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Structural and thermal behaviour of a timber-concrete prefabricated composite wall system

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Abstract

Wood is the oldest building materials and still now it plays an important role in the construction sector. There are many general advantages in using timber for building purposes. First of all, it is an environmentally friendly, easily recyclable material; it has a low weight in relation to strength, which is advantageous for transport, handling and production; moreover wood has aesthetic qualities, which give great possibilities in architectural design. Lastly wooden structures have an excellent performance in case of earthquake if compared to traditional structures. In Europe the development of the timber-concrete composite structures (TCC) began during a shortage of steel for reinforcement in concrete in the beginning of XX century. TCC application was primarily a refurbishment technique for old historical buildings, during the last 50 years interest in TCC systems has increased, resulting in the construction also of new buildings. This paper presents the analysis of the structural and thermal behaviour of an timber-concrete prefabricated composite wall system, the Concrete Glulam Framed Panel (CGFP) which is a panel made of a concrete slab and a structural glulam frame. The research analyses the structural performance with quasi-static in-plane tests, focused on the in-plane strength and stiffness of individual panels, and the thermal behaviour of the system with steady state tests using an hot box apparatus. The results validate the efficacy of proposed system ensuring the resistance and the dissipative structural behaviour through the hierarchy response characterized by the wood frame, the braced reinforced concrete panel of the singular module and by the rocking effects of global system. On the other side hot-box measures demonstrated a high level of thermal resistance of the system reaching U-values around 0,20 W m^{-2} K^{-1}. Moreover experimental data permitted to calibrate a FEM model with which will be possible to study and analyse the panels in different conditions and configuration in both mechanical and thermal field.

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Keywords: Timber-Concrete.Structure; glued laminated timber (Glulam), thermal analysis; structural analysis.

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1. Introduction

In Europe wood has been used as construction material mainly coupled with other traditional materials such as brickwork or stone. The usage of wooden structural elements in order to improve the seismic resistance of masonry buildings has been a practice widespread as consequence of disastrous earthquakes that destroyed buildings made with traditional constructive systems [1]. Timber-concrete composite structures (TCC) were developed in the first decades of 1900 and a system of nails and steel braces aimed to connect concrete slab and timber beams was patented by Muller (1922). TCC application was primarily a refurbishment technique for old historical buildings, during the last 50 years interest in TCC systems has increased, resulting in the construction of bridges, upgrading of existing timber floors, and the construction of new buildings. [2]. Recently the development of this kind of systems takes always more spaces in the scientific literature with the introduction of new materials and new inter-layers connections. In this terms, [3] and [4] presented studies and analysis of properties of timber-concrete composite systems, with different types of shear connectors.

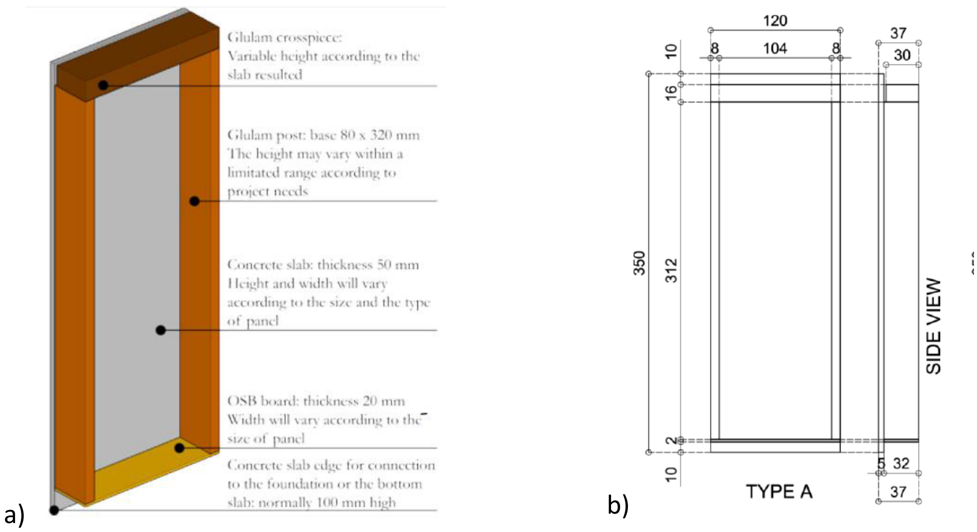


Fig. 1. (a) Prospective view of panel of type A (b) Cross-section of panel of type A and B with door.

Pozza et al. [5] presented a wide investigation of constructive system which mixes a typical platform frame with three thin external reinforced concrete boards acting together as a diaphragm against the horizontal forces. The construction system presented here in addition considers the sustainability throughout all their life cycle: from conception and construction to decommissioning. Keeping in mind that the management of building will greatly affect its impact on the environment, the paper approach is aimed at defining, at the same time, the structural and the thermal behavior in the conviction that these two aspects have to be considered together in the development of a sustainable building system.

2. Description of the CGFP specimens

In order to accurately characterize the thermal and structural properties of concrete-wood composite systems a framed panel (Figure.1a) was analyzed. It was composed essentially of two parts, a slab of reinforced concrete (RC) with a thickness of 50 mm connected with special connectors, integrated to the armature, at the timber frame of spruce homogeneous glulam with resistance class GL24h. This frame is formed by two posts of 80mm x 320mm section and by a crosspiece of 300mm depth, same width of the panel and variable height according to the slab resulted. In order to allow a wide range of architectural solutions the system provides certain types of standard panels. All the panels have basic characteristics like depth, type of concrete slab and section of the timber frame which are the same for all.

The differences are on the geometric characteristics as widely explained in Boscato et al [6]. From inside to outside there are: two plasterboard sheet, an air gap, the insulation layer (the standard is made of polystyrene foam with graphite), a ventilated air gap, the reinforced concrete slab and the external smoothing with the colored cement finishing. A building made of CGF (Concrete Glulam Framed) panels for load-bearing walls and floors is a modular system where, according to architectural and structural requirements, all the panels are prefabricated. For each panel an innovative type of connection enables the manufacture of the reinforced concrete slab, with a specially designed mesh, separately from the laminated wood frame. The individual panels are then assembled providing insulation inside the frames and then are easily transported to the site thanks to its small size. In the ground, after having set up a foundation curb, the panels are hooked to it and to each other with nails and screws. Once all the modules are assembled the construction ends with the plant, doors, windows and interior and exterior finishes.

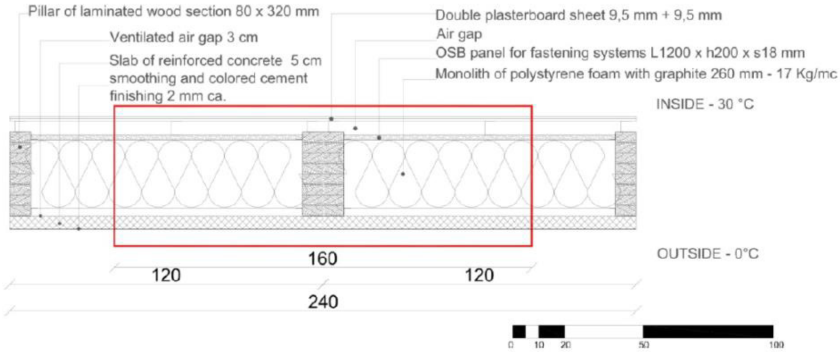


Fig. 2. Section through a panel of type A. Red box describe the area analyzed in the hot-box apparatus.

3. Experimental characterization of CGF panels

For the reasons above, the research program proceeded keeping in parallel the structural and the thermal point of view. It can be summarized in three main phases: the first phase was the laboratory experimentation, the second one was the analysis of the results and the related FEM modeling and calibration, and the last one was the numerical analysis of aspects that have not been tested experimentally. The experimental step, concerning the structural aspects, started with tests in order to measure the strength and stiffness in the plane of wall panels in various combinations according to the UNI EN 594:2011 [7]. In the thermal field, it was tested the behavior of the system, determining the steady state thermal transmittance with an hot box apparatus.

3.1. Mechanical Experimental analysis.

Mechanical characterization of the panels started with a Quasi-Static Ramp Tests test of in-plane stiffness according to UNI EN 594:2011 [6]. They were performed on panels with geometric characteristics as it is shown in Figure 1b. An horizontal load was applied in the plane at the top of the panel by an hydraulic actuator fixed, in turn, to a contrast structure wall [7]. At the same time, a vertical load was also applied at the top of the panel by an hydraulic jack, fixed to another contrast frame, in order to simulate the load resulting from an upper floor (Figure 3). Three tests were performed on a single panel "Type A" (test 1, 2, 3). Figure 3 presents the relationship between the force applied by the actuator and the displacement of the top of the panel. This shift was measured by a wire and displacement transducers, [7]. The results show a good agreement between the structural response of the three tests. The curves confirm the linear behavior until the ultimate load (circa 22kN) of CGFP panels; a dissipative capacity was recorded by Test 2 with bi-linear response. In detail, after the first failure load achieved together Test 1 (around 17kN), the Test 2 guarantees a strength capacity with deformable behavior (between 60 to 95mm) up to the collapse load. The failure mechanisms involve the link at the base, with local damage, and the bracing role of RC panel with flexural behavior followed by in plane shear collapse.

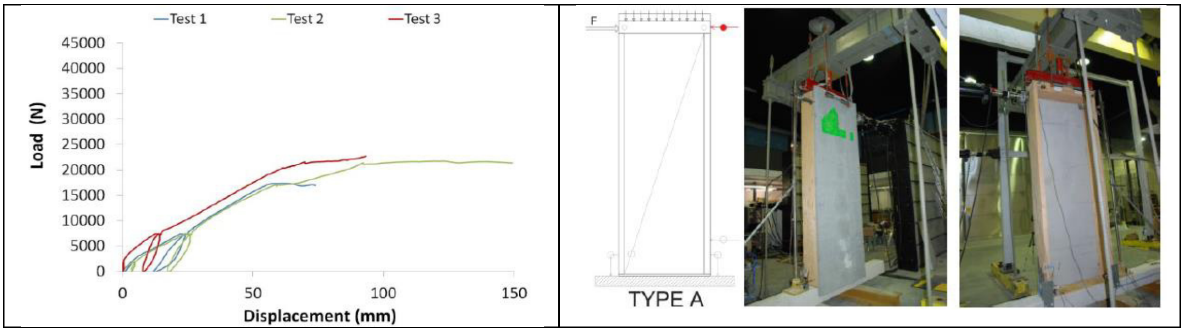


Fig. 3. Displacement as a function of applied load and Mechanical experimental set-up for panel Type A.

3.2. Thermal Experimental analysis.

Concerning to the control and limitation of energy consumption, the building system has been subjected to experimental tests carried out using an hot-box with reference to the standard UNI EN ISO 8990 [8]. In the tests performed, it has been considered the standard solution that involves the use of polystyrene foam as insulation. In particular, according to this solution two different samples were tested. In the first configuration was analyzed the system without the concrete slab and the ventilated air gap outside the package, while in the second configuration was measured the transmittance of the complete package, considering the air gap outside as a non-ventilated air gap (see Figure 2). For each samples we performed two tests: the results are presented below. In the first configuration the two tests performed the air temperature difference of the two wall sides was of 29,6°C and the transmittance value resultant were respectively 0,20 W m^{-2} K^{-1} and 0,19 W m^{-2} K^{-1}, therefore the results can be considered converged to the average value of 0.195 W m^{-2} K^{-1}. In the second configuration the air temperature difference of the two sides of the wall was of 29,4°C and the transmittance value resultant was 0,19 W m^{-2} K^{-1}. As we expected the concrete slab has not a great relevance in term of thermal resistance, therefore the values measured were approximately the same of the first configuration.

4. Numerical simulation

After the experimental characterization of the panel a FEM modeling phase was carried obtaining a numerical model of the system. The model was tuned on the basis of the collected data so that its static and thermal behavior reflects the values measured experimentally. In relation to the structural outlook, the calibration was performed taking into account the load applied and the displacement at the top of the panel; otherwise, concerning the thermal prospect, the correct material properties were set up and finally the experimental result was verified. The numerical analysis was carried out applying the Strand 7 code [9]. In the structural standpoint, the FEM models obtained will be useful in other researches in order to compare, for example, this system with others or to verify the performance of the system resisting earthquake action. In the thermal point of view, we could model the main building interface between technological units and we could investigate, verify and quantify the presence of thermal bridges. The phases of numerical modeling carried out are the following: creation of the numeric model of the individual panels and of the experimental mechanical configurations; set up of special connectors between the parties and their calibration according to the experimental results.

4.1. Mechanical numerical analysis.

The numerical model was used to simulate the performance of CGFP panel. The FE model was built by 2464 brick elements with mechanical and physic characteristics of constituent materials, such as Reinforced Concrete (RC) Panel and Wood frame, measured by experimental destructive tests. In the numerical model RC material has been characterized considering the isotropic behavior with Elastic modulus (E)=30960MPa and density=2400kg/m^3. The wood material has been modeled with orthotropic behavior, anisotropic along the fibers (direction 1) and isotropic transversally (direction 2). The characteristics assumed are E_1=14000MPa and E_2=7000MPa; for the shear modulus (G) = 300MPa, while the density is 650 kg m^{-3}. The FE model has been fixed at the base and restrained at the top in Z direction (see Figure 4a) to avoid the displacements out of plane. Considering the experimental response of the three tests (Figure 3) the linear static analysis was carried out. Figure 4a shows the performance of the panel considering the displacement in X direction to evaluate the in plane structural response. Through the maximum displacements at the top, recorded experimentally and numerically, the interface between wood frame and RC panel was calibrated changing the elastic modulus of steel connectors that link together the two elements, Figures 4b.Figure 4c shows reliability of updated FE model (blue curve) compared to experimental tests.

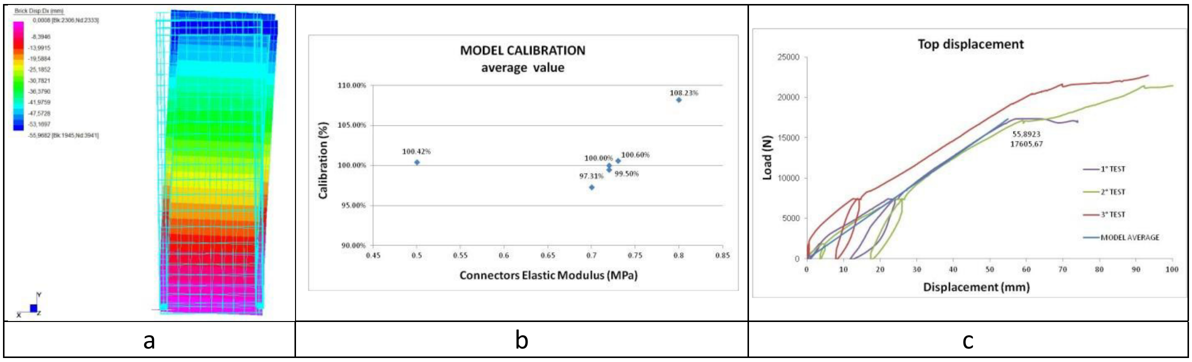
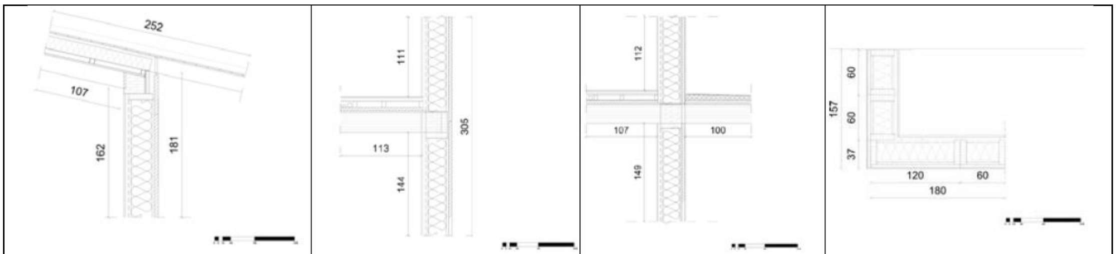


Fig. 4. Displacement as a function of applied load and numerical simulation results for panel Type A.

4.2. Thermal numerical analysis.

From the thermal point of view, in order to check the experimental result with the regulation directive, we calculated the transmittance using the thermos-physical data for different materials and weighting the results on area of glulam frame and insulation middle panel areas. The weighted transmittance in relation to the first and the second configuration converged to the value of 0,13 W m^{-2} K^{-1}, quite far from the values measured with hot-box. At this point, in order to verify the results so far obtained, we followed the same approach adopted in the structural field. We developed FEM models with the characteristics of the experimental tests and then we compared the results. The modeling is exclusively referred to the portion of the wall affected by measurement in particular it is related to the test of the second configuration. The thermal transmittance was calculated starting from the average heat flux from the simulation performed by setting the same boundary conditions recorded during the experimental test. The result derived from the numerical model is almost coincident with the experimentally measured data with a thermal transmittance of 0,189 W m^{-2} K^{-1}. We can assume that, in similar cases with a strong wall unevenness, the simple calculation of the transmittance according to the regulation does not return a correct value because it ignores the major losses due to the discontinuity of the wall package.



L^{2D}=0,50 W $m^{-1}K^{-1}$	L^{2D}=0,33 W $m^{-1}K^{-1}$	L^{2D}=0,53 W $m^{-1}K^{-1}$	L^{2D}=0,53 W $m^{-1}K^{-1}$

Fig. 5. Characteristics of thermal bridges in structures realized by panels of Type A.

On this basis and using the finite element modeling, it has been possible to investigate, verify and quantify the presence of thermal bridges in the structures built with this construction systems. This has therefore interested three of the main interfaces between technological units: the interface between vertical perimeter wall and floor; the interface between the perimeter wall and balcony; the interface between the perimeter wall and vertical coverage angle. In Figure 5 are reported some linear coefficients obtained for typical configurations. Values are quite low compared with similar configurations in more traditional constructive systems. A detailed analysis and data base of various connection is reported in [10].

5. Concluding remarks

This paper presents the outcomes of an experimental and numerical research project on the Concrete Glulam Framed Panel system (CGFP). The constructive system combines, with innovative dry connections, a slab of reinforced concrete to a frame of laminated wood. Panels that are mainly designed for the construction of residential buildings aimed at improving the quality construction, maintaining the link between economic sustainability and environmental sustainability. Through this research the first considerations can be drawn: 1) the structural performance results show that the assembling phase not implies imperfections and different response of CGFP panels; 2) in seismic field the dissipative capacity, that could be improved by complex configuration through the rocking response between different panels assembled together, offers encouraging results, 3) the results show the agreement between experimental and numerical approach confirming the simplicity of the proposed system thus reducing the variables at play. The U-value appears very low around 0,20 W m^{-2} K^{-1} in both analyzed configurations, and also the thermal bridges characterizing the use of this construction systems show to have limited dispersion effects compared to similar situation in traditional construction systems.

The completely dry prefabrication in small panels of this new construction system goes to meet different needs in terms of environmental, economic and logistics sustainability. The possibility of building the concrete slab separately from the frame of glulam allows great flexibility and speed in terms of both production and transport.

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