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Steel-timber composite beam-to-column joints: Effect of connections between timber slabs

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ABSTRACT

Studies of steel-timber composite (STC) connections and STC beams under sagging bending have been reported elsewhere in the literature using push-out and four-point bending tests respectively. However, the structural behaviour of STC beam-to-column connections under hogging bending moments (with the prefabricated timber slabs in tension) have hitherto not been investigated. In particular, the connection between the two prefabricated timber slab panels (across the column) has a major influence on the structural performance of a STC beam-to-column connection and is the focus of the current study. Eight full-scale STC beam to steel column cruciform specimens with different connections (half lap, single and double surface spline with timber and/or steel plate) for the timber slabs were fabricated and tested under a monotonically increasing downwards displacement, and these are described in this paper. The bending moment capacity, rotation capacity, failure mode, stiffness and ductility of the STC connections are evaluated and discussed. The composite steel-timber system exhibits both appreciable ductility and rotation capacity which fulfil the existing design requirements for semi-rigid composite connections in Eurocodes EC3 and EC4. Furthermore, the negative bending moment capacity of STC connections is significantly higher than that of bare steel connections without a timber slab.

1. Introduction

Currently, the most used material in the construction industry is concrete made up of water, aggregates and Ordinary Portland Cement (OPC), the latter being one of the largest contributors worldwide to anthropogenic greenhouse gases, particularly CO_2. With growing pressure to reduce the carbon footprint of the construction industry, architects and engineers are challenged to reduce the negative environmental impacts while improving the functionality and cost-competitiveness of buildings.

The life cycle assessments of different types of structures have demonstrated that reinforced concrete slabs have the highest or second highest levels of embodied energy and carbon [1]. Accordingly, replacing conventional heavy-weight concrete slabs with lightweight timber panels (particularly in steel-concrete composite floors) can potentially reduce the embodied energy and carbon footprint as well as the total cost of construction [2]. Moreover, using structural timber elements within the building envelope can extend durability and life-cycle of the timber and provide opportunity for more effective carbon sequestration.

Steel-timber composite (STC) floors comprising of prefabricated timber (e.g. cross laminated timber and/or laminated veneer lumber) panels connected to steel beams significantly reduce the construction time, number of different trades and workforce, and costs of labour and building site preparation [3]. In conventional steel-concrete floors, the shear studs welded to the top flange of the steel profiles typically provide the means for effective shear transfer and development of near full composite action between the beam and slab [4]. However, the demolition of such floors with welded shear connectors is time and energy consuming, being associated in addition with a large amount of construction waste, noise and dust. In response, several studies have been undertaken in recent years to develop sustainable steel-concrete floors with precast geopolymer concrete slabs and post-installed bolted shear connectors which can be easily dismantled at the end of building's service life [5,6]. These deconstructable floors can also minimise construction waste by maximising the possibility of recycling and reuse.

Over the past decades, different types of composite floors have been developed and extensive studies have been carried out, mainly to evaluate the structural performance of steel-concrete [7], timber-concrete [8,9] and timber-timber [10] composite floors. These studies have covered various aspects of the composite behaviour such as the short-term stiffness, strength and ductility of the shear connectors subjected to static, cyclic and fatigue loads [11–15], developing novel high-performance shear

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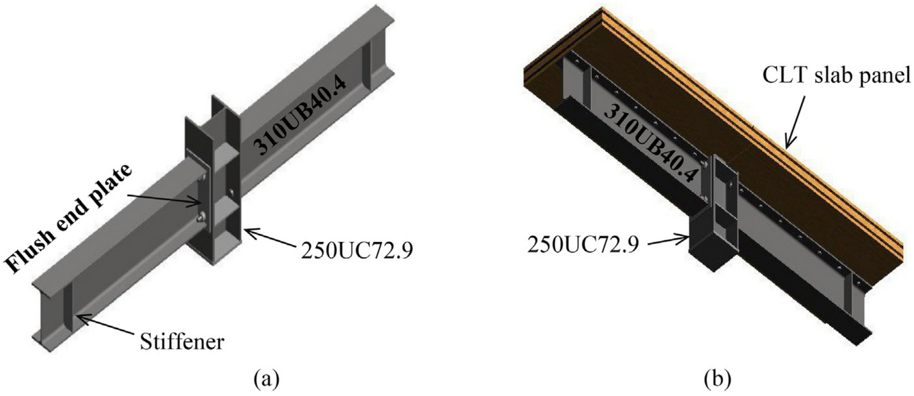

Fig. 1. Outline of specimens, (a) before and (b) after connecting CLT slab panels to top flange of beam.

connectors [16,17], short-term bending moment capacity and flexural behaviour of the composite beams under sagging bending moments [18–20], long-term deflection of composite beams [21,22] and human-induced vibrations in composite floors under service loading conditions [23,24]. Quite recently, STC systems have been introduced but very little research has been reported on the structural behaviour of these systems [25–28]. STC beams are usually comprised of prefabricated cross laminated timber (CLT) panels connected to the top flange of steel beams by means of mechanical connectors (bolts or screws) and/or adhesives. Thus far, the research on STC systems has focused predominantly on the load-slip response of different mechanical connectors during push-out tests [29,30], the application of the pockets of cementitious grout in conjunction with high strength bolted connectors to enhance the stiffness and load carrying capacity of the STC system [31], the flexural behaviour of STC beams under sagging bending moments [32,33] and the nonlinear finite element analysis of STC connections and beams [34,35]. However, the structural response (stiffness, ultimate strength and failure mode and rotation capacity) of STC beam-to-column joints subjected to negative bending moment remains largely unexplored.

Steel beam-to-column connections or joints are typically classified into three categories: rigid (or continuous), semi-rigid (or semi-continuous) and pinned (or simple) [36,37]. No specific guidelines to determine the type of joints are provided in most standards [37], and only EC3 provides details on the moment-rotation behaviour of joints. Rigid connections should be able to sustain bending moments greater than M_p and the bending moment capacity of the nominally pinned connections should remain below $0.25M_p$ (M_p being the plastic bending moment capacity of the beam). Furthermore, in unbraced and braced frames the ratio of the initial stiffness $K_{connection}$ of the rigid/semi-rigid connections to the plastic stiffness of the beam $K_{(p)beam} = M_p/\theta_p$ (θ_p being the rotation corresponding to plastic bending moment) should not be less than 25 and 8.3, respectively [38]. Semi-rigid beam-to-column joints can provide a good comprise between high stiffness and strength and low cost of construction. Additionally, the rigidity and ductility of semi-rigid joints provides for considerable moment redistribution in steel frames subjected to extreme loading conditions. Accordingly, several construction details along with mathematical moment-rotation (M-θ) models for the semi-rigid connections have been proposed [39].

Beam-to-column connections with a flush end plate are frequently used in the construction of moment resisting frames (with and without bracing), because of their relatively high strength, stiffness and rotation capacity as well as the simplicity of their fabrication. As a result, the structural behaviour of flush end plate joints in steel and steel-concrete composite frames has received considerable attention over the past three decades [40,41]. In particular, the significant influence of the slab-to-slab (across the column) connections on the bending moment and rotation capacity of such joints with precast slabs have been demonstrated in recent studies by Ataei et al. [42–44]. However, effect of CLT-to-CLT slab connections (across the column) on the structural behaviour of the novel STC beam-to-column joints with having a flush end plate has not been investigated. It is hypothesised that the ductile crushing of the timber in front of the mechanical connectors in conjunction with the high-tensile strength of steel plates and/or timber panels (to be used for connecting the prefabricated CLT slabs across the column) can significantly improve the ductility and rotation capacity of these semi-rigid STC beam-to-column connections.

This paper presents the results of push-down tests conducted on eight full-scale semi-rigid cruciform subassemblies with flush end plate STC beam-to-column joints. The main variable in the experimental program was the type of connection between the two CLT slab panels across the column to resist tensile forces. The load-displacement and moment-rotation responses and the strain distribution through the STC section depth are provided and the failure modes and ductility of the joints are discussed. It is shown that the flush end plate STC beam-to-column joints satisfy the minimum rotation capacity requirement of the EC3 [36] and EC4 [45] for joints. The deconstructability of the STC floors with semi-rigid connections was demonstrated by removing the bolts and screws and easily dismantling all cruciform subassemblies at the end of the push-down tests.

2. Laboratory testing program

2.1. Fabrication and details of the specimens

As noted, the main purpose of the experimental program was to evaluate the effect of the CLT-to-CLT slab connections on the structural performance of the semi-rigid STC frames. To this end, six cruciform specimens with flush end plate steel-CLT composite beam-to-column joints (Fig. 1) with different types of connection (spline joints with single/double steel plates or laminated veneer lumber (LVL) panels, half lap joints, glued butt joint) between the two juxtaposed CLT slabs were constructed. A further two cruciform specimens were fabricated: one without a CLT slab (Fig. 1a) and the second one with high strength screws (dogscrews) directly connecting the flanges of the steel column to the edges of the CLT slab panels (with no direct connection between the two CLT panels). In all STC joints, the CLT slab panels were connected to the top flange of the universal beams by means of 100 mm long and 16 mm (diameter) self-tapping coach screws (Fig. 1b). The first pair of coach screw shear connectors were installed at a section 100 mm away from the face of flush end plate. In total, fourteen coach screws with spacing of 200 mm were used to connect each CLT panel to the universal steel beam. Details of the CLT-to-CLT panel and CLT-to-steel column connections and designation of all specimens are