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FIBER REINFORCED CONCRETE. PART II: APPLICATION

Abstract.

The present paper is the second part of two companion papers related with the design and application of fiber reinforced concrete (FRC) in structural elements. It is presented a case study regarding the use of FRC in the development and construction of a new sustainable building system based on the assembly of structural prefabricated sandwich panels formed by thin outer layers of steel fiber reinforced self-compacting concrete (SFRSCC) and an insulation core. The outer layers of SFRSCC are connected with innovative glass fiber reinforced polymer (GFRP) connectors. The structural concept is presented and the numerical and experimental work carried out for the construction of a real scale prototype is briefly described.

Keywords: *fiber reinforced concrete; case study; FRC application;*

1. Case study - Sustainable pre-fabricated modular houses - LEGOUSE

A modular house construction system (named by LEGOUSE) was selected in this section to demonstrate the potentialities of FRC in structural applications. In this respect the expression “modular system” refers to the complete structure that is built-up by assembling of pre-fabricated elements.

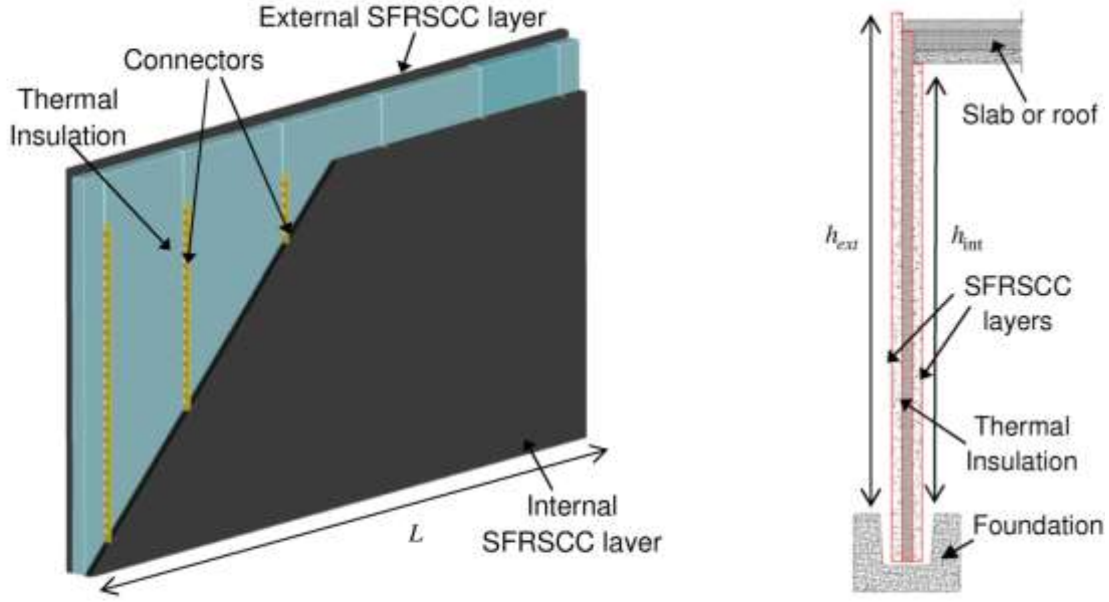
The concept of LEGOUSE building system is based on the assembly of structural prefabricated panels, for the erection of walls and slabs of buildings, namely single-family houses (**Figure 1**). The vertical panels carry loads to continuous foundations elements, and the horizontal panels behave as one-way slabs supported on the vertical panels. The panels are designed to fulfill the mechanical requirements of each structural element, and also present adequate acoustic and thermal properties. The sandwich panels are manufactured in facilities optimized for prefabrication, incorporating electrical, telecommunication, water and sewage facilities, and then are transported for the construction site for assemblage. Small number of constructions phases are required, reducing significantly the time to have a typical house completely operational, while being a competitive solution considering the costs and the global quality [1].

This project has involved the development and the characterization of physical and mechanical properties of the materials that compose the structural elements of this housing concept, the optimization of structural systems, the building and testing of the structural elements of the modular system, the full-scale construction and testing of a family modular house, and the development of the technical specifications, and design rules. This section presents a resume of part of the extensive experimental activities involved in the development of this project, and the construction technology adopted to build the real scale prototype.

Figure 1 - Representative single-family houses based on the LEGOUSE concept [1].

The panels have a composite constitution, made up of thin outer layers of steel fiber reinforced self-compacting concrete (SFRSCC) and an insulation core. To assure proper stress transfer between both outer SFRSCC layers, innovative glass fiber reinforced polymers (GFRP) connectors of low cost and reduced thermal bridge effect are used (**Figure 2**). During development, several GFRP connectors geometries were analyzed by carrying pull-out and push-out tests [2]. By eliminating conventional reinforcements, the weight and the production time of the sandwich panels are significantly decreased, while the durability is increased and the maintenance costs are decreased [1].

The sandwich panel used for the roofing of the LEGOUSE is similar to the panel for the facades, but since the span length and actuating loads are generally higher, the GFRP connectors have superior mechanical performance, and the bottom SFRSCC layer is reinforced at its middle surface with conventional steel bars in the direction of the span length, while the fiber reinforcement contributes for the flexural capacity of the panel and assures the transversal flexural demands.



(a) (b)

Figure 2 – Constitution of the sandwich panels of LEGOUSE building system: (a) Components of the devised load-bearing sandwich wall panel; (b) System cross section [2], [3].

In the scope of the LEGOUSE project, a real scale prototype of a single-family one story modular house with living area of about 100 m^2 was designed and built according to the plan presented in **Figure 3**. This prototype aimed to work as an open laboratory for continuous monitoring purposes in terms of material durability, and thermal and acoustic performance assessment.

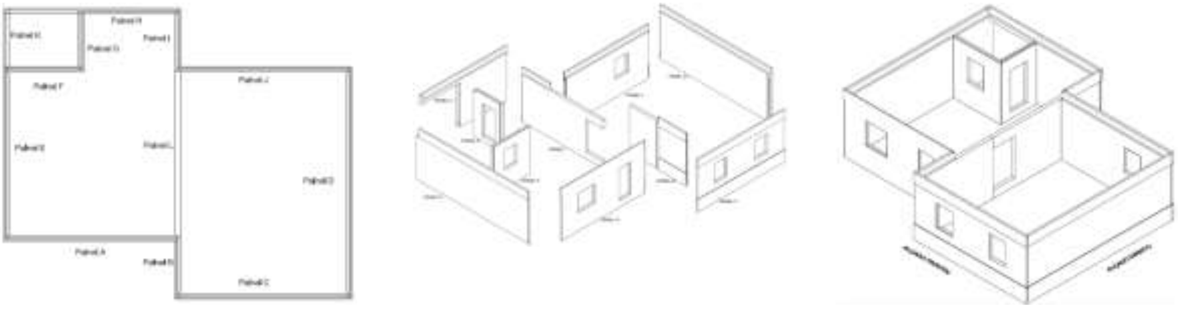
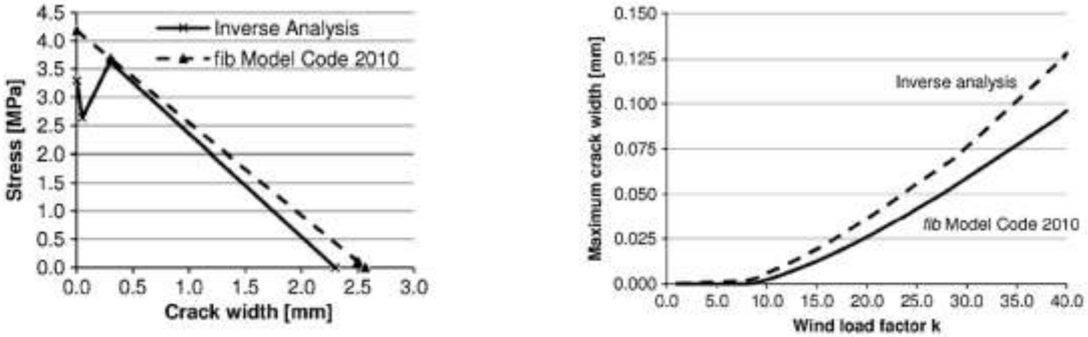


Figure 3 - Plan of assembling of sandwich panels for LEGOUSE real-scale prototype.

The configuration of the panels adopted in the prototype, namely the arrangement of the GFRP connectors and thickness of SFRSCC layers, was appraised by conducting a parametric study, based on the execution of numerical simulations on a FEM-based software, FEMIX, considering the material nonlinear behavior of the SFRSCC [3].

In order to assess the influence of the casting procedure on the fiber orientation and distribution, and their consequence on the SFRSCC post-cracking stress-crack width ($\sigma - w$) relationship in the context of the design of the developed sandwich panels, specific experimental and numerical research was conducted in this respect [4], [5]. The panels were designed assuming submitted to self-weight, load transferred by the roof slab and to wind loads. The FRC was of the strength class C40/50 and toughness class 7b. Two approaches were followed to define the $\sigma - w$ diagram (**Figure 4a**): i) a diagram based on MC2010; ii) a diagram derived from inverse analysis of load-CMOD curves obtained from 3-point bending tests of the SFRSCC notched prismatic beams. As can be seen in **Figure 4b** (where the wind load factor k represents the relationship between the applied wind load and the characteristic value defined in Eurocode 1 – Part 1-4), a reasonable agreement between both approaches was attained, where the $\sigma - w$ relationship obtained according to the MC2010 recommendations exhibited a slightly lower maximum crack width than the inverse analysis approach [3].



(a) (b)

Figure 4 – (a) $\sigma - w$ diagrams adopted in the analysis of post-cracking models influence. (b) Relationship between the maximum crack width and the wind load factor k for the two approaches adopted to determine the $\sigma - w$ diagrams [3].

The optimization of the SFRSCC composition, and the material characterization were performed by CiviTest company, member of the consortium of LEGOUSE project formed by Mota-Engil company, Structural Composites research group of Minho University and PIEP.

The composition of the SFRSCC is indicated in **Table 1**, where hooked-end steel fibers were used (length, lf, of 33 mm; diameter, df, of 0.55 mm; aspect ratio, lf/df, of 60 and a yield stress of 1100 MPa).

Table 1 - Mix proportions of steel fiber reinforced self-compacting concrete per m3.

Cement, kg	Water, kg	W/C	SP, kg	Filler, kg	Coarse aggregate, kg	Fine sand, kg	Coarse sand, kg	Fibres, kg
413	127.8	0.31	7.83	353	640	195	713	60

By executing compressive tests according to the [6], [7] recommendations, an average Young's modulus of 36.9 GPa and average compressive strength of 61.9 MPa were obtained at 28 days.

The post-cracking behavior of this SFRSCC was assessed by carrying out tests according to [8], [9]. At 28 days the following results were obtained (average values): f_{Lm} =6.3 MPa, f_{R1m} =9.81 MPa; f_{R3m} =5.79 MPa [2].

Additional tests were performed in order to evaluate the SFRSCC properties at fresh state and durability indicators. The detailed results and analysis are presented in [10].In **Figure 5 to 11** are shown a set of photos of the relevant phases of the construction of the prototype. For the roof panels, the top SFRSCC layer was cast in place in order to avoid joints between consecutive panels. The finishing of the external surface of the roof is constituted by an impermeable membrane. The construction of the prototype has ended with the installation of the infrastructures for water supply, sewage flow, electricity and communications, and painting (facultative due to the good finishing quality of the external faces of the panels).

Preliminary thermal and acoustic tests were carried out in the prototype, and comfort indexes similar, and even better, to those registered in traditional good constructions made by two leafs of clay masonry bricks of 11 cm thickness separated by 4/5 cm thick EPS (or mineral wool) insulation material were measured [11]. Two weeks were necessary to conclude the construction of the prototype and, according to the contractor, the cost of the building system in September of 2013 was about 400€/m^2.


Figure 5 - Casting the bottom SFRSCC layer.


Figure 6 - Application of the EPS insolation core material and continuous GFRP connectors.

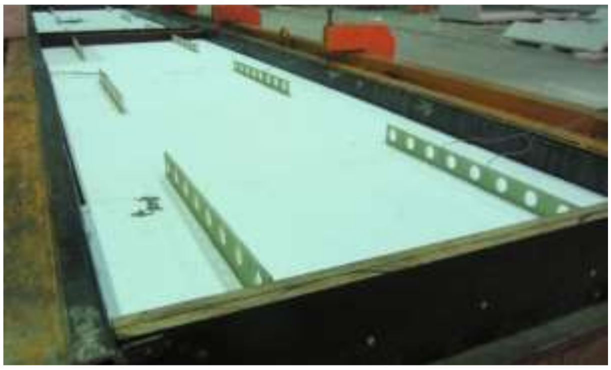


Figure 7 - Application of discontinuous GFRP connectors.


Figure 8 - Casting the top SFRSCC layer.


Figure 9 - Installation of the sandwich panels.

Figure 10 - Installation of the roof sandwich panels.

Figure 11 - Different views of the built prototype.

Conclusions

In this work were presented the principal considerations and dimensioning procedures to be adopted in the design of FRC structural elements, based on the fib Model Code 2010 recommendations [12]. The main topics focused were related to the classification of FRC, namely the meaning and determination of the mechanical properties related the toughness class; the calculation of the post-cracking residual tensile strength and of the structural characteristic length; the definition of constitutive relationship of FRC, namely the stress-crack width and stress-strain diagrams. It was also described and exemplified the determination of the fiber reinforcement contribution in the behavior of FRC structural elements at ultimate and serviceability limit states, namely in the calculation of the bending and shear resistance, and crack width.

As an example of the potentialities of FRC, it was presented a case study regarding its use in a new building system based on the assembly of structural prefabricated sandwich panels, formed by thin outer layers of SFRSCC and an insulation core. During the development of this building system, namely in the design of the real-scale prototype, were applied the design recommendation of MC2010.

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