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Connections for steel–timber hybrid prefabricated buildings. Part I: Experimental tests

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HIGHLIGHTS

- Steel–timber hybrid construction systems foster a sustainable built environment.
- The structure is developed in order to use standardized hybrid components.
- Several tests are presented on different steel–timber and timber–timber connections.
- Designed connections permit the prefabrication of floor and shear wall components.
- Friction should not be disregarded in the design of CLT panel-to-panel connections.

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ABSTRACT

Steel–timber hybrid construction systems, in particular structures with steel frames, composite steel–timber floors and shear walls with Cross-Laminated Timber (CLT) sheets, combine the industrialized construction technology typical of steel systems with the advantages offered by CLT panels, namely lightness and in-plane stability. The paper proposes some original engineered solutions for joining CLT panels with steel elements. Specifically, it examines connections which allow both prefabrication of the components in the factory and their quick assembly on site. Experimental tests performed on a number of different connections will be presented and discussed. The first Part of the paper addresses some fundamental aspects and potentialities of steel–timber hybrid prefabricated systems. Two innovative steel–timber hybrid components to build floors and shear walls will be described in detail in the companion paper (Part II).

1. Introduction

Hybrid constructions have proved to be effective structural solutions for the fabrication of modern buildings, especially when the constructions are built by joining modular prefabricated elements on site. Hybrid structures can cover a wide range of constructions [1,2]. However, for contemporary multi-storey buildings, the most common ones are timber–concrete, steel–timber or timber–timber construction systems. Canada, New Zealand, the USA, Japan and Europe are areas with widespread use of buildings with a hybrid-based structure. In Europe, in particular, there are three important cases of hybrid tall buildings, built in England (Banyan Wharf Place), in Austria (Lifecycle Tower [3]) and in Norway (Treet, under construction [4]).

Hybrid structures are generally construction systems assembled through the connection and mutual interaction of structural elements made of different materials. The combination of materials can be defined depending on whether it refers to the construction elements and components or to the subsystems of the structures. This paper refers specifically to hybrid structures which combine steel and timber at the component level (hybrid slabs and shear walls) [5].

Several studies have been carried out regarding the hybrid construction systems in which steel and timber are the main structural materials or are joined in order to enhance the load-bearing capacity. Some recent literature can be cited: Asiz and Smith [6], Dickof et al. [7], Bhat et al. [8], He et al. [9] and Okutu et al. [10]. Such studies deal primarily with construction systems designed to build

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mid-rise buildings and with a view to the implementation of high-rise buildings. The strong interest in these innovative technologies has pushed the research into cost-effective, reliable and, above all, efficient solutions which allow hybrid buildings to compete against the most traditional and widely used construction methods [11–16]. The research presented hereafter deals with innovative hybrid construction systems that allow a quicker assembly of the construction elements, mainly prefabricated in the factory, reducing the time of on-site assembling operations and the construction costs. Under these conditions, the component manufacturing is highly industrialized and allows the building processes to take place even in areas exposed to harsh weather conditions.

Generally, the design of new residential buildings needs to meet important requirements and standards, which can include the use of natural and sustainable materials or ensure sufficient architectural flexibility regarding possible future changes in the use of internal spaces. Hybrid steel–timber frame-based structures allow buildings to be designed with an open architectural plan and a sustainability perspective [17–19], since this technology can cover long spans and limit the use of non-recyclable materials as much as possible. This research work concerns the implementation of hybrid construction systems with steel frame bearing elements, floor slabs and bracing systems produced by fastening Cross-Laminated Timber panels (CLT) to the steel beams or columns. The research evaluates different joining solutions suitable to develop an effective interaction between steel and timber elements. We discuss several solutions that provide adequate structural stability of the system and allow the development of a composite action between materials. Some of these solutions allow a quick assembly of the elements on site through the use of mechanical fasteners (dry solutions), while others require the use of epoxy-based resin. In both cases, each connection has been designed for an easy assembly of structural components, in particular considering the installation clearances (tolerances) related to the construction system and materials. Moreover, some joining solutions for CLT panel-to-panel connections will be analysed. Connections using self-tapping screws effectively transfer both in-plane and out-of-plane shear actions. This work investigates some arrangements of screws in order to maximize the floor stiffness or the inelastic deformation capacity of the bracing system.

The strength and stiffness properties of the connections, assessed via experimental tests, are reported together with the recorded load-slip curves. The experimental campaign is included within an industrial research project financed by a public fund for the utilization of local resources and for sustainable development.

The paper is organized as follows. The construction system is briefly described in Section 2. Section 3 discusses the evaluation of the floor behavior, considering in particular the structural hierarchy and the role of the different connections. Section 4 describes the fastening configuration designed to join the steel elements with the timber CLT panels. The same Section defines some mechanical solutions for assembling CLT panels. Section 5 reports and describes the experimental tests, while the recorded data are shown in Section 6. Section 7 discusses the experimental outcomes, particularly pointing out the feasibility of making steel–timber composite floors.

From the single connector to prototypes of a floor element and a shear wall component, the companion paper (Part II, [20]) will present two innovative prefabricated components. Moreover, it will describe some aspects concerning the behavior of shear walls, and more generally the lateral-load resisting system. With specific reference to the floors, the discussion will demonstrate the competitiveness of hybrid steel–timber structural systems compared to those using timber–timber or concrete–timber solutions.

2. Construction system

The reference building is aimed at the residential housing market. In addition to the modularity and easy assembly on site of the structural components, the structure has to provide architectural flexibility in the distribution of the internal and external spaces, to allow not only for flexibility in current use but also for possible modifications throughout the building life. The architectural plan permits different distribution layouts of the single housing units and, if required, volumes to be added to the building facades (Fig. 1).

The reference hybrid structure effectively exploits both the highly industrialized technology typical of steel construction systems and the advantages offered by the use of solid wood-based panels, such as lightness, structural in-plane stability, and low environmental impact, as well as the possibility to recycle and replace the degraded elements. In particular, it is possible to merge the assembly technologies typical of steel structures with those characteristic of timber constructions. In the construction system, the CLT panels replace the traditional plate and shell elements such as concrete floor slabs, shear walls or cores, with the aim of lightening the structure and improving the industrialization processes involved. The construction site organization, the quality control of the materials and the assembling process are significantly improved, leading to a considerable reduction in the construction time.

The construction system is regular and repeatable in space, with linear steel elements and flat timber components. Referring to Fig. 1, the main structure is built by placing steel frames along the two main directions of the building. The floors are assembled with steel beams forming a grid structure, which supports the steel–timber horizontal components, properly connected to ensure both the out-of-plane and in-plane diaphragm behavior to withstand the vertical loads and horizontal forces, respectively. The lateral stability of the structure is provided by some walls braced using steel–timber vertical components joined following a well-defined configuration. Fig. 2 illustrates the construction system of a generic intermediate storey for the reference building, with a detail of the structural arrangement of the bidimensional hybrid steel–timber components for the floors and shear walls.

Hybrid steel–timber components can be made of steel elements with different cross-section shapes, assembled with CLT panels using different connections and connection arrangements. Any of the following technologies can be used, as preferred: hot-rolled steel beams, asymmetric elements with welded flanges, cold-formed steel elements or even hollowed cold or hot formed sections (Fig. 2). Part II [20] of this work will describe in details innovative prefabricated steel–timber components for highly industrialized buildings. Specifically, floor and shear wall components are assembled joining timber and steel elements with standardized dimensions in order to increase the manufacturing efficiency. Connections are selected and designed to provide adequate transmission of shear actions among the resistant elements, or to develop the energy dissipation and deformation capacity of the structural system.

The next Section 3 discusses the structural behavior of the floors, considering both their in-plane diaphragm behavior and out-of-plane bending behavior.

3. In- and out-of-plane behavior of floors

The floors can be built using modular highly prefabricated steel–timber prototype elements as depicted in Fig. 2. Fig. 3 shows two three-dimensional views of a portion of the floor, pointing out the difference between the in- and out-of-plane behaviors.