Hybrid wood-based structural systems for multi-storey buildings

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ABSTRACT: This work concerns modern buildings with a highly prefabricated hybrid steel-timber construction system. The paper shows in detail an innovative modular structure built using standardized construction components. The floors consist of an assembly of composite steel-timber elements with flat CLT slabs, while the main structural framework is an ensemble of concentrically braced steel frames. The document presents two new construction technologies developed for the realization of ultra-light and sustainable composite floors. This study focuses particularly on the problem of the connections required to provide a flexibility-based collaboration between the steel and wooden elements. Several engineered connection solutions have been developed by considering the assembly methods and structural requirements, as well as the manufacturing time and related costs. This document discusses results obtained from an exclusive experimental campaign which includes short and long-term shear tests on connections and bending tests on prototypes of floor elements.

1 INTRODUCTION

More and more frequently, modern buildings, especially multi-storey residential or commercial buildings, are required to be flexible in response to different building functions. In addition, buildings have to reduce the energy consumed during their lifespan and the related emission of carbon dioxide into the atmosphere.

The housing industry is promoting green construction technologies for energy-efficiency buildings built limiting the use of non-sustainable and non-recyclable materials (Wanninger & Frangi 2014, Professner & Mathis 2012). This paper describes a special integrated and sustainable construction technology with a modular and prefabricated steel-timber structure. It is an innovative solution which makes it possible to quickly assemble the individual prefabricated building elements, minimizing the construction times and limiting the costs of the erection of the building. The horizontal prefabricated elements are made by joining cross-laminated timber (CLT) panels with cold-formed steel beams, while the main structural framework is composed of steel frames stabilized in both directions by means of concentric steel bracings or mixed timber-steel systems (Loss et al. 2015a). The production of the prefabricated floor components makes use of *ad hoc* connections (Loss et al. 2015b). The structure allows the replacement of the bearing elements or composite components at any time and, also thanks to its smart assembly method, rapid deconstruction.

The hybrid construction system presented in the next Sections exploits the advantages offered by two modern engineered products, CLT panels and customized cold-formed steel beams, providing a highly industrialized solution which can compete with other recognized environmentally-friendly timber and hybrid timber-based construction systems (Tesfamariam & Stiemer 2014, Smith & Frangi 2014, Buchanan et al. 2012).

The exploded view of a residential multi-storey building and related structural system are illustrated in Figure 1. The developed construction system represents a modern version of the classical steel-concrete composite structure and is simply derived by replacing traditional concrete slabs used in floors, vertical walls and bracing cores with CLT panels.

With specific reference to Figure 1, the main structural framework is composed of steel frames stabilized in the two main directions by means of traditional concentric bracing systems or modern hybrid steel-timber shear walls as shown in (Loss et al. 2015a), while the horizontal elements are made of composite steel-timber elements with CLT slabs. The on-site assembly of the elements and prefabricated parts makes use of common mechanical connectors or devices, such as bolts and brackets. The method of erection has been studied in order to minimize the execution times for construction and to allow construction work even under unfavorable climatic conditions.

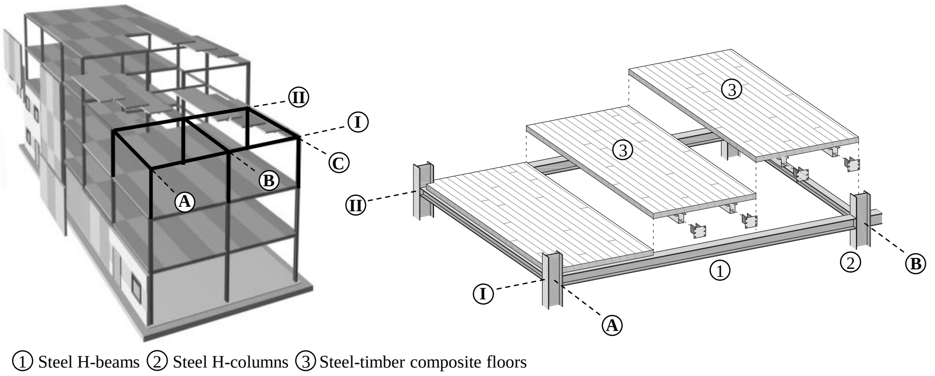

Figure 1. Hybrid steel-timber construction system for multi-storey buildings

Considering the three-dimensional response of the building, the gravity load flows from the floors to the frames, first loading the composite components and then transferring the relative vertical forces into the columns (Fig. 2a). These forces are later downloaded to the foundation. For the horizontal loads, each floor acts as a truss system transmitting the forces from the point of origin to the vertical bracing systems. In the truss system, each steel beam is braced by the CLT panels and their related beam-to-panel and panel-to-panel connections (Fig. 2b). The steel beams also perform a stabilizing function preventing any possible out-of-plane instability of the CLT panels. The global behaviour of the whole system is mainly guided by the steel frames under gravity loads. For seismic and wind forces, acting mainly in horizontal directions, the resistant mechanism is governed by the interaction between the diaphragms and the vertical bracing systems.

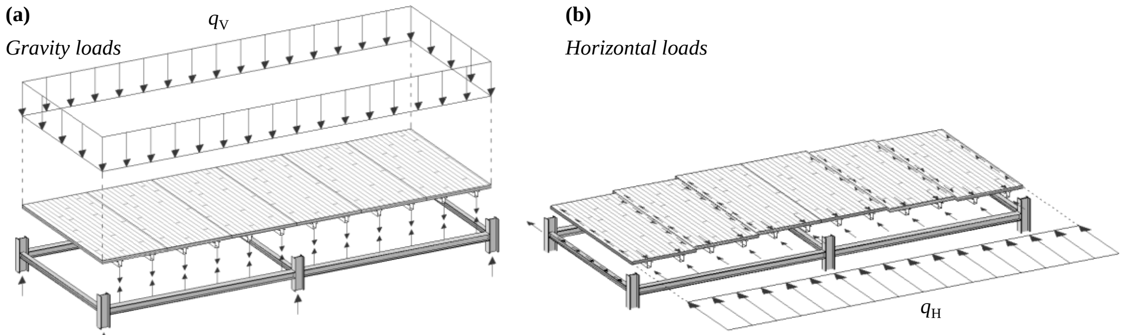

Figure 2. The flow of loads through the construction elements and within the structural system.

In this paper, the discussion mainly focuses on the implementation of the composite floor elements. Connections with ‘dry’ mechanical connectors or using epoxy-based resin will be considered for the production of the floor elements. In particular, the cross-section structure has been defined in order both to obtain a slim floor that is light, but has marked structure performance under flexural loads, and to optimize the use of steel and wood.

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is required with A2 connectors to obtain a composite system with performance compatible to that made utilizing type B3 connectors.

With regard to the long-term behaviour of connections, the charts in Figure 7 display the variation in the slip over 210 days. The applied loads, which are around the 30% of the connections' load-carrying capacity, were defined in order to simulate the service condition of floors. The outcomes of tests demonstrate that creep in wood and epoxy-based resin is particularly high in the first 60 days, and tends to consistently reduce the initial stiffness of connections, particularly in case type B3. After about 60 days, the increase in slip becomes contained and tends to be negligible after six months. Although temperature and relative humidity were measured during the tests, Figure 7 does not demonstrate a clear correlation with the increase in slip. In practical terms, based on these preliminary results, in the evaluation of the long-term behaviour of connections we have to consider a reduction in the elastic stiffness of about 59% and 66% for connections type A2 and B3, respectively.

The next Section will show the floor implementation and the evaluation of the flexural behaviour of the innovative composite steel-timber floor modular elements.

5 PROTOTYPE OF COMPOSITE STEEL-TIMBER FLOOR ELEMENTS

This Section deals with the development of modular prefabricated floor components. Four innovative steel-timber composite floor elements were defined, based on the connection technologies presented above. Figure 8 shows three different solutions for a residential floor with a 6 m span designed in accordance with Eurocodes 3 (CEN 2005) and 5 (CEN 2009). The abovementioned fourth solution is not reported here to protect the current patent pending. The floor components were defined by joining customized cold-formed steel beams, equipped with preformed parts, to CLT panels. The timber and steel sections were optimized in order to reduce the self-weight and the amount of material used in the formation of the construction components.

In brief, we have the following configurations:

- Floor-M-1, assembled using type A2 of connections, a 2.4 m width CLT panel and two Ω-shaped cold-formed steel beams. The full-threaded screws are inserted with variable pitch and inclined at 45° at the ends of the beams and at 90° in the middle.
- Floor-M-2, assembled using type A2 of connections, a 2.4 m width CLT panel and two Ω-shaped cold-formed steel beams. The full-threaded screws are inserted with variable pitch and inclined at 30° at the ends of the beams and at 90° in the middle.
- Floor-M-3, assembled using type B3 of connections, a 2.4 m width CLT panel and two U-shaped cold-formed steel beams equipped with perforated plates. The panel is fixed to the steel beams through the application of epoxy-based resin.

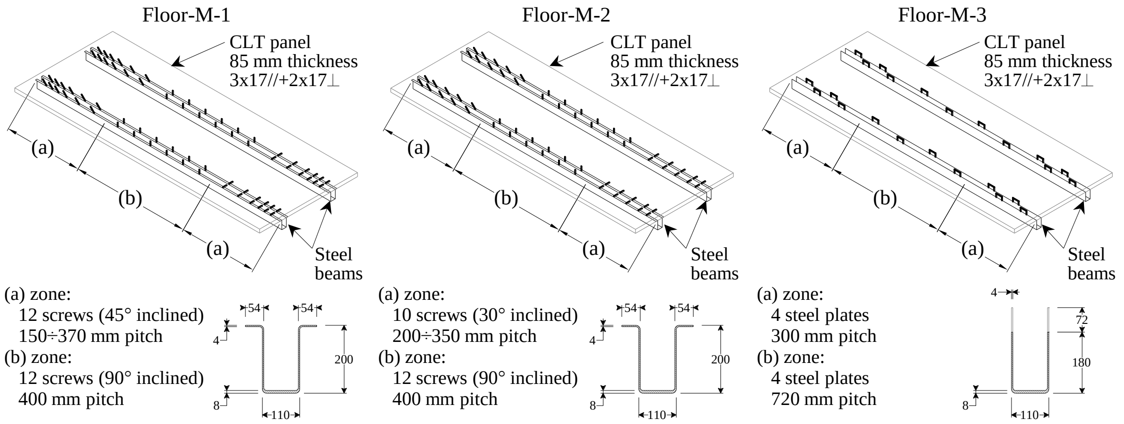

Figure 8. Design of three innovative steel-timber composite modular floor elements.

The behaviour of the floor modular elements was investigated via experimental tests. We used three different specimens for each floor configuration in order to perform displacement-controlled monotonic and force-controlled cyclic tests and to also take into account two restrained conditions. Figure 9a reports some details of the bending tests, including the *ad hoc* setup designed to apply the loads on the specimens, the installed instruments and the loading protocol.

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The floors have been implemented by using composite steel-timber elements made offsite by joining CLT panels with cold-formed custom-shaped steel beams. Two specific connection solutions have been presented and studied via experimental tests. The behavior of the connections has been investigated with short and long-term tests. The document provides several innovative modular floor elements with connections in different configurations.

The findings demonstrate that with this new technology it is very simple to design a floor with ductile behaviour. Tests have also helped in the identification of the failure mechanisms which can be used for the future definition and calibration of reliable design models

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