Engineering Structures 132 (2017) 695–713

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Innovative composite steel-timber floors with prefabricated modular components

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ARTICLE INFO

*Article history:*
Received 10 July 2016
Revised 27 November 2016
Accepted 28 November 2016

*Keywords:*
Slim floors
Composite floors
Steel-timber connections
Prefabrication
Modular components
Flexural behavior
Hybrid solutions
Cross-laminated timber
Sustainability
Green design

ABSTRACT

An innovative steel-timber composite floor for use in multi-storey residential buildings is presented. The research demonstrates the potential of these steel-timber composite systems in terms of bearing capacity, stiffness and method of construction. Such engineered solutions should prove to be sustainable since they combine recyclable materials in the most effective way. The floors consist of prefabricated ultralight modular components, with a Cross-Laminated Timber (CLT) slab, joined together and to the main structural system using only bolts and screws. Two novel floor solutions are presented, along with the results of experimental tests on the flexural behavior of their modular components. Bending tests have been performed considering two different methods of loading and constraints. Each prefabricated modular component uses a special arrangement of steel-timber connections to join a CLT panel to two customized cold-formed steel beams. Specifically, the first proposed composite system is assembled using mechanical connectors whereas the second involves the use of epoxy-based resin. In the paper, a FEM model is provided in order to extend this study to other steel-timber composite floor solutions. In addition, the paper contains the design model to be used in dimensioning the developed systems according to the state of the art of composite structures.



## 1. Introduction

As part of a process of sustainable development, in the last few years there has been a growing interest in reducing the resources and materials used in building construction, as well as in limiting both the energy consumed during the whole building lifecycle and the related carbon dioxide emissions ($CO_2$) into the atmosphere. Innovative structural systems combine different materials, structural elements, and construction detailing as well as smart construction techniques in a way that fulfills specific performance criteria and contributes to a more sustainable built environment [1–3]. The combination of materials in composite construction systems is a way to minimize the use of resources, therefore reducing the environmental impact of the building construction process. In addition, composite systems commonly provide overall performance higher than the sum of their individual components [4]. The literature shows a wide variety of composite systems which commonly includes the combination of steel with concrete, timber with concrete, timber with timber, steel with timber or other less common mixes of materials.

The most usual and widespread use of composite solutions is for the realization of floors or slabs. Composite floors are commonly built by joining two or more materials to form a collection of T-shaped coupled beams. In general, the composite technique is characterized by the connection systems used in forming the floors and the type of materials combined. Under flexural gravity loading, the upper element works in compression whereas the bottom element is loaded in tension. The connections transfer the shear forces between elements and keep them continuously tied along their extensions. Much research on composite steel-concrete and timber-concrete floors has been done in the past. Particularly, great effort has been devoted to the development of connections to be used in composite systems as well as in studying the effects of long-term loads on their effective behavior. The literature on steel-concrete and timber-concrete floors shows an incredible number of solutions available. Works dealing with the implementation of Timber-Concrete Composite (TCC) floors include, but are not limited to: [5–8]. For a brief state of the art on the TCC floors, we recommend [9]. We point out here that composite timber-concrete floors are very effective solutions for

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http://dx.doi.org/10.1016/j.engstruct.2016.11.062
0141-0296/

the rehabilitation and strengthening of existing buildings, as demonstrated in [10–12].

With specific reference to composite steel-concrete floors, an increasing amount of research has been performed over the last century in response to technological development. A remarkable number of documents is available, with a European code [13] specifically dedicated to the design of such composite solutions. The use of composite steel-concrete floors is very common with a wide range of construction applications, ranging from new residential buildings, to open-space structures and to skyscrapers and bridges [14–16].

Although composite concrete-based floors have become very common technologies, the use of non-renewable resources, the high demand of energy for production and transportation and the difficult recycling process impact on their sustainability. Possible other inconveniences are the required curing time, which sometimes can complicate on-site construction; the inherent self-weight of the structural components, which typically affects the costs of transportation; the limited number of prefabricated solutions currently available [17]. As 'dry' alternatives to the above-mentioned concrete-based traditional solutions, more recently timber-timber and steel-timber composite solutions have attracted more attention. The idea is to replace concrete slabs with innovative engineered wood products such as timber panels made of Cross-Laminated Timber (CLT) or Laminated Veneer Lumber (LVL). To the authors' best knowledge, very few publications address the issue of the composite timber-timber and steel-timber floor systems, as do for example [18–20].

The purpose of this paper is to discuss two innovative composite steel-timber solutions for residential floors of the next generation of multi-storey buildings [21]. This article introduces research work on modular prefabricated composite steel-timber floors made by combining CLT panels with customized cold-formed steel beams. The main challenge of this work was to develop a composite system which satisfies several strict requirements in terms of lightness, prefabrication, modularity, assembly method, sustainability, on-site installation, structural performance, and related manufacturing costs. In this composite system, the combination of steel and wood offers benefits in terms of construction process, as well as off-site production of the structural components in a factory. Based on the rational use of steel and timber, the implementation of composite floor components offers advantages, such as limiting their self-weight, and therefore, seismic action and the gravity loads transferred to the foundations; simplifying the execution on-site reducing construction time and the related costs; and finally increasing the sustainability of the final construction system, thanks to the use of recyclable and natural materials and to the ability to deconstruct and reuse the structural components. As the final product is a prefabricated standardised structural component suitable for dry construction, it will be possible to rapidly respond to the current housing demand. These floor solutions support the objective of sustainability by reducing the use of resources, therefore, lowering the embodied environmental impact of buildings.

This paper provides design details of these novel steel-timber composite solutions for floors and gives a comprehensive introduction to their design. The work provides an overview of the next generation of composite floors made by combining engineered wooden and steel products. The remainder of the paper is organized in six sections. Section 2 describes two innovative hybrid steel-timber solutions to develop composite floors. Experimental tests on prototypes of floors and the data measured are presented in Section 3. Section 4 discusses the FEM model developed to numerically study composite steel-timber systems. In addition, recommendations are made for the model implementation. The proposed design procedure is discussed in Section 5. Finally, Section 6 summarizes the results of this work and draws conclusions.

## 2. Innovative steel-timber composite components for residential floors

The composite steel-timber technology presented in this paper is engineered to obtain prefabricated modular floor components with excellent structural and non-structural performance. The construction components have been designed paying particular attention to sustainability. Fig. 1 gives the details of the prototypes of floor components, including particulars of the steel and timber elements, cross-section description and both the type and arrangement of connections. These novel solutions are realized by combining a very slim CLT panel with two custom-made steel beams equipped with special parts to quickly join them using connections in steel-to-timber shear configuration. Each mounted floor component is symmetrical in the two main directions and the self-weight is less than 0.5 kN/m$^2$.

With reference to the construction system depicted in Fig. 2, the modular composite steel-timber components can be quickly joined to a 'steel frame' structural system using only bolts at the ends of beams, and self-tapping fully-threaded screws along the panel perimeter, therefore permitting the building processes to take place even under unfavorable climate conditions. Without loss of generality, we have considered dimensions of a frame for a common residential building erected in Italy. Nevertheless, modular floor elements could be also included within other construction types, e.g. timber frame or massive wall panel systems.

The collaboration between the CLT panel and the steel beams is provided by a special arrangement of connectors, which are installed at a variable spacing from the centre to the ends of the steel beams. The cold-formed steel beams have a custom-made profile manufactured with special steel parts that provide the support for the installation of the steel-to-timber connections. With reference to Fig. 1, in the floor solution named Flo-S-1 the beams are joined using fully-threaded self-tapping screws, whereas the solution Flo-S-2 uses epoxy-based resin poured into the cavities and holes created in the CLT panel. In detail, for the composite solution Flo-S-1, elements are assembled by using type I screws at the extremities of the beam and type II screws in the middle. Type I screws are installed with an insertion angle of 30° while type II screws have connectors driven perpendicularly to the axis of both elements. The Ω-shaped cross-section steel beams are equipped with special mechanical devices welded to the flanges to facilitate the insertion of the screws. For Flo-S-2, modular components are assembled by gluing the CLT panel to beams, using epoxy-based resin to fill the cavities between the timber and steel elements. The U-shaped cross-section steel beams are fabricated by including steel perforated plates with a specific design pattern.

Tables 1 and 2 summarize the mechanical characteristics, the geometry and the construction details of the industrialized modular components for a 6 m span residential floor, designed for 2 kN/m$^2$ and 3.5 kN/m$^2$ live and permanent loads [22], respectively. Table 2 also includes the number of connectors and the volume of materials required. The amount of wood, steel and other materials used is also expressed as a ratio of kilograms or cubic meters per unit area of floor, as there is a strong correlation between these ratios and the manufacturing costs. We remark here that this paper provides two different methods of assembly, which vary not only in the equipment required but also in the manufacturing time, and in the skills and level of specialization required of the workers. In addition, in assembling the Flo-S-2 floor system we have to consider the environmental conditions (i.e. temperature and humidity) that can affect the mechanical properties of