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Development of sandwich panels combining fibre reinforced concrete layers and fibre reinforced polymer connectors. Part II: Evaluation of mechanical behaviour

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ABSTRACT

In the first part of this paper the authors describe an innovative sandwich panel that comprises Glass Fibre Reinforced Polymer (GFRP) connectors and two thin layers of Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC). This second part of the paper reports the investigation performed by the authors based on the numerical simulation of these sandwich panels. The simulations use the Finite Element Method (FEM) software implemented by the second author (FEMIX). Through linear static analyses and consideration of Ultimate Limit State loading scenarios, parametric studies were performed in order to optimise the arrangement of the GFRP connectors and the thickness of the SFRSCC layers. Moreover, models considering a specific nonlinear behaviour of SFRSCC were also constructed in order to simulate the progressive damage of the panel induced by cracking. In the scope of the nonlinear analyses, emphasis is given to parameter estimation of fracture modelling parameters for the fibre reinforced concrete based on both inverse analysis and the fib Model Code.

1. Introduction

In the first part of this paper [1] the authors proposed an innovative insulated panel to be used as a load-bearing wall of modular buildings. This panel comprises Glass Fibre Reinforced Polymer (GFRP) connectors and two thin outer layers of Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC). Although different types of FRP connectors have been already investigated for reinforced/prestressed concrete sandwich panels [2–6] and the SFRSCC was suggested as the material for sandwich panels [7], the combination of FRP and SFRSCC to obtain a sandwich panel that takes advantage of both materials is unknown at present phase.

Besides the use of unconventional materials, the proposed construction system has other peculiarities that turn it attractive. The walls act as the primary load carrying components of the structure transferring the loads to the foundation of the structure. The single storey wall panels span vertically between foundations and floor/roof panels without the need for additional intermediate supports. For aesthetic and practicality reasons, the vertical load is applied only in the inner SFRSCC wythe. In this context, the GFRP laminar connectors proposed and evaluated experimentally by the authors in the first section plays an important role in the structural system to make the two layers of SFRSCC act jointly to withstand the actions to which the structural panels are exposed.

This paper arises thereby from the need for a better understanding of the structural behaviour of the proposed system. Efforts are made for assessing the best solutions for the geometry of the panel components and arrangement of GFRP connectors, through parametric analyses. The studies include analyses of the panel subjected to the combined action of axial loadings (i.e.: slab's reaction) and wind load pressure. The forces due to seismic action were disregarded, since the dwellings have been initially designed for non-seismic areas. In the parametric studies, the proposed wall system is analysed at the Ultimate Limit State (ULS) using linear Finite Element (FE) analysis procedures. Through these analyses the geometry and arrangement of the panel components are designed to resist the imposed loadings in the elastic range with no or minor damage. For a better understanding of how the proposed solution for the structural system performs when subjected to extreme loading conditions such as high winds, a nonlinear design of the sandwich panels is also performed taking into account the degradation (i.e.: cracking) of the SFRSCC layers. Through the nonlinear analyses, the ductility of the proposed system under severe conditions is verified, providing the evolution of inelastic phenomena such as crack widths and deflections.

Although the FE numerical modelling of the mechanical behaviour of sandwich concrete panels have been already presented in

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the literature by other authors [8–10], this work differs from the other researches due to the laminar nature of the GFRP connectors and also due to the particular loading condition that characterises the proposed structural system (i.e.: vertical load applied only to the internal SFRSCC layer). Moreover, due to the specific proposal of using SFRSCC layers without any reinforcing bar, in this paper emphasis is given to the choice of the fracture parameters that characterises the SFRSCC, where two different approaches to model the nonlinear behaviour of the SFRSCC are compared.

2. Parametric studies for the design of the sandwich panels

To better understand the structural behaviour of the panel, a set of systematic parametric studies based on linear elastic modelling of the sandwich panels was carried out. At an initial stage, focus was given to the optimum arrangements and properties of the parts of the sandwich panel. The parameters considered in these studies were: the position, orientation and continuity of the GFRP connectors and the thickness of the SFRSCC layers. The FEM-based software FEMIX [11] was used for these analyses. A linear and elastic analysis was adopted for this phase of the design process, since preliminary tests with small size prototype systems of the sandwich panel have indicated that damage due to cracking of SFRSCC had minor relevance even for loading levels corresponding to the ultimate limit state design conditions [12]. This decision was also caused by the relatively high computing time of material nonlinear analysis of real size sandwich panels requiring to find the best configuration for the constituent elements of the panel.

2.1. Common features: geometry, mesh, loading, support conditions and material properties

In this work all the analyses were limited to a reference sandwich panel of 8.00 m length, with an external (h_{ext}) and an internal (h_{int}) SFRSCC layer of 2.60 m and 2.40 m free height, respectively (see Fig. 1 from the first part of this paper [1]). The length of the panel was determined by transportation and handling constraints. In turn, the height of the internal SFRSCC layer was related to the minimum ceiling height of the building. The height of the external SFRSCC layer was defined as the height of the internal layer plus the thickness of the slab or roof that is supported by the internal layer. The thickness of the insulating material was kept equal to 100 mm, whereas the thickness of the SFRSCC layers was one of the variables studied. These dimensions are consistent with the ones of the conventional sandwich panels, according to the PCI Committee on Precast Sandwich Wall Panels [13].

Similar finite element (FE) meshes were adopted for the different panels, differing only on the position of connectors. The FE meshes of the sandwich panels consisted of Reissner–Mindlin flat shell eight nodes finite elements for modelling the internal and external SFRSCC wythes, as well as the GFRP connectors (see Fig. 1). The FE mesh coincides with the middle surface of these components of the sandwich panel. The Gauss–Legendre integration scheme with 2×2 points was used in all elements. The FE models assumed that bond between materials (SFRSCC and GFRP) is perfect. In the first part of this paper, the pullout responses for different types of connections were presented and a high initial rigidity of these connections was observed. In the authors' opinion, this observed behaviour justifies the possibility of considering perfect bond between both materials during the linear stage.

The contribution of the thermal insulating material for the structural behaviour of the panel is disregarded. In fact, previous experimental research has shown that the contribution to the composite action of sandwich panels provided by the bond between the concrete layers and insulation is less than 5% [6]. Moreover, due to the movements that the panels are subjected, caused by thermal gradients and/or wind load, the bond between concrete and insulating material cannot be guaranteed along all the service life of the structure.

The panels are subjected to both horizontal (*x* direction according to the referential defined in Fig. 1) and vertical loads (*z* direction). It is considered that the roof/floors transfer the vertical forces to the load-bearing walls and into the foundation through the SFRSCC layer that faces the interior of the building, herein designated as internal layer of the sandwich panel (Fig. 2). The lateral loads (i.e.: wind) are withstood by the sandwich wall panels that span between the floor/roof and the foundation. Floor/roof systems, herein designated as slabs, are considered to act as horizontal diaphragms, in the sense that horizontal loads are carried through these diaphragms into the shear walls (the sandwich wall panels in orthogonal direction to the panel studied herein). These supporting conditions are shown in Fig. 2.

The vertical loads correspond to the self-weight of the wall panel and the load (R_{SL}) transferred by the slab (10.0 m of span), which is simulated by a centred line force applied to the upper edge of the internal SFRSCC layer (see the schematic representation in Fig. 2). In order to guarantee this condition in practice the connections between the wall panels and the slabs are designed to

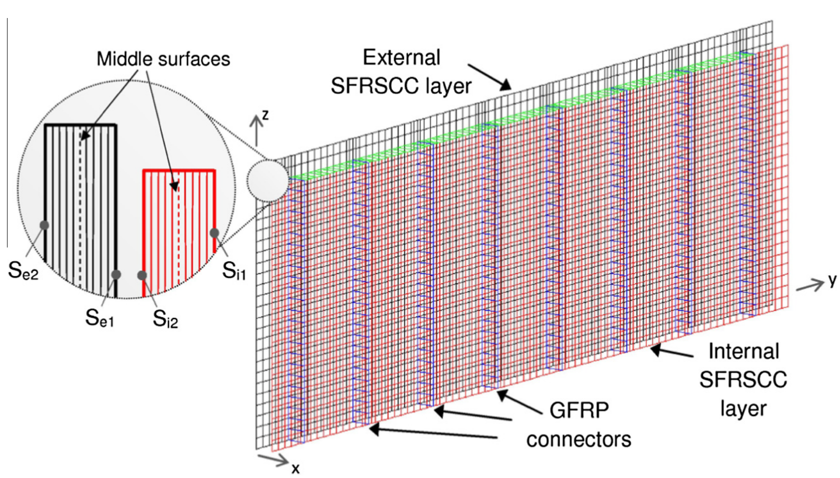

Fig. 1. View of FE mesh adopted for panels consisting of arrangements C, D and E, and detail of the layered shell elements.