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Innovative Composite Steel-Timber Floors with Prefabricated Modular Components

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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 behaviour 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.

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

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 [1,2,3]. 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], [6], [7] and [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 the rehabilitation and strengthening of existing buildings, as demonstrated in [10,11] and [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.

Fig. 1. Prototypes of innovative modular prefabricated floor components developed using a particular steel-timber composite technology.

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.

Fig. 2. Construction system and corresponding method of assembly of the composite steel-timber prefabricated floor components.

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.

Table 1 and Table 2 summarize the mechanical characteristics, the geometry and the construction details of the industrialized modular components for a 6 meter 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 the epoxy-based resin and the related curing time. The use of self-tapping screws is less sensitive to the environmental conditions. However, particular attention must be paid in driving the screws, following the guidelines provided by producers and using screwdrivers with a torque limiting device.

Table 1

Mechanical properties and specifics of the steel beams, CLT panels and connections.

Table 2

Construction details of the innovative steel-timber composite floor components.

	$n_{s,I}$	$n_{s,II}$	n_p	W_{CLT}		W_{BEAMS}		W_{CON}		V_{CLT}		V_{BEAMS}		
				kg	kg/m^2	kg	kg/m^2	kg	kg/m^2	m^3	m^3/m^2 (x10^{-3})	m^3	m^3/m^2 (x10^{-3})	m (x1
Flo-S-1	40	24	-	500	34.75	125	8.71	35.58	2.47	1.19	82.73	0.016	1.11	4.5
Flo-S-2	-	-	24	499	34.67	100	6.96	5.40	0.37	1.19	82.55	0.013	0.89	2.

Note: $n_{s,I}$, $n_{s,II}$ number of type I and II of screws, respectively, n_p number of steel plates, W_{CLT} weight of CLT panels, W_{BE} of steel beams, W_{CON} weight of connections, V_{CLT} volume of CLT panels, V_{BEAMS} volume of steel beams, V_{CON} volume of c

Both of the proposed solutions have been implemented in order to support the expected design loads for the main floor of a residential building and considering the deflection limits (l/300 for the instantaneous deflection where l is the floor span) under serviceability conditions in accordance with the European design code EC5 [23]. Since this work mainly refers to the singular modular components, in the design of floors for serviceability limit states we have ignored vibrations, although these may well prove critical for a lightweight floor system. Furthermore, this work was not aimed at identifying the governing design conditions for the composite floor system but rather to analyse the flexural behaviour of elements dimensioned starting from a normalised simplified loading condition. The effective load-deflection responses of the floor components have been studied by carrying out several full-scale bending tests and considering different methods of testing, as will be discussed in the next Section.

3. Bending behavior of the floor components for vertical loads

The flexural response of these innovative floors was investigated by performing experimental tests on full-scale prototypes of composite steel-timber modular components. For each of the abovementioned floor configuration, Flo-S-1 and Flo-S-2, three different tests were carried out in order to cover different methods of testing. Fig. 3 shows how, for testing method 1, the simply supported floor components were monotonically loaded under displacement control; for testing method 2, the simply supported floor components were loaded according to the EN 380 standard [24]; and, finally, for testing method 3 the floor components were fixed to the setup and later monotonically loaded under displacement control. The modular elements were connected to the setup using special steel devices which reproduce the effective stiffness of the beam-to-beam steel joints used during the building erection. For testing method 2, we defined the protocol of loading assuming first force levels (F_a, F_b and F_c of Fig. 3) comparable to the evaluated loads at the Serviceability Limit State (SLS) [23]. These six tests were performed at the Laboratory of Materials and Structural Testing (LMST) of the University of Trento. Due to different restraint conditions, the free span of the specimens in testing method 3 is 0.375 m higher than in testing methods 1 and 2. This needs to be remembered when comparing the experimental results, especially when considering the measured mid-span deflection or the related bending stiffness.

Fig. 3. Testing methods adopted in the bending tests performed at the Laboratory of Materials and Structural Testing (LMST) of the University of Trento.

3.2 Method of loading and specimen instrumentation

Tests were performed adopting a refined loading system as depicted in Fig. 4. The set up was designed to impose a stress state on the floor components comparable to that induced by a distributed constant load [25]. Loads were applied by using rollers that maintain the loading configuration at large deformations and by fastening thick steel plates covered with polythene sheets to minimize any possible relative friction (Fig. 4). Specimens were loaded considering eight distinct load imprints centred along the longitudinal axis of each steel beam. The area of loading was defined in order to avoid any crushing of the timber caused by the compression stress perpendicular to the grain. Fig. 4 also shows the restraint conditions adopted for the specimens. All tests were carried out under controlled environmental conditions, with a standard humidity and temperature corresponding to a service class 1 in accordance with EC5 [23].

Fig. 4. Specimen before a bending test with a three-dimensional view of the setup and some testing details.

Considering that the behavior of the composite steel-timber systems is mainly affected by the connections, testing was in accordance with the EN 26891 [26], EN 12512 [27] and EN 380 [24]. The monotonic loading was set at a displacement rate of 0.05 mm/s (Method 1 and 3), whereas in the EN 380 loading protocol (Method 2) the force rate was set equal to 115×10^{-3} kN/s. The EN 380 [23] loading protocol was used to understand the effective load-deflection response of the system under serviceability conditions, by loading and unloading the specimens at fixed design load levels and evaluating the variation of their mechanical characteristics within this range. For each specimen, particular attention was paid to the installation of the measuring instruments, placing them symmetrically on both main directions. The specimens were monitored during the tests by recording the local strain, both in the steel and timber elements, and the relative slip between the beams and the CLT panel, as well as the mid-span deflections and other vertical displacements near the ends of the composite floors, including settling at the restraints. The measurement points are illustrated in Fig. 5, while Fig. 6 shows the technologies used to monitor the tests.

Fig. 5. Scheme of arrangement of the measuring devices adopted in the bending tests.

Fig. 6. Measuring devices used to record the strain of materials and deformation of the specimens.

For testing methods 1 and 2, 35 devices were installed, whereas for testing method 3 there were 43 instruments in total to also take into account the effect of the fixed beam ends in the final response of the specimens. The load, strains and the displacements were recorded continuously during the test, with a frequency of 5 Hz.

3.1 Geometry and mechanical properties of the modular prefabricated components

The specimens were built using a 5.84m length by 2.4m width CLT panel and 6m length custom-made cold-formed steel beams. The CLT panels were manufactured with 5 layers of C24 [28] of 17mm thick timber boards. The grain direction of the outer layers was oriented in the main direction of the steel beams. The CLT panels were provided by a local factory with the required European Technical Approval [29]. The beams were manufactured by welding (Fig. 7a and Fig. 7b) two cold-formed customized preformed profiles of structural steel S355 [30]. The beams have a 4mm section thickness while the height varies from 180 to 200mm for Flo-S-1 and Flo-S-2, respectively. The beams were processed and reinforced at their edges by welding on transversal stiffeners and ribs (Fig. 7c). For testing method 3, the specimens were restrained using special supports rigidly anchored to the setup in order to eliminate rotation and/or sliding at the ends of beams. The supports were made by welding several flanges and ribs to a short thick steel pipe (Fig. 7d). The arrangement of holes in the supports was designed to easily fix the specimens to the setup.

Fig. 7. Some steps relating to the production of steel beams (a,b and c) and special restraint devices as built (d).

3.3 Assembly methods for the developed composite floors

This Section highlights the main differences in the mounting process of the composite floors, comparing the Flo-S-1 solution (Fig. 8a), joined using self-tapping screws, with the Flo-S-2 systems (Fig. 8b) built using epoxy-based resin. The work relating to the assembly of the prototypes of floor components was fundamental to understanding any possible difficulties in the manufacturing process recognizing the need to minimize the production time and costs.

As discussed in Section 2, the proposed Flo-S-1 innovative solution benefits from 'dry' technology. Fig. 8 shows the main working stages required for the assembly of the floor components. From this Figure, it can be seen that the insertion of inclined self-tapping screws requires particular attention as installing the screws tends to move the steel elements from their initial position. In addition, screwdrivers with a torque limiting device (such as an overload clutch) should be used in order to avoid any possible damage to the timber fibres induced by their local overload. For the proposed complementary Flo-S-2 'wet' floor solution, attention must be paid in preparing the epoxy-based resin, mixing together the resin, hardener, and aggregate components and working under controlled environmental conditions (temperature and humidity). During the subsequent pouring, it is necessary to avoid any leakage of the resin through the cracks in the CLT panels or other fissures. Also, the space between the steel parts and timber surfaces must be properly filled so it is important that resin does not leak out during the installation of the steel beams. Finally, temporary (at least for 8 hours) ballasting of the steel beams and panel is required ( ) to ensure good contact between them during the curing of the resin (Fig. 8d).

Fig. 8. Main stages of assembly for the Flo-S-1 (a) and Flo-S-2 (b) floor specimens; (c) Flo-S-1 specimens as built ballasted during the curing time of the epoxy-based resin; (d) Flo-S-2 specimens as built.

3.4 Preliminary tests to characterize the mechanical properties of the steel and timber elements

Within this experimental programme, several preliminary tests were conducted in order to evaluate the mechanical behavior of the CLT panels and steel beams. Bending tests were conducted using a loading device and measuring systems derived from those used for the composite floor components. Fig. 9 shows the charts of the load-deflection curves measured. A set of three specimens for each element: CLT panels, type 1 steel beams (Flo-S-1) and type 2 steel beams (Flo-S-2) was considered a statistically representative sample for this experimental study. From the charts of Fig. 9, it can be seen that the load-deflection curves of the steel beams are superimposed, whereas the response of the CLT panels is slightly variable. Assuming an elastic behavior of the elements, based on the Euler–Bernoulli beam theory [31], we estimated the Young's modulus (E) of the steel beams and the maximum normal stresses.

Fig. 9. Preliminary tests performed on the floor components: steel beams and timber panels.

Table 3

Comparison between the nominal and effective mechanical characteristics of the timber and steel elements

		CLT Panels			Ω-Beams			U-Beams	
F_R	kN		7.00			18.00		7.00	
Δ	ID	1	2	3	1	2	3	1	2
	mm	10.20	9.30	10.20	12.72	12.50	12.66	9.53	9.81
Δ_{mean}	mm		9.90			12.63		9.67	
Dev. St	-		0.52			0.11		0.20	
CV	%		5.2			0.9		2.0	
E*	N/mm^2		12000			210000		210000	
E	N/mm^2		12008			208622		214589	
E_E	%		0.1			0.7		2.2	
σ^*_+	N/mm^2		1.60			73.50		41.00	
σ_+	N/mm^2		1.62			69.47		40.74	
$E_{\sigma+}$	%		1.3			5.5		0.7	
σ^*_-	N/mm^2		-1.60			-93.00		-77.42	
σ_-	N/mm^2		-1.30			-86.36		-73.77	
$E_{\sigma-}$	%		18.8			7.2		4.7	

F_R : Force level; E* : Young's modulus (declared); σ^* : Normal stress (Theoretical); E_E : Error of E

Δ : Deflection; E : Young's modulus (evaluated); σ : Normal stress (evaluated); E_σ : Error of σ

For the CLT panels, the recognized model developed at Graz University [32,33] was used to estimate the equivalent elastic modulus E* and the normal stress σ^* acting at each cross-layer of the panels. Table 3 gives an overview of the main parameters measured by the tests, the mechanical characteristics estimated and those declared in the certificates of products. In accordance with the European probabilistic model code [34], assuming a normal distribution and lognormal distribution for the elastic modulus, E, of steel and timber the calculated effective coefficient of variation (CV) is less than 13% and 3%, respectively. In addition, the difference in normal stresses is always less than 20% in both cases and tends to be negligible for the steel beams. Therefore, these preliminary tests confirmed that the elastic behavior of the timber and steel elements is as expected.

3.5 Experimental results

This Section discusses the results obtained in tests of the six specimens. The data are organized in different representative graphs: global load-deflection relationship of the systems; deflection and slip between the beams and the panels along their lengths; strain curves of the composite sections. In Figs. 10 and 11, the variation in deflection (b), slip (c) and strain distribution (d) were plotted for five representative levels of load. With reference to the load-deflection curves ((a) in Figs. 10 and 11), F is the total load acting on the floor while Δ is the mean deflection measured at the middle of the specimens. The flexural deformation and slip were derived by interpolating 3 and 6 points, respectively, and averaging the values obtained from both beams. The elastic strain in the midsection of the specimens was evaluated by considering a linear distribution in both the elements. Therefore, the charts refer only to the loading conditions in which elements behave elastically. The arrangement of the measuring instruments allows the strain to be plotted in both the vertical and horizontal direction of the CLT panel. In other words, the shear lag effects in the transversal direction of the slabs were directly measured for each specimen. The main parameters directly measured or derived from the tests, in accordance with the testing standards recommendations, are also listed in Table 4. A comparison study on the load-deflection curves and elastic bending stiffnesses is given in Fig. 12 and Table 5. The charts in Fig. 12 also show the yield points of the systems estimated in accordance with the EN 12512 [27]. The corresponding yield load, yield deflection, initial stiffness and the stiffness in the second branch of the load-deflection curves are illustrated in Table 5.

Figs. 10 and 11, together with Table 4, demonstrate that the developed composite steel-timber systems have an extraordinarily ductile behavior, with a load carrying capacity (F_C) about three times higher than the relative design loads ($F_{d,ULS}$) in the less favorable case.

Fig. 10. Experimental behavior of Flo-S-1 floor components under different testing methods.

Fig. 11. Experimental behavior of Flo-S-2 floor components under different testing methods.

Fig. 12. Comparison study of the developed modular floor components.

Table 4

Data measured by tests on 6 different specimens of composite steel-timber floor components.

Test type	Level	Flo-S-1							Flo-S-2						
		F_{LS}	Δ	δ_{max}	timber		steel		F_{LS}	Δ	δ_{max}	timber		steel	
					ε^{+}_{max}	ε^{-}_{max}	ε^{+}_{max}	ε^{-}_{max}				ε^{+}_{max}	ε^{-}_{max}	ε^{+}_{max}	ε^{-}_{max}
		kN	mm	mm	10^{-4}	10^{-4}	10^{-4}	10^{-4}	kN	mm	mm	10^{-4}	10^{-4}	10^{-4}	10^{-4}
Testing Method 1 (MT1)	LS1	82.8	12.6	0.4	0.67	-2.47	5.11	-2.98	82.8	12.3	0.1	0.53	-2.39	5.36	-1.80
	LS2	113.2	17.4	0.6	0.99	-3.49	7.06	-4.16	113.2	16.8	0.2	0.72	-3.28	7.36	-2.48
	LS3	300.0	48.0	1.8	3.21	-9.89	9.91	-11.53	310.0	46.7	0.5	2.11	-9.09	-	-
	LS4	370.0	69.7	3.0	6.19	-13.91	-	-	410.0	84.5	1.5	7.48	-15.47	-	-
	LS5	411.2	100.0	4.8	11.76	-18.92	-	-	428.1	100.0	2.5	9.98	-17.64		
Testing Method 2 (MT2)	LS1	82.8	12.9	0.4	0.72	-2.09	5.22	-3.13	82.8	13.0	0.1	0.38	-2.43	5.34	-1.90
	LS2	113.2	17.7	0.5	0.98	-2.96	7.14	-4.31	113.2	17.5	0.2	0.52	-3.39	7.27	-2.59
	LS3	320.0	56.6	2.3	3.94	-8.94	-	-	320.0	47.4	0.6	1.59	-9.46	-	-
	LS4	380.0	86.7	4.0	9.20	-13.29	-	-	420.0	83.6	1.7	6.89	-16.07	-	-
	LS5	387.3	100.0	4.6	11.22	-14.66	-	-	435.3	100.0	2.6	9.69	-18.86	-	-
Testing Method 3 (MT3)	LS1	82.8	10.5	0.2	0.40	-1.72	3.99	-2.12	82.8	10.9	0.1	0.01	-2.34	4.16	-1.59
	LS2	113.2	14.6	0.3	0.60	-2.42	5.60	-2.93	113.2	15.2	0.1	0.05	-3.28	5.82	-2.22
	LS3	400.0	58.6	1.8	3.65	-9.24	-	-	400.0	58.8	0.8	1.32	-12.30	-	-
	LS4	500.0	93.5	3.8	9.15	-13.97	-	-	499.9	92.1	1.7	5.95	-18.35	-	-
	LS5	565.9	150.0	7.1	18.97	-22.47	-	-	557.2	150.0	5.0	13.65	-24.94	-	-

F_{LS} force corresponding to level LS, Δ deflection, δ_{max} maximum slip, ε_{max} maximum strain measured in traction (+) and compression (-)

Table 5

Behavioral parameters evaluated from the tests in accordance with testing standard methods (EN 12512, EN 26891 and EN 380)

Floor type	Testing Method	F_y kN	Δ_y 10^{-3}m	k_e kN/m	k_p kN/m	k_e/k_p -	F_C kN	W_p kN	$\eta_F=F_C/W_p$ -
Flo-S-1	Method 1	358.6	56.9	6322.1	1189.7	5.3	387.3	7.4	52.2
	Method 3	503.4	68.2	7303.5	763.8	9.6	565.9		76.3
Flo-S-2	Method 1	380.9	56.1	6793.1	1073.5	6.3	435.3	6.9	63.0
	Method 3	500.2	69.6	7127.7	708.9	10.1	557.2		80.6

F_y yield load, Δ_y yield deflection, k_e elastic bending stiffness, k_p inelastic bending stiffness, F_C load carrying capacity, W_p self-weight of specimens η_F capacity-to-self-weight ratio

For all the specimens the tests were concluded without reaching their collapse or loss of strength (Fig. 13). In fact, the setup did not allow deflections of more than 300 mm. Picture (c) of Fig. 13 shows an instance in which the secondary loading bar touch the main loading bar. Since the effective maximum and ultimate loads were not reached, a conventional maximum load (F_C) has been assumed corresponding to a deflection limit of 100mm and 150mm (l/60 and l/40, where l is the floor span) for simply supported and fixed specimens, respectively, which is representative of an ultimate condition in terms of accepted damage and potential local breakages in the steel beams. The stiffnesses of the floor components was evaluated by considering the behavior of the specimens between 10% and 40% of the maximum recorded loads. As expected, the stiffness is very sensitive to the type of connection used. In addition, the neutral axis of the composite system varies considerably between Flo-S-1 and the Flo-S-2, as it is mainly affected by the collaboration induced by the connectors. For these solutions, Flo-S-2 exhibits an excellent structural efficiency and a high capacity-to-weight ratio η_F ($\eta_F=F_C/W_p$) of about 63, which allows the thickness of the floors to be kept small resulting in lightweight systems. In accordance with Annex B of Eurocode 5, the estimated structural efficiency of the Flo-S-2 composite system is 43% higher than that of floor Flo-S-1 (Fig. 15). The inelastic deformation capacities of the composite systems are mainly due to response of the steel beams; the floors can undergo large deformations if we also consider the plastic deformation capacity (ductility) of the connections. The deformation mechanism involves the steel parts and not the CLT panel, and therefore, any possible brittle failures in timber elements or related instability of the compressed slabs is prevented. Some damage or local failures observed during the tests are depicted in Fig. 14. For Flo-S-1, instances of pulled out screws and local buckling in the flanges of the mid-span section are reported. In the case of Flo-S-2, pictures show the local buckling of the steel beams in correspondence with the connection locations, as well as deformation at the restraints. The experiments revealed that the CLT panels remain substantially intact after the tests, and in only one case was there a local fracture on an external timber board triggered by a knot.

As can be seen by comparing Figs. 10, 11 and 12, the response of the floor components in terms of resistance and deformation is similar when the systems are simply supported at their ends. Furthermore, the bearing capacity and the stiffness can be increased more than 39% and 26%, Flo-S-1 and Flo-S-2 respectively, when the steel beams of the floors are fixed (fully-restrained) at their edges. In the above-mentioned percentages, for stiffness, an adjustment factor η_k (about 1.2), has been considered, defined by Eq. (1), to take into account the different spans of the test specimens.

$$\eta_k = \left(l_1/l_2\right)^3 \tag{1}$$

where l_1 and l_2 are spans of simply supported and fixed specimens, respectively.

Fig. 13. Deformed shape of the system at the maximum imposed loads, more than 450 kN.

Fig. 14. Local damage observed during the tests in the members of the specimens.

Without loss of generality, to understand the behavior of the systems in more detail, first focus on the simply supported components (testing method 1 and 2). As shown in Fig. 12b, the connections play an important role in transferring the internal actions between the elements. Considering Flo-S-1 and Flo-S-2, about 46.5% and 71%, respectively, of the bending stiffness is provided by composite action between the elements thus the type of connector used in the assembly of the floor components is influential. A more detailed analysis regarding the elastic bending stiffness also highlights that the contribution of the CLT panel is very low while that of the steel beams varies considerably since the cross-section and the height of the steel profiles were different. This is mainly due to the low elastic modulus of timber compared to that of steel and demonstrates that the developed systems help to overcome the limits of the timber elements in terms of deformability under service loads.

The effects on the bending behavior of the cyclic loads under serviceability conditions were also evaluated with testing method 2, by applying the EN 380 loading procedure to the specimens. Referring to Fig. 15, the composite floor components, as hyperstatic systems, have a force-displacement response affected by the number and distribution of connectors. The behavior of the systems in the first cycle of loading was different from that of the subsequent cycle. Particularly, this phenomenon tends to be non-negligible as the number of connections employed increases, and it increases the effective stiffness. This phenomenon also demonstrates that there was a redistribution of the stresses in the connectors and, consequently, a new initial unloaded configuration which provides an increase in the relative initial stiffness. The effectiveness of the connections and the stress distribution adjustment are therefore very different from the Flo-S-1 and Flo-S-2 solutions. The more effective the connection systems are, the closer the neutral axis is to the interface of the elements. The neutral axes are plotted in Fig. 15, in addition to the calculated structural efficiency, which will be discussed in Section 5.

On the basis of these findings, considering also the cost-to-performance requirement, the number of connectors, thickness and the self-weight of the floor components, Flo-S-2 is the recommended solution. Indeed, Flo-S-2 is 265mm in height (about l/23, where l is the floor span) and can be produced using only 24 steel glued plates. The related self-weight is about 7 kN (0.5 kN/m^2), with an estimated bending stiffness and yield load of about 6.8 kN/mm and 380 kN, respectively. The cost of production is generally influenced by the number of connections and the volume of materials used in the manufacturing process, although the time to cure the resin is an important consideration. These results thus demonstrate that the Flo-S-2 is a more efficient solution compared to Flo-S-1.

4. Numerical simulation of the bending behavior of the floor components using a FEM model

This paper shows two innovative solutions to quickly fabricate ultralight slim floors. The originality of the solutions lies in the fact that the steel and timber act compositely in order to maximize the flexural collaboration between the elements.

Fig. 15. (a) Location of the neutral axes and (b) load-deflection response of the composite systems under cyclic loading complying to the EN380 standard.

Furthermore, the connections and the steel beams used in these systems have been specifically developed in order to obtain a reliable, economical and robust composite solution. In order to extend this study to other configurations, an FEM numerical model of the composite floor component has been developed to perform non-linear analyses, and allow characterization of the structural behavior of the floor components with sufficient accuracy. To this end, the model was developed in Sap2000© [35], using frames to reproduce the behavior of the steel beams and connections and shells to represent the timber CLT panels. In the model, all the frame and shell elements have been defined assuming linear elastic behavior of materials. The nonlinear mechanical behavior of the connections and steel beams have been accounted for by using plastic hinges. The constitutive laws for wood and steel have been derived from the rules for materials provided in Eurocode EC5 [23] and Eurocode EC3 [36], respectively.

In the model implementation there are five main points to be addressed: (i) in defining the CLT panel, a multi-layered material with different mechanical properties for each layer has been used to take into account the cross-directions of the boards and the grain direction of timber; (ii) the mechanical characteristics of both the steel and timber elements have been calibrated based on the main values obtained by the preliminary tests discussed in Section 3.4; (iii) the load-slip curves of the connections have been modelled by combining special frame elements with plastic hinges; (iv) in order to replicate the shear mechanism of the connections in all directions, the plastic hinges were defined considering appropriate surfaces of interaction; (v) in the FEM model, special link elements have been included to account for the interaction of CLT panels with the steel beams.

Fig. 16 illustrates the proposed model as built, in addition to all the FEM details, and the relative stress-strain constitutive laws adopted for timber and steel, as well as the load-slip curves of the connectors.

Fig. 16. Proposed Finite Element Model (FEM) for studying composite steel-timber slim floors.

The model shown in Fig. 16 was used to numerically simulate the experimental tests performed. Non-linear incremental analyses of the simply supported floor components loaded under displacement control were executed and their results compared with that extracted by the experimental tests. Fig. 17 reports the comparison between the experimental and numerical studies for both floor solutions. Considering the load-deflection responses of Fig. 17, the offset between the curves is always less than 9.5%, and the differences are very marginal for the Flo-S-1 floor solution. The FEM model calibration suffers from the effective load-slip curves assumed for the connections; the load-slip curves were both derived from [37, 38] following the same procedure for both the floor solutions.

Analyses at four reference points representative of the design (ULS, SLS), elastic (LS1) and plastic conditions (LS2) confirmed that the FEM model should only be used to numerically evaluate the local behavior of the system for preliminary studies. Fig. 17 depicts the comparison between the predicted and measured values expressed in terms of normal stress, bending deformation and relative slip. The error in the prediction can rise by up to 58.85% if the local stress distribution in the mid-span floor section is considered, particularly in the wood, which is also affected by its intrinsic complex state of stress. Similarly, the slip that occurred, which affects the forces acting on the connectors, tends to diverge from that numerically evaluated as the deflection increases. Thus, the findings suggest that this model is more attractive for practical use, while a more refined fiber-based model is suggested when the study of the local behavior of the components is the primary objective of the analysis.

Fig. 17. Comparison between the experimental and numerical studies of the non-linear behavior of the Flo-S-1 and Flo-S-2 floor components.

5. Model for the design of the composite floor components

The laboratory tests have revealed that the behavior of the composite floor components, as very slim systems, is mainly guided by the deflection limitations and not the bearing capacity (F_C), which is several times higher than the ultimate design loads ($F_{d,ULS}$). From Fig. 12, it follows also that design loads calculated in accordance with the Italian Building Code [39] are lower than the first yield loads. In other words, the measured load-deflection behaviors are markedly linear-elastic. The design problem of composite systems with semi-rigid connections, such as those presented here, was first studied in the 1956 by Möhler [40], and afterwards researchers concentrated on applying this model to other case studies [41,42]. In the Möhler approach the underlying assumptions are: (1) for both elements the simple bending theory can be used, (2) the shear deformation is disregarded in solving the equilibrium and deformation differential equations, (3) the connection of elements is assumed as continuous, (4) the cross-sections and stiffness of connections are constant along the main direction of the composite system and (5) the load-slip behavior of connection is assumed linear elastic. Accepting some minimal errors, tolerable for engineering purposes, in the case of simply supported composite system it is possible to define an equivalent bending stiffness to be used in the final solution of the differential equation. Moreover, for simple load cases, i.e. uniformly distributed load, the differential equation can be reduced in a closed form and the model extended to more complex cross-section beams as reported in Appendix B of EC5 [23].

The general formulae to obtain the bending stiffness is shown below:

$$(\mathrm{EI})_{\mathrm{ef}} = \sum_{i=1}^{2} \mathrm{E_i I_i} + \mathrm{E_2 A_2 a_2}^2 + \gamma_1 \cdot \mathrm{E_1 A_1 a_1}^2 \qquad (2)$$

where

$$\gamma_1 = \left[1 + \pi^2 \mathrm{E_1 A_1 s} / (\mathrm{k} \cdot \mathrm{l}^2)\right]^{-1} \text{ and } \gamma_2 = 1 \qquad (3)$$

l is the free span length of the composite system, k is the slip modulus of the connections, s is the spacing assumed for the connections and the other parameters are defined in Fig. 18.

Fig.18. Basic behavior of a composite system with a semi-rigid connection and relative design scheme.

The first analysis focuses on the behavior of each floor solution at the serviceability limit states reveals that the bending stiffness evaluated by Eq. (2) is compatible with that experimentally recorded or numerically predicted using the FEM model. Table 6 summarizes the main parameters considered in the comparative analysis. In addition, the bending stiffness in the case of noncomposite action (EI_0) and fully-composite action (EI_∞), as lower-bound and upper-bound limit cases, is listed. With reference to Eq. (2), the effective bending stiffnesses were calculated by substituting the EI of the CLT panel provided in the European Technical Approval [29] and the derived shear stiffness of the connections, here assumed amounting to 62.5×10^3 kN/m/m and 257.5×10^3 kN/m/m, in the case of Flo-S-1 and Flo-S-2, respectively. The $(EI)_{ef}$ were used to calculate the mid-span deflection of the floor components under serviceability loads, and then the results compared to those experimentally and numerically obtained. The predicted deflection is demonstrated to be comparable to the effective values, with a maximum error of about 20% in the most unfavorable case.

Table 6

Stiffnesses, deformation and stresses in the composite solutions according to the experimental measurements, finite-element analysis and analytical prediction.

SLS

			Experimental	FEM	Theoretical	Experimental	FEM	Theoretical
	EI_0	EI_∞	EI_{eff}	EI_{eff}	EI_{ef}	Δ_{SLS}	Δ_{SLS}	Δ_{SLS}
	x10^{12} N/mm^2	x10^{12} N/mm^2	N/mm^2	N/mm^2	N/mm^2	mm	mm	mm
Flo-S-1	7.41	22.63	13.5	12.91	11.69	12.6	13.84	15.3
Flo-S-2	4.24	18.65	14.3	12.90	16.30	12.3	13.86	11.0

ULS

	Timber						Steel					
	Experimental		FEM		Theoric		Experimental		FEM		Theoric	
	σ^+_{max}	σ^-_{min}	σ^+_{max}	σ^-_{min}	σ^+_{max}	σ^-_{min}	σ^+_{max}	σ^-_{min}	σ^+_{max}	σ^-_{min}	σ^+_{max}	σ^-_{min}
	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2
Flo-S-1	1.2	-4.2	1.1	-4.8	2.2	-4.9	148.2	-87.3	147.2	-100.8	178.1	-114.4
Flo-S-2	0.9	-3.9	0.2	-5.5	0.4	-4.7	154.6	-52.2	153.5	-58.1	158.4	-30.4

Referring to the ultimate limit state (ULS), Eq. (4) provides the normal stress in the timber and steel elements:

$$\sigma_i = \left(\frac{\gamma_i \cdot E_i \cdot a_i}{(EI)_{ef}} \pm \frac{0.5 \cdot E_i \cdot h_i}{(EI)_{ef}} \right) \cdot M_d \tag{4}$$

The design bending moment for the simply supported systems can be evaluated according to Eq. (5), assuming a relative design load of Eq. (6).

$$M_d = q_{d,ULS} \cdot l^2 / 8 \tag{5}$$

$$q_{d,ULS} = (\gamma_G \cdot G_k + \gamma_Q \cdot Q_k) \cdot b_T \tag{6}$$

where γ_G (=1.3) and γ_Q (=1.5) are the partial factors for permanent and live actions, respectively, and G_k and Q_k are permanent (including self-weight) and live loads, expressed per-unit area and b_T is the floor width.

For the floor in this work, the design load per square meter $q_{d,ULS}$ is applied to a floor width of 2.4m resulting in a load of 19.7 kN/m over a span l of 5.75m, and a corresponding bending moment of 81.3kNm. The corresponding normal stress distribution in the CLT panel and steel beams for this level of loading is shown in Table 6. As expected, the maximum normal stress in the members tends to be overestimated compared to the effective normal stress or the stress numerically measured. However, the analytical prediction is conservative and so suitable for design purposes.

It is evident that Möhler's model is in good agreement with the real observed behavior for both systems, especially in serviceability conditions. It can be considered a reliable method to quickly evaluate the mid-span deflection and the stress state in the members, even though the above-mentioned composite systems are assembled using nonhomogeneous materials and without a constant spacing of the connectors, hence without satisfying all the underlying assumptions. The maximum stress in the CLT panels diverges more than in the case of steel beams because the CLT is made up of a large variety of materials and types of boards, which increases the uncertainty of the mechanical properties of the wood. Furthermore, the strain in the CLT panel is affected by the intrinsic uncertainty of the wood, and thus a numerical model cannot take into account its anisotropic behavior without increasing the complexity of the problem solution. Möhler's model has proved to be an effective way to simply design these developed composite systems since their slenderness makes them susceptible to the serviceability requirements expressed in terms of deflection limits. The steel beams, CLT panels and connections behave elastically for code-defined [39] ultimate loads, here demonstrated to be very low compared to the real bearing capacities of the systems.

6. Conclusion

Construction systems with modular and prefabricated elements represent viable alternative solutions for the rapid erection of multi-storey residential buildings. The challenge for a more sustainable built environment has recently moved the community to devising building construction technologies that pay particular attention to energy-efficiency. Buildings have to drastically reduce the energy consumed during their whole life cycle, and the related emission of carbon dioxide (CO_2) into the atmosphere. This paper has clearly shown that the combination of new construction products with new construction and erection techniques can help to support the objectives of sustainability and is a very promising way to build green residential buildings in a fast and easy way. The research has focused on the realisation of innovative engineered floors based on prefabricated steel-timber composite components. The floor cross-section has been optimized to maximize its structural efficiency and to reduce the use of materials. Floor components are made offsite by joining CLT panels with cold-formed custom-shaped steel beams. Two particular technologies have been described that offer benefits in terms of lightness, sustainability, ease of construction and, when no longer required, ease of deconstruction and reuse.

The behavior of the developed floor components has been investigated through experimental tests, studying both the elastic and inelastic force-deformation responses, in addition to their local mechanisms and damage. The findings demonstrate that with this new technology it is very simple to design ductile floors with an exceptional load-carrying capacity, while at the same time limiting their cross-section height. The results suggest that the design of such floors is mainly guided by the serviceability requirements and the behavior remains elastic even at high loading levels. Tests have also helped in the implementation of a numerical FEM model for studying other steel-timber composite solutions. A manual calculation procedure has been presented for design purposes. This analysis includes common rules provided by the current standards for timber and steel structures.

The findings of this research allow the following general conclusions to be drawn:

- The developed systems are innovative not just in the combination of CLT panels with cold-formed beams, but also in the particular profiles of the steel beams which are equipped with special mechanical parts used in the assembly of the elements. These solutions are derived from a more general composite technology currently protected by patent rights.

- From the point of view of construction, the solutions presented here have several advantages in the way they are mounted on-site, allowing floors to be built in a faster and easier way than traditional concrete-based composite solutions. Modular elements are fastened using only bolts and screws.
- Both of the tested systems showed an exceptional bearing capacity compared to the design loads, with a considerable structural efficiency (close to 0.7 for Flo-S-2) and effective yield loads almost three times higher (F_y=381kN compared to q_y=27.6 kN/m^2).
- The structural performance is very significant considering the amount of wood and steel used. Averaging Flo-S-1 and Flo-S-2, a square meter of 6m span floor takes about 35kg of wood, 7kg of steel and 0.4kg of epoxy-based resin, and thus uses about 82% natural material, 17% recyclable material and only 1% non-recyclable material. This composite steel-timber technology is therefore an effective solution to supporting the objectives of sustainability in construction.
- The floor systems force the inelastic deformation into the steel beams, although, at high loading levels, (four or five times higher than the design loads) connections can undergo plastic behavior. Any damage occurs in the steel beams, while the CLT panel remains elastic. The floor systems remain in equilibrium since the instability of the timber and steel elements is prevented by the connections, which provide a very high slip ductility capacity even for a large flexural deformation.
- The adoption of fixed restraints at the ends of the steel beams can considerably increase the stiffness (up to about 40%) and strength (up to about 37%) of the floors. The beam joint details for both floor solutions can be adapted to suit the design needs without affecting their manufacturing process.
- Two models are provided for studying the bending behavior of the floor components. The FEM model is recommended to perform numerical simulations to establish the most likely behavior of composite steel-timber floors. A manual calculation analysis based on the recognized γ-method derived from Möhler and included in the current Eurocode standard is then given to design the presented floor solutions.

In future research, the diaphragm behavior of floors made with these modular prefabricated elements will be investigated. An experimental study of a full-scale prototype of floor system has been presented in [43]. Further studies relating to the issues of long-term behavior of the floors under constant loads, their fire resistance and vibrational performance remain to be addressed. On the basis of the promising findings presented in this paper, work on the remaining issues is continuing and appears fully justified.

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