FLEXURAL AND SHEAR BEHAVIOUR OF PRECAST SANDWICH SLABS COMPRISING THIN WALLED STEEL FIBRE REINFORCED SELF-COMPACTING CONCRETE

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ABSTRACT

Insulated sandwich panels are often composed of external concrete layers, mechanically connected through metallic elements, such as trusses. Due to their high thermal conductivity, metallic connectors tend to cause thermal bridges on the building envelope. In view of this problem, an innovative solution for sandwich slabs is proposed within the framework of a pre-fabricated modular housing system. The referred slabs are based on a sandwich solution composed by two thin layers of Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) that are connected by thin perforated plates of Glass Fibre Reinforced Polymer (GFRP), used together with a thermal insulation core-layer. The bottom concrete layer is reinforced with conventional steel rebars and steel fibres, whereas the upper one does not have conventional reinforcement. This paper presents a preliminary experimental program aiming to assess the flexural and shear behaviour of this type of sandwich panel solution. The obtained results confirm the feasibility of the proposed sandwich slab system, revealing its capacity in terms of load carrying capacity and ductility performance. In addition, the flexural behaviour of the tested specimens was numerically analysed for the serviceability limit states using the finite element method with consideration of the material non-linearity.

Keywords: sandwich panels; modular housing system; steel fibre reinforced self-compacting concrete (SFRSCC); glass fibre reinforced polymer (GFRP) connectors

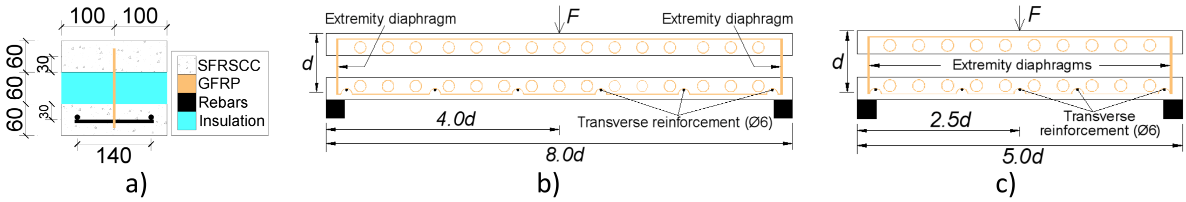
INTRODUCTION

The main interest on using sandwich panels for buildings is justified by their structural and thermal efficiency. However, concrete sandwich panels used for slabs or walls usually consist of two external concrete wythes, separated by a insulation layer and mechanically connected through steel trusses, which penetrate the insulation layer, causing undesirable thermal bridge effects due to their high thermal conductivity [1, 2]. To overcome this issue, an innovative solution is currently under study [3], based on the use of thin outer wythes of Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) together with Glass Fibre Reinforced Polymer (GFRP) connectors which are used jointly with a thermal insulation core-layer. The role of SFRSCC is related to the inherent benefits of using fibre reinforced concrete instead of concrete with conventional reinforcement, resulting in structurally efficient and lightweight elements and in a reduction of the labour costs by eliminating the need for placing the reinforcing bars in the outer concrete layers. The GFRP connectors are partially embedded in the SFRSCC layers and constitute a promising solution for modular housing application, due to their low thermal conductivity, high durability under aggressive environments and low maintenance requirements. The sandwich slab panel studied in this research work is part of a pre-fabricated modular housing system and assumes a span length of 6.00 m. The typical cross sectional dimensions and configuration/position of different elements (SFRSCC, GFRP, rebars) was defined with basis on the execution of a systematic parametric study for optimization of the structural concept [4]. This paper focuses on the pilot experiments performed for the assessment of the behaviour of strips that are representative of the defined SFRSCC-GFRP sandwich panel solution. To this end, an experimental program was executed, comprising flexural and shear tests for both service and failure conditions.

SPECIMEN PROTOTYPES AND MATERIALS

To assess the structural performance of the sandwich slabs in terms of shear and flexural behaviour, the experimental work was conducted on small 20cm wide sandwich slab strips with the cross-sectional dimensions presented in Fig. 1a. The thickness (60 mm) of the SFRSCC and insulation layers (extruded polystyrene foam) and the amount of conventional reinforcement (ribbed steel reinforcing bars) in the bottom SFRSCC layer (two longitudinal 10 mm rebars) were determined through the execution of the aforementioned parametric study [4]. Two different types of specimen prototypes were studied. For the first set of prototypes, the ratio between the span and the effective depth of the cross-section (l/d) was established as l/d=8 (see Fig. 1b) in order to test the specimens subjected to bending (three specimens named as F1, F2 and F3). The second set of prototypes had l/d=5, as depicted in Fig. 1c, aimed to evaluate shear behaviour (two specimens named as S1 and S2).

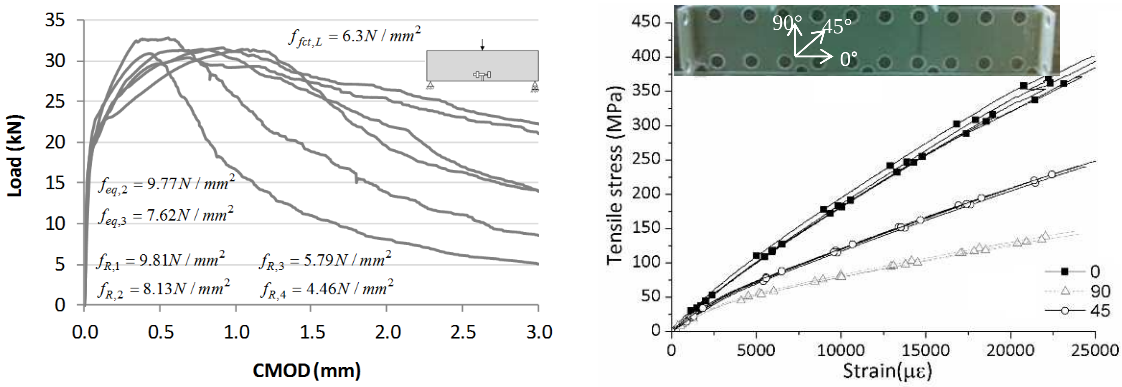
Figure 1. Slab prototypes: a) cross-section adopted for the sandwich slab strips (dimensions in millimetres); b) specimens with l/d=8; (c) specimens with l/d=5



The mixture composition of the developed SFRSCC can be summarized as: cement CEM I 45.5R – 412 kg/m^3; limestone filler – 353 kg/m^3; water – 124 kg/m^3; superplasticizer – 7.8 kg/m^3; fine sand – 179 kg/m^3; river sand – 655 kg/m^3; crushed stone – 588 kg/m^3; hooked steel fibres – 60 kg/m^3. The fibres (hooked end steel fibres) have 37 mm length, 0.5 mm diameter, aspect ratio of 74 and a yield stress of 1300 MPa. Compressive strength and modulus of elasticity were assessed at the age of 28 days by testing cylinders with 150 mm diameter and 300 mm height, obtaining an average value of the compressive strength equal to 69.2 MPa with a standard deviation of 2.7 MPa. The average elasticity modulus was 35.4 GPa. The flexural behaviour and the parameters related to the post-cracking behaviour of the SFRSCC were assessed by using seven 150×150×600 mm^3 notched beam specimens under three point bending test [5]. The corresponding load *versus* crack mouth opening displacement (CMOD) curves are depicted in Fig. 2a. The average values for the limit of proportionality ($f_{fct,L}$), equivalent ($f_{eq,i}$) and residual ($f_{R,j}$) flexural tensile strength parameters are provided in this figure, and were obtained according to [5, 6].

The GFRP connectors used in this research work were all manufactured through the Vacuum Assisted Resin Transfer Moulding (VARTM) process. The composite was comprised of a thermosetting polyester resin matrix and E-glass fibres fabricated by crossplying unidirectionally-reinforced layers in a 0° to ±45° stacking sequence. The reinforcement consisted of 50% of the fibres in the 0° direction (longitudinal direction), and 50% of the fibres in the ±45° direction. The produced laminates were 5.0 mm thick, having the necessary content of resin to impregnate the fibres, totalizing about 60% of fibres and 40% of resin, in volume. The GFRP profiles were produced and then the holes of 30 mm diameter (with 75 mm spacing) were made afterwards using a drilling machine. Tensile tests were executed with representative samples of the GFRP laminates utilized in this investigation in order to determine their tensile strength, stiffness and stress-strain relationship up to failure, with the specimens being loaded along three different directions (0°, 90° and +45°) due to the different direction of the fibre reinforcement. The mean values of the tensile strength obtained were 391.66 MPa (standard deviation of 17.6 MPa), 136.6 MPa (st. dev. of 7.5 MPa) and 139.6 MPa (st. dev. of 8.69 MPa) for the directions 0°, 90° and +45°, respectively (as shown in Fig. 2b). The specimens presented an ultimate strain of 24915 μm/m (st. dev. of 1586 μm/m), 22488 μm/m (st. dev. of 1946 μm/m) and 23073 μm/m (st. dev. of 1663 μm/m) for the directions 0°, 90° and +45°, respectively. Moreover, the average modulus of elasticity obtained were 16.49 GPa (with a st. dev. of 0.52 GPa), 6.79 GPa (with a st. dev. of 0.38 GPa) and 9.82 GPa (with a st. dev. of 0.34 GPa) for the directions 0°, 90° and +45°, respectively. The stress-strain relationship obtained through the direct tensile tests conducted on GFRP laminate samples is shown in Fig. 2b.

Figure 2. Material characterization: a) load-CMOD curves obtained in the three point notched SFRSCC beam bending tests; b) stress-strain relationship of the GFRP laminates, obtained through direct tensile tests

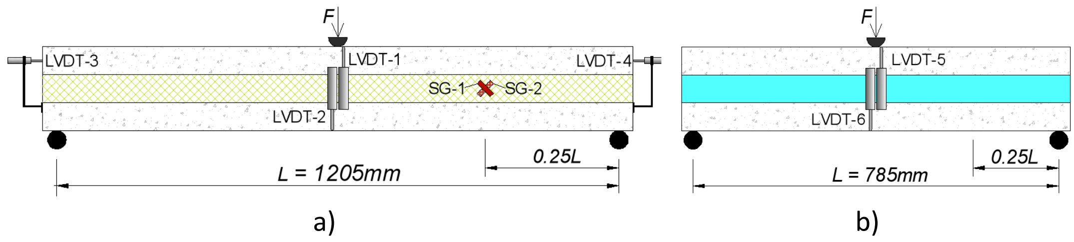


a) b)

TEST SETUP AND PROCEDURE

The SFRSCC-GFRP sandwich panels were simply supported with a roller and pin configuration at 30 mm from the end, creating a span length of 1205 mm for F1-F3 and 785 mm for S1-S2 specimens. The experiments were carried out with displacement control by a servo-hydraulic actuator at mid-span, centred with the specimen. A rate of 0.01 mm/s was applied to the controlled displacement up to a maximum of 50mm. The instrumentation of specimens F1-F3 is shown in Fig. 3a. Two Linear Variable Differential Transducers (LVDT) were used to measure the mid span vertical deflection at the top of the upper SFRSCC layer (LVDT-1) and at the bottom of the specimen (LVDT-2). An additional pair of LVDTs was used to measure the relative displacement between the two wythes of SFRSCC (LVDT-3 and LVDT-4). Two strain gauges were positioned in the GFRP laminate to assess the development of strains due to load transfer between SFRSCC wythes: sensors SG-1 and SG-2 shown in Fig. 3a. The insulation layer was removed from specimens F1-F3 in order to enable the visualization of the GFRP connectors during testing. The test configuration adopted for S1-S2 specimens includes two LVDTs that measure the vertical deflection of both SFRSCC layers (LVDT-5 and LVDT-6 illustrated in Fig. 3b). As no strain gauges were mounted in the GFRP laminate, the insulation layer was maintained throughout the testing process.

Figure 3. Test configuration and instrumentation adopted for specimens F1-F3 (a) and S1-S2 (b)



RESULTS AND DISCUSSION

The results obtained through the LVDTs for specimens F1-F3 are shown in Fig. 4. It can be seen that all specimens exhibited a ductile behaviour, which is clearly noticeable in post-peak behaviour of mid-span LVDTs shown in Fig. 4a. The load-deflection response obtained through all LVDTs until peak load is shown in Fig. 4b, where a very similar pre-peak response is observed for all specimens in both SFRSCC wythes, which is a good indication of the composite action of the structural system. In regard to the overall behaviour under flexural loading, three distinct stages can be identified when analysing the typical load-deflection behaviour obtained during the experiments (see Fig. 4c): (i) linear elastic behaviour until appearance of the first crack; (ii) stiffness reduction due to cracking in the bottom SFRSCC layer (see Fig. 5a); (iii) post-peak softening phase, with appearance and continuous opening of localized macro-crack in both SFRSCC wythes (see Fig. 5b) and characterized by perforation of the concrete cover of the upper SFRSCC layer by the GFRP connector (see Fig. 5c). The data collected through the LVDTs utilized for measuring the relative displacement between SFRSCC wythes is shown in Fig. 4d, where it can be seen that the SFRSCC layers registered some extent of relative displacement (reaching up to 3 mm), mainly due to slippage between SFRSC and GFRP connector, which is more evident after crack formation phase. Once again, quite homogenous results were obtained for all specimens in the pre-peak behaviour range. In addition to the above-mentioned results, the data collected through the use of strain gauges is shown in Fig. 4e. It can be seen that the strains obtained for both specimens exhibit that the GFRP laminate behaves linearly throughout the tests, even for unloading.

In regard to the assessment of the structural behaviour under shear loading (S1-S2), Fig. 6a illustrates the load-deflection results obtained through the LVDTs (in accordance with Fig. 3a), showing once again a noticeably ductile behaviour. Specimens S1 and S2 showed very similar behaviour under shear loading, reaching a peak load of approximately 70 kN at 3.5 mm deflection. The behaviour of the tested specimens can essentially be divided in three phases, similarly to the flexural loading case: (i) linear elastic behaviour until appearance of first cracks; (ii) stiffness reduction due to cracking in both SFRSCC layers (localized mainly in the central part of the specimen – see Fig. 6b); (iii) softening range (post-peak behaviour), characterized by the appearance and continuous opening of macro-cracks in the central part of both SFRSCC layers (see Fig. 6c), with perforation of the concrete cover of the upper SFRSCC layer by the GFRP connector (this effect is even more pronounced in the case of shear loading).

Figure 4. Results obtained for F1-F3 specimens: a) load versus deflection of the upper SFRSCC layer; b) load-deflection obtained through all LVDTs until peak load; c) typical load-deflection curve; d) relative displacement between SFRSCC wythes; e) strains in the GFRP connector

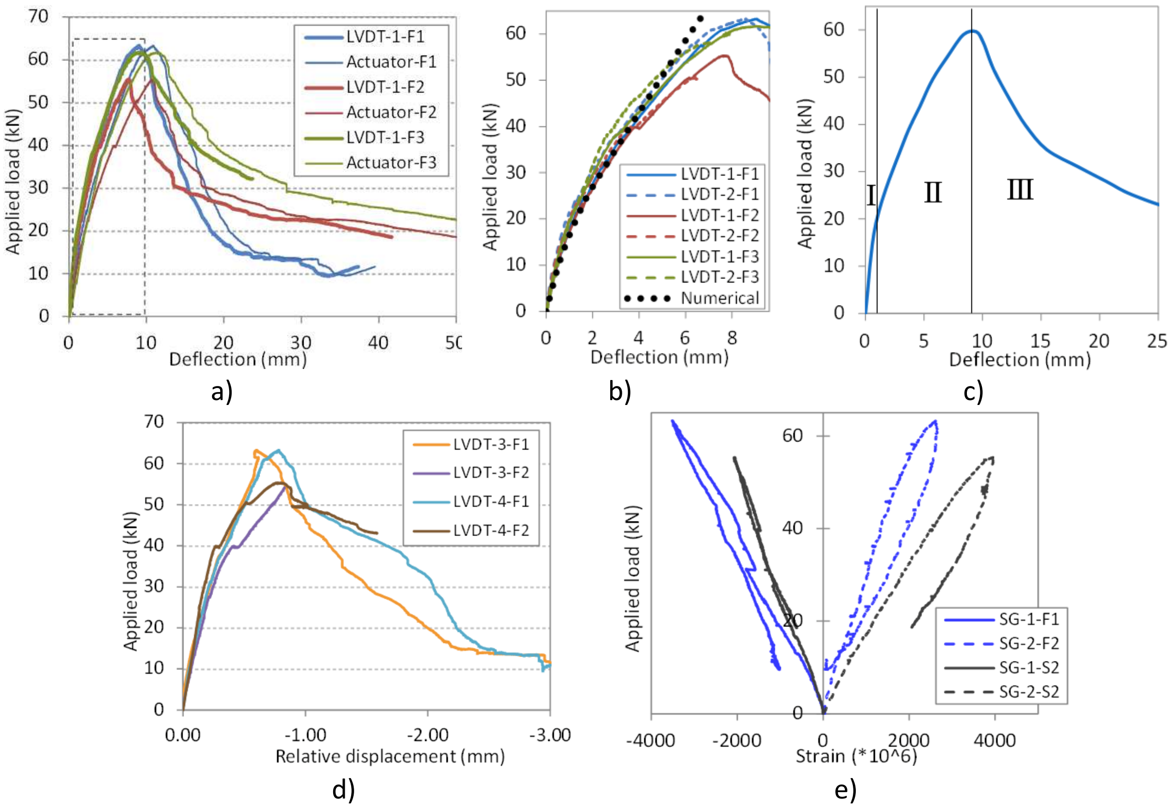


Figure 5. Failure mode for specimens F1-F3: a) development of cracks in the bottom SFRSCC layer; b) development of macro-cracks in both SFRSCC wythes; c) perforation of the concrete cover by the GFRP connector

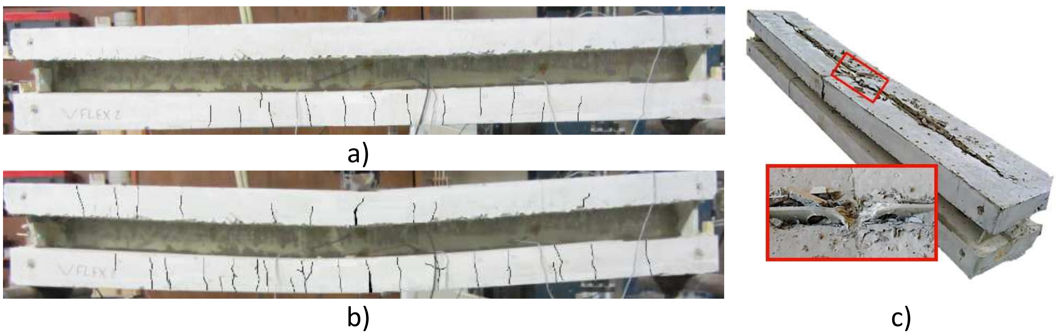
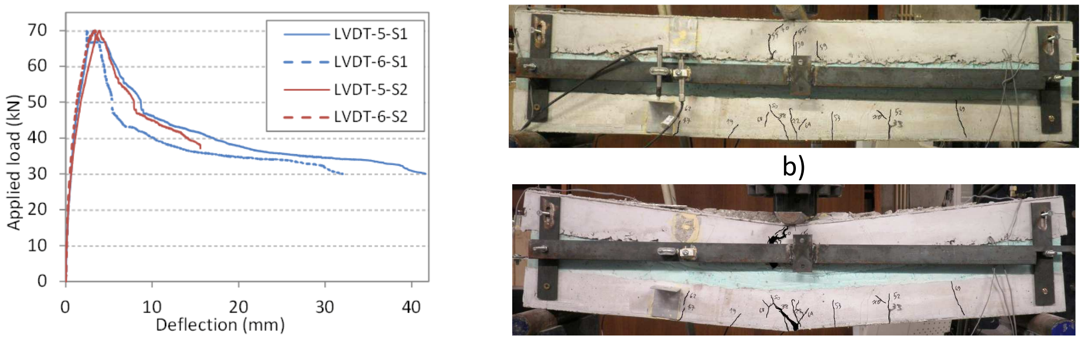


Figure 6. Experimental study on the shear specimens: a) obtained results; b) failure mode



a) b) c)

In addition to the experimental program, a finite element method (FEM) based analysis was conducted in order to numerically simulate the behaviour of the SFRSCC-GFRP sandwich slab panels under flexural loading. This analysis focused mainly on the in-service behaviour of the sandwich slabs. The material properties used in the numerical analysis are based on the data collected through the aforementioned material characterization, namely by adopting average values determined from experimental tests conducted on SFRSCC and GFRP laminates. For the simulation of the SFRSCC fracture properties, a trilinear tension softening diagram was adopted, according to the values obtained experimentally and by conducting inverse-analysis. The inverse analysis and the adopted 3D smeared crack mode are described in [7]. The numerically simulated deflection at mid-span in the SLS deflection range is superimposed to the experimental results of Fig. 5b as black dots. It can be seen that a reasonably good coherence can be achieved, with a good simulation of the stiffness reduction after cracking. The observed coherence also validates the assumption of perfect bond between concrete and GFRP for this load/deformation level.

CONCLUSIONS

In this study, an innovative sandwich slab panel solution comprising SFRSCC layers and GFRP laminate connectors is proposed and experimentally tested on prototypes. The experimental work confirms that SFRSCC-GFRP sandwich slab panels can withstand significant flexural and shear loading actions, while exhibiting a considerably ductile behaviour. In general, collected data presented very consistent results until peak-load, with more disperse results for the softening range of the structural behaviour. Moreover, it is important to note the predominantly linear behaviour evidenced by the GFRP laminate connectors throughout all experiments, exhibiting in some cases remarkably linear behaviour even for the unloading process, which is an important conclusion in specific regard to the proposed sandwich slab system. The results presented in this research work confirm the feasibility of the proposed sandwich slab system for the modular housing construction concept in development under the framework of this applied research project. Real scale sandwich panels are being prepared for experimental testing.

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