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Experimental investigation on in-plane stiffness and strength of innovative steel-timber hybrid floor diaphragms

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ABSTRACT

An innovative steel-timber hybrid floor diaphragm with modular prefabricated composite elements is presented. Building elements have been designed to be quickly joined on site using only bolts and screws. The paper mainly deals with an experimental study on the response of the hybrid floor under horizontal loads. Monotonic and cyclic shear tests of a full-scale floor were executed in order to investigate the in-plane stiffness, bearing capacity, effective stress state and strain state, as well as damage to floor components. The forces transmitted through the timber and steel components were also assessed. The test results showed that the main deformations of the floor were localised at the beam-to-beam steel joints while the steel-timber hybrid elements behaved elastically without breakages. The use of CLT panel-to-panel connections was very effective in increasing the stiffness and the ability to recover the initial non-deformed shape after the removal of the acting loads. The findings revealed how the diaphragm behaviour of the floor was influenced by the mutual interaction between the modular staggered composite elements and in particular by the response of the connections. Several design recommendations for steel and timber connections are therefore provided here.

1. Introduction

The availability of non-traditional Engineered Wood Products (EWPs) such as Cross-Laminated Timber (CLT) panels, beech glulam or Laminated Veneer Lumber (LVL) has encouraged the evolution of timber construction systems. This reflects that EWPs often have superior structural characteristics and related design advantages for the realisation of new buildings and the reinforcement of existing buildings. CLT was developed in Europe at the beginning of the nineties, where the first building applications also began. It rapidly gained a consistent market share, first in Europe and later in several countries around the world [1]. A very wide variety of methods of building construction have been implemented during the last decade and some other advanced techniques are still under development [2,3]. Currently, such techniques include construction systems with only timber elements or hybrid solutions in which the timber elements are combined with other materials, very frequently steel or concrete [4]. One of the major benefits of hybrid systems is the possibility to use the strength of one material to compensate for the weaknesses of another. Although the hybridization of materials can lead to benefits without demanding their full structural collaboration, composite systems (e.g. composite beams, slabs or walls) offer generally superior structural performance and support the objectives of sustainability in construction, reducing the use of resources. Many buildings recently erected in different states around the world have hidden under their envelope a hybrid timber-concrete- or steel-timber- based construction system [5]. The growing spread of multi-storey timber buildings in North America, Europe, Australia, New Zealand and Japan has promoted research interest in studying these new systems. Several publications have appeared in recent special issues on seismic resistant timber structures [6] and on performance of timber and hybrid structures [7].

Focusing on CLT buildings, built only from CLT panels, the SOFIE Project was one of the first experiences in Europe to show the advantages offered by this new wood product. During the Project, structural problems [8], seismic response [9] and fire response [10] were carefully investigated and reliable design models then studied. However, several other related structural and non-structural problems (e.g. serviceability) were not addressed. Quite recently, considerable effort has been devoted to studying the mechanical properties of CLT [11], providing rules for the design of connections

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[12–14], guidance for the method of assembly of seismic-resistant buildings [15–17] and also considering other design issues.

Current research on timber construction is mainly focused on the implementation of tall buildings. The construction of high-rise CLT buildings is something new and needs to consider several structural issues [5]. To support the realisation, several researchers have proposed innovative construction systems which differ from the 'conventional' platform frame method used in mid-rise light-frame wood buildings (structures of no more than 6 storeys [18]). Solutions which falls under the umbrella of the above-mentioned hybrid structures are gaining attention in many countries. Van de Kuilen et al. [19] studied a wood-concrete tall building and showed that it was possible to merge a core made of reinforced concrete with CLT floors and walls anchored using special integrated tension bars. In the paper, a wood-concrete skyscraper concept and the implications of such a building from a sustainability perspective were discussed. Another proposed new solution is described in [20]. The main lateral load resisting system is made by combining post-tensioned CLT walls with heavy timber frames. Post-tensioned timber core-walls coupled with energy-dissipating U-shaped flexural plates provide an optimum seismic-resistant ductile system. In a recent paper by Polastri et al. [21] the building has a superstructure in which beam-and-column frameworks resist the effects of gravity loads, and core substructures and exterior CLT shear walls resist the effects of lateral forces. Advantages of such a structural arrangement can include the creation of large open interior spaces, high structural efficiency and economical use of material. An interesting literature review on tall timber buildings is reported in Foster et al. [22]. The authors critically discussed the criteria to classify tall timber buildings and also suggested a classification for timber-based mixed or hybrid structural systems.

To the authors' knowledge, a very limited variety of new steel-timber hybrid construction systems are available, in particular, those that utilise CLT panels, although the advantages obtained by combining steel with timber in forming a building system are demonstrated in [23–26]. This lack is also very surprising since modern timber construction systems have connections made of steel and, generally, employ restraint devices or anchoring systems produced from steel. From a certain point of view, therefore, the combination of timber with steel elements or components appears as a natural consequence of the method of construction refinement. Referring to an interesting research carried out in Japan, Koshihara et al. in [27] and Isoda et al. in [28] presented the results of the first building fabricated in Japan using a timber-based hybrid technology. Concerning the research on steel-timber solutions in Canada, several studies [29,30] have been executed to develop an innovative building system called 'Finding the Forest Through the Trees' (FFTT). In FFTT buildings, the shear walls and floor slabs are constructed using large CLT panels which are connected all together through steel beams.

Even though the work on hybrid steel-timber-based solutions is still ongoing [31–33], more research needs to be undertaken to explore all their potentials, especially considering the role of timber in answering the global communities goal of 'sustainability'. Furthermore, there are still some interesting and significant structural design problems to be addressed. This paper introduces an innovative prefabricated modular solution for ultra-light steel-timber hybrid floors, based on the promising results of a recent industrial research project presented in [34] and [35]. Specifically, such findings demonstrated how it was possible to create seismic-resistant buildings with a dissipative structural behaviour starting from industrialised modular prefabricated components made of timber and steel. In this paper, the attention is focused on the development of a new engineered in-plane rigid and strong floor diaphragm for seismic-resistant buildings.

Standards such as Eurocode 8 [36], the International Building Code (IBC) [37] or other recognised building codes provide criteria according to which wood-based diaphragms are permitted to be prescriptively idealised as rigid. However, such criteria apply only to certain types of construction systems. In general, without design guidance to classify diaphragms as rigid, buildings have to be analysed considering the relative stiffness of both the diaphragm and lateral load resisting systems. Works which deal with the in-plane shear stiffness and load-carrying capacity of timber-based floors can be found in [38–40]. Referring to the conventional CLT floors, their diaphragmatic behaviour depends on that of the single panel. More specifically, the in-plane behaviour of CLT floors is mainly influenced by the response of the panel-to-panel connections, the length-to-width ratio of the floor and the aspect ratio of the CLT panels [38]. In general, the structural features of the building system, the spacing among bracing systems and the stiffness of the bracing systems also affect the final load-deflection in-plane response of floor diaphragms [41].

The floor diaphragm implemented within this research has an internal microstructure made of steel-timber composite elements. The seismic force acting on a storey flows through the modular composite elements to the main beams of the steel frames and then to the bracing systems, the latter joined by appropriate collector members. In order to measure the performance of the floor under applied horizontal loads and assess its relationship with the design details of the connections and other design parameters, we have carried out specific experimental tests. Two cyclic shear tests of a full-scale residential floor were executed, varying the connection arrangements. A monotonic test was then performed to push the specimen up to failure, monitoring every possible mechanism of deformation and unexpected failure in the components.

2. An innovative steel-timber composite floor diaphragm

2.1. General description

The floor has a hybrid layered section obtained by merging a slab of CLT panels with a grid of steel beams. The main steel beams hold up the steel-timber composite modular elements and are joined to columns at their ends. The panelized floor elements are displaced staggered from one bay to the next, moving along the longitudinal direction of the reference building, as shown in Fig. 1. The steel elements of the framework are realised using hot-rolled H-beams in accordance with the European product standard [42]. However, solutions made of wood with heavy timber beams and columns (*e.g.* presslam, glulam or LVL beech) are also feasible with this new technique. The fundamental unit of this innovative slim floor, which is repeatable, modular and prefabricated, is constructed offsite under controlled environmental conditions by joining a CLT panel with two custom-shaped cold-formed steel beams in a way that provides composite action. Each module is equipped with four special beam-to-beam joints, inserted within the secondary steel beams prior to being lifted into place and later positioned in contact with the web of the main beams. The joints are then quickly fixed on site to the main construction system by means of 8 torque controlled tightening bolts. The assembly of the floor components is completed by installing self-tapping screws along the edges of the CLT panels. The dimensions of the composite floor elements have been selected to facilitate transport and installation.

As it can be seen from Fig. 1, the on-site process of construction is designed to assembly floor components very quickly and through a few simple steps. The moving steel links of the joints have been developed in order to be integrated within a common