of the timber under multiaxial stress states [30,31,33]. Among various theoretical frameworks (e.g. hypo-elasticity, fracture mechanics and cohesive zones, plasticity etc.), continuum damage mechanics can provide a practical, efficient and unified framework for formulating constitutive laws that can adequately capture both brittle and ductile failure modes of timber under multiaxial static stress states [30,31,34]. Furthermore, these continuum damage models can be easily calibrated with respect to physically-meaningful mechanical properties of timber obtained from laboratory experiments such as 3-point bending, uniaxial tension and compression and shear tests [30].

STC joints with BCGP connections comprise of various components (i.e. bolt, steel profile, cementitious grout and timber panel) with different geometry, material and mechanical properties, each of which can significantly affect the structural behaviour of the entire STC joint. Accordingly, a non-linear 3-D continuum-based FE model of the joints is developed in this paper and it is validated against available test data. Extensive non-linear 3-D FE simulations are then carried out to determine the influence of different material and geometric parameters on the load-slip, stiffness and peak load capacity of STC joints with BCGP connections. The results of the parametric studies are used to make recommendations for efficient design of STC joints.

2. Summary of push-out test results

A series of push-out tests was conducted on BCGP connections with the geometry and details shown in Fig. 1 and Table 1 [8]. A symmetric CLT-steel beam-CLT configuration was used for fabrication of the push out specimens [35]. Bolt shear connectors were installed on the steel flange using double nuts on each of the flange and the bolts were prestressed by a torquemeter wrench to a shank tension of $0.3f_y$ (f_y being the yield strength of the bolts). The steel profile was an Australian 310UB40.4 with a flange thickness and