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Modelling of steel-timber composite connections: Validation of finite element model and parametric study

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ABSTRACT

This paper investigates the mechanical behaviour of lap steel-timber composite connections using a 3-D continuum-based finite element (FE) model. In the FE models developed, the non-linear behaviour and failure of the timber is captured by a stress-based failure criterion formulated in the framework of continuum-damage mechanics. Yielding of the steel plates and fasteners (*i.e.* coach screws and bolts) is captured by an elastic-hardening plastic constitutive law. These FE models are validated by experimental (push-out) tests conducted on laminated veneer lumber (LVL)-steel and cross-laminated timber (CLT)-steel composite lap connections. It is shown that the FE models developed in the paper can replicate adequately the load-slip response and failure mode of the hybrid steel-timber composite connections tested. The validated FE model is used to undertake a parametric study that elucidates the influence of the yield strength and the length of the fasteners and the post-tensioning force in the bolts on the stiffness, load carrying capacity and load-slip behaviour of hybrid steel-timber composite connections.

1. Introduction

The structural performance of timber elements can be improved by hybridising timber with steel and/or reinforced concrete at different levels (*i.e.* members, structure). The timber-concrete and steel-concrete composite beams comprising of a reinforced concrete slab connected to timber or steel joists have been extensively investigated and used in the past few decades [1–14], however, the steel-timber composite floor comprising of a timber slab connected to steel girders is a relatively novel concept developed just in recent years. The steel-timber composite (STC) floors can reduce the self-weight of the structure and the need for craneage and rigging and increase the speed of construction dramatically. Moreover, the STC system can reduce the size of foundation, facilitate the construction on soft and problematic soils and improve the sustainability of buildings by lowering the self-weight of the structure and subsequently reducing the energy- and carbon-intensive construction materials (*i.e.* steel and concrete).

The structural behaviour of hybrid (composite) steel-concrete, timber-concrete and steel-timber composite (STC) systems is significantly influenced by mechanical behaviour (stiffness and load carrying capacity) of connections the. The mechanical behaviour and load-slip response of the fasteners in composite connections is usually characterised by the results of experimental push-out tests. The results from push-out tests conducted on steel-concrete composite connections with different types of fasteners have been widely reported in the literature [1–5]. Moreover, the tests have been used to evaluate the service stiffness and load-carrying capacity and to characterise the load-slip behaviour of timber-timber [6] and timber-concrete composite connections [7–14].

In addition to laboratory push-out tests, finite element (FE) models have been used to simulate the load-slip response and to predict the stiffness and the peak load carrying capacity of fasteners and composite connections. The FE models used for the non-linear analysis of composite connections can be classified to 1-D frame [15,16], 2-D [17] and 3-D continuum-based FE models [3,10,14,18–21]. The 1-D FE models take advantage of beam on elastic/inelastic foundation theory to capture the linear as well as the non-linear behaviour of dowel-type fasteners. For the 1-D FE models, the fasteners (*e.g.* nails, screws or bolts) are modelled by beam elements and linear/non-linear springs parallel and perpendicular to the axis of the dowels are used to model the behaviour of the foundation (*i.e.* timber or concrete). 1-D FE beams can represent the non-linear behaviour of the dowels adequately, as well as the load-slip response of hybrid timber-timber, timber-concrete and steel-timber composite connections with dowel-

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type fasteners [22,23]. However, the accuracy of such 1-D FE models depends strongly on the mechanical characteristics of the springs (representing the timber foundation modulus) that can be obtained from embedding tests. Accordingly, there have been attempts to develop 2-D and 3-D continuum-based FE models that can accurately capture the behaviour of dowel-type fasteners in steel-concrete, timber-timber and timber-concrete lap connections without the need of embedding test results; relying only on the basic mechanical properties (*e.g.* compressive, tensile and shear strength) of timber, concrete and steel. Nguyen and Kim [19] used ABAQUS software to develop a 3-D FE model of steel-concrete composite connections with headed stud shear connectors. In the model developed, damage and failure (being material non-linearities) of the concrete, headed stud, steel beam and reinforcing were taken into account. More recently, Pavlović et al. [21] reported 3-D FE models of steel-concrete composite joints with embedded high-strength bolted shear connectors and analysed the models using ABAQUS with its explicit solver. The strength, failure mode, ductility and the load–slip behaviour of the steel-concrete composite joints predicted by the 3-D FE models showed good correlation with push-out test data [19,21]. Similar numerical modelling has been reported by Liu et al. [24] for high-strength friction-grip bolts as shear connectors between precast concrete and steel composite beams. However, the development of detailed 3-D continuum-based FE models that can accurately predict the behaviour of timber lap connections with dowel-type fasteners has been hampered by strong geometrical and material non-linearities associated with the anisotropic nature of timber (and engineered wood) and by the combination of different brittle and ductile failure modes in shear and compression, as well as scarcity of reliable experimental data on the behaviour and failure of timer under multi-axial stress states required for calibration of timber constitutive laws [25,26]. Moreover, the strain hardening behaviour and the strength gain associated with wood densification (due to compression) in the perpendicular to the grain direction can add another layer of complexity to the non-linear behaviour of timber under multiaxial stress states [27].

The constitutive laws used for modelling the behaviour of timber behaviour and for capturing timber failure under multiaxial stress states can be classified as (*i*) elasticity-based models, that take advantage of equivalent uniaxial and invariant-based models [27,28]; (*ii*) plasticity-based models, that employ a yield surface to represent the onset of yielding and the evolution of the yield strength [26,29–34]; (*iii*) models based on progressive damage and fracture mechanics [35,36]; (*iv*) continuum damage models, and (*v*) a combination of plasticity with damage and fracture models [37]. Amongst existing timber constitutive laws, the elasticity-based models are applied mainly for representing timber behaviour/failure under 2-D plane stress conditions [27,28]. The plasticity-based models tend to overestimate the strength and stiffness of the timber, owing to quasi-brittle and brittle nature of the behaviour of timber (associated with progressive damage and fracture) that cannot be accommodated in the framework of plasticity [38–40]. Furthermore, the plasticity-based models typically do not take account of the unequal tensile and compressive strengths of timber [33] and accordingly, the framework of continuum damage mechanics or a combination of continuum damage and plasticity appear to be one of the most accurate frameworks for formulating the non-linear behaviour of timber [41].

In this paper, 3-D FE models of STC connections with dowel-type (*i.e.* coach screw and high-strength bolt) fasteners are developed and analysed using ABAQUS software. In the FE formulations developed, the timber is modelled by an eight-parameter stress-based failure criteria formulated in the framework of continuum-damage mechanics by Sandhaas [41]. The non-linearity of the steel plates, screws and bolts are represented by an elastic-hardening plastic model. Moreover, geometrical non-linearities and the non-linearity of the interface between the timber, steel plate and dowel-type fasteners are considered in the FE models developed. The accuracy of the numerical models is verified against the results of push-out tests conducted on STC connections and a parametric study is carried out to determine the influence of different parameters (*i.e.* the length and yield strength of the fasteners, coefficient of friction and post-tensioning force in the high-strength bolts) on the load-slip, stiffness and peak load capacity of STC lap connections with dowel-type fasteners.

2. Outline of push-out tests

The geometric outline of the symmetric STC connections used for validation of the FE models is shown in Fig. 1. The symmetric configuration of the push-out test provide a uniform shear stress distribution and minimise the parasitic stresses due to friction and imperfection at the interface between timber panels and steel profile and accordingly reduce the variability of push-out test results. Furthermore, symmetric configuration can significantly facilitate the testing. In the tested STC connections, either coach screws or high strength bolts were used to connect two LVL or CLT timber panels to the flanges of a 310UB32.0 steel beam [22]. The timber panels in the push-out specimens were 400 mm wide and 600 mm long. The LVL panels were 75 mm thick hySPAN manufactured from Radiata Pine by Carter Holt Harvey Australia and the CLT panels were 120 mm thick with 5 lamellas manufactured from European Spruce. The size of steel profiles (*i.e.* 310UB32.0) and thickness of CLT timber panels (120 mm thick with 5 lamellas) in the push-out test specimens were determined with respect to the preliminary design of a STC floor for a hypothetical 8-storey residential building with 6 m long steel girders and 1.2 m spaced steel joists. A 3D finite element model of the building was developed and analysed and accordingly the timber slab was designed to comply with minimum strength and serviceability limit state design requirements of AS1720.1 [42]. The 120 mm thick CLT slabs could provide up to two-hour fire rating based on a charring rate of 0.7 mm/min. Furthermore, the possible annoying vibration of the STC floor was addressed by limiting the maximum short-term deflection and maximum allowable impulse velocity of the timber slab to the values specified in EC5 [43] and ensuring that the first natural frequency of the STC floor is bigger than 8 Hz [43].

Details of the push-out test specimens including the type of timber slab and the diameter and type of fasteners are given in Table 1. In addition, the adopted mechanical properties of the LVL and Spruce wood (used for fabrication of the CLT panels) including their elastic moduli, compressive strength f_c, tensile strength f_t and shear strength f_v are given in Tables 2–5, respectively. The coach screws were made of Grade 4.6 steel with a yield strength of 240 MPa and an ultimate tensile strength of 400 MPa, and the screws were AS/NZS 1393 [44] compliant. The high strength bolts complied with the minimum requirements of AS1110.1 [45] and AS1112.1 [46] and the bolts had a proof yield strength of 660 MPa and an ultimate tensile strength of 830 MPa.

The variability of timber mechanical properties and fabrication methods can significantly affect the structural behaviour of steel-timber composite joints. Accordingly, three identical specimens were fabricated and tested for each type of STC joint to ensure the precision and repeatability of the push-out test results [22]. Four linear variable differential transformers (LVDTs) were mounted on each push-out specimen, to measure the relative slip between the timber slab and steel flange and also capture any possible twist in the specimens. The push-out test procedure and load protocol followed the EN 26891 [47] specifications. The specimens