Flexural Behaviour of Hybrid FRC-GFRP/PUR Sandwich Panels

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Abstract. The present work has been developed in the scope of the research project "Easyfloor – Development of composite sandwich panels for building floor rehabilitation". This project aims at developing a hybrid sandwich panel, constituting an alternative construction system to conventional floor solutions, mainly for buildings rehabilitation. The developed hybrid sandwich panel is composed of a top face layer of steel fibre reinforced self-compacting concrete (FRC), a core of polyurethane (PUR) closed-cell foam and a bottom face sheet and lateral webs of glass fibre reinforced polymer (GFRP). The composite (GFRP/PUR) is manufactured by pultrusion, and its cross-section includes a sheet of GFRP between the FRC and PUR. After the production of the composite part, fresh FRC is poured onto the FRP component to materialize the top face of the panel.

Full-scale tests on the developed sandwich panels have been carried out to characterize their flexural behaviour. The experimental programme included flexural tests i) on single supported panels, ii) on two panels side adhesively bonded and iii) on single panels with different connection solutions to walls.

The present work includes a detailed description of the developed panels and of the experimental programme. It also presents and discusses the relevant results. The observed performance of the tested specimens is critically analysed.

Keywords: Sandwich panels · Composites · GFRP · PUR · Fibre reinforced concrete

1 Introduction

Fibre reinforced polymers (FRPs) are used in civil engineering structures due to its competitive advantages, namely the high stiffness and strength, low self-weight and high corrosion resistance. Also, their ability to be moulded into complex shapes during the manufacturing process, allows the production of prefabricated composite solutions, applicable to new construction or on the rehabilitation of existing structures [1, 2]. The use of prefabricated structural elements leads to lower costs and to the improvement of the manufacturing quality [3, 4]. Moreover, the use of composite sandwich panels in the rehabilitation of degraded wooden floors of old buildings appears to be a valuable solution, particularly in the case of applications in limited spaces.

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The main goal of the research project "Easyfloor – Development of composite sandwich panels for building floor rehabilitation" was to develop a pultruded sandwich panel for building floor rehabilitation. In this paper, a sandwich panel, composed of a top face layer of steel fibre reinforced self-compacting concrete (FRC), a core of polyurethane (PUR) closed-cell foam and a rectangular component of glass fibre reinforced polymer (GFRP) that enclosed the PUR foam, is investigated throughout an experimental campaign composed of flexural tests, complemented with numerical modelling. The next sections provide details about different aspects of the work carried out.

2 Materials and Experimental Program

2.1 Materials

The developed hybrid sandwich panels involved the following materials: i) steel fibre reinforced self-compacting concrete (FRC), ii) a core of polyurethane (PUR) closed-cell foam and iii) glass fibre reinforced polymer (GFRP). These materials were experimentally characterized.

The compressive and tensile properties of the FRC were assessed throughout compression and flexural tests, using the NP EN 12390–3 (2011)/NP EN 12390–13 (2013) and EN 14651 (2005), respectively. Four FRC batches were used to cast all the studied panels (B1, B2, B3 and B4), and their characterization was carried out approximately at similar age of the tested panels. The main results are presented in Table 1, namely: (i) the elastic modulus, E_c, and the compressive strength, f_c, from the compression tests; and the (ii) stress at limit of proportionality, $f_{ctl,L}$, calculated for a deflection $\delta_L = 0.05$ mm; the equivalent flexural tensile strength $f_{eq,2}$ and $f_{eq,3}$; and the residual flexural tensile strength f_{R1}, f_{R2}, f_{R3} and f_{R4} for the crack mouth opening displacement (CMOD) of 0.5, 1.5, 2.5 and 3.5 [mm], respectively, from the flexural tensile tests.

The material characterization of the core foam (PUR) included compressive (C365/C365M standard), tensile (ASTM C297/C297M standard), and shear (ASTM C273 standard) tests. From these tests, the following results were obtained: an elastic modulus in tension and compression of 10.9 MPa (CoV: 12%) and 6.0 MPa (CoV: 8%), respectively; tensile and compressive strength of 0.32 MPa (CoV: 4%) and 0.33 MPa (CoV: 11%), respectively; shear modulus of 5.6 MPa (CoV: 3%); and shear strength of 0.32 MPa (CoV: 3%).

GFRP faces/webs were manufactured using the pultrusion process, and the tensile properties of top and bottom faces and lateral webs were determined. The characterization was performed by [5]. Results showed a longitudinal and transverse tensile strength of 315.9 MPa (13%) and 34.7 MPa (2%), respectively; a longitudinal and transverse tensile strain at failure of 11.7% (14%) and 3.7% (5%), respectively; and a longitudinal and transverse elastic modulus of 27.1 GPa (9%) and 11.0 GPa (10%), respectively.

2.2 Design of the Sandwich Panels

The design of the present sandwich panel was supported in genetic algorithms (GA) aimed at the minimization of self-weight, manufacturing cost, and carbon-footprint of

Table 1. Properties of the FRC

FRC Batch	E_c [GPa]	f_c [MPa]	$f_{ctl,L}$ [MPa]	$f_{eq,2}$ [MPa]	$f_{eq,3}$ [MPa]	f_{R1} [MPa]	f_{R2} [MPa]	f_{R3} [MPa]	f_{R4} [MPa]
B1	26.91 (6.87%)	49.61 (4.64%)	6.13 (15.30%)	12.51 (9.47%)	11.78 (12.02%)	12.22 (9.27%)	12.07 (10.99%)	10.92 (10.42%)	9.37 (12.48%)
B2	27.05 (2.18%)	48.07 (3.29%)	3.34 (29.10%)	10.03 (20.65%)	8.96 (25.26%)	9.66 (22.23%)	9.70 (24.15%)	7.82 (25.69%)	6.32 (30.36%)
B3	26.65 (2.86%)	46.02 (2.67%)	2.98 (29.05%)	8.82 (19.08%)	8.12 (19.91%)	13.60 (70.79%)	7.95 (19.94%)	7.32 (19.39%)	6.31 (20.11%)
B4	24.47 (4.66%)	43.26 (2.94%)	3.54 (30.15%)	7.52 (27.98%)	7.18 (27.29%)	7.30 (31.51%)	7.60 (22.88%)	6.60 (26.69%)	5.69 (28.31%)

Note: the values between parentheses are the corresponding coefficients of variation (CoV)

the solution [6]. Due to technical limitation of the pultrusion equipment, a width of 0.5 m was fixed, whereas a length of 5 m (longitudinal direction) was considered, based on the current needs in terms of rehabilitation market. The genetic algorithms were set to find the best solution, within several boundary conditions, defined based on the manufacturer requirements (e.g. panel's width) and the fulfilment of structural standards (EN 1990:2002; EN 1991–1-1:2002; CNR DT 205/2007) in terms of Ultimate and Serviceability Limit States. The design also included the evaluation of the thermal and acoustics performance, and the incorporation of a snap-fit type of connection between the panels. In total, the GA included a total of 21 variables (geometric: 7; material: 14), grouped into 5 genes, within 1 chromosome. The optimal solution is depicted in Fig. 1a, and the main characteristics are: 140 mm (height) by 500 mm (width); 29.9 kg per meter of panel; top layer of FRC – thickness of 20 mm at the middle and 36.5 mm at the extremities; hybrid carbon and glass FRP lateral (4 mm thick) and bottom (5 mm thick) faces; core made of polyisocyanurate (PIR) closed-cell foam with a density of 40 kg/m^3; 3 mm glass FRP (GFRP) skin between the foam core and the FRC. Additional details regarding the design of the EasyFloor hybrid sandwich panels are available at [6, 7].

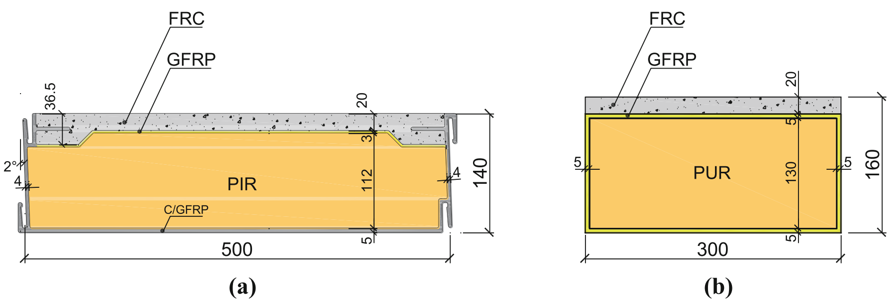


Fig. 1. Final geometry of the hybrid sandwich panel: (a) final design and (b) test specimen. Units in [mm].

The experimental work was developed using a simplified version of the final design, presented in Fig. 1b. This tested prototype has a width of 300 mm and height of 160 mm, comprising a 20 mm top layer of FRC, top and bottom and lateral webs of GFRP with 5 mm of thickness, enclosing a polyurethane (PUR) core foam (130 mm by 290 mm) with a density of 60 kg/m^3.

2.3 Test Program

The test program was composed of 10 sandwich panels with 4.7 m of length. Figure 2 shows the specimens geometry, test set-up and instrumentation.

Two panel configurations were studied: the (i) single panel (SP), composed by a single sandwich panel; and the (ii) two-panel (TP), composed by two panels adhesively bonded, side-by-side, with the S&P Resin 220 epoxy adhesive [8].

The scope of this work also included the evaluation of different support conditions, designed to be used as panel-to-wall connections. In this subject, three different connections types were studied: (i) the 1L connection, where the composite panel is fixed against a 120 mm "L-shaped" steel profile using two M10 threated rod; (ii) the 2L connection, with two 120 mm "L-shaped" steel profile, on the top and bottom surfaces of the composite surface, fixed using also two M10 threated rod; and (iii) the 2LA, which is identical to the 2L, but has an epoxy adhesive layer (S&P Resin 220 [8]), applied between the steel profiles and the composite panel. These connection types were tested with the SP configuration and a detail drawing is presented in Fig. 3. Moreover, these three connection types present different rotation and displacement restrictions, with increasing magnitude from the 1L connection (lowest) to the 2LA (highest), which is similar to a fixed support.

All tests were performed at Structural Laboratory of Civil Engineering of the University of Minho (LEST) and were conducted under a four point bending configuration, using 5 linear variable differential transducers (LVDT1 to LVDT5) to record the deformation along the longitudinal axis of the slab, and several strain gauges (SG1 to SG4) to measure the strains in the different components of the sandwich panels (see Fig. 2). LVDT1, LVDT3 and LVDT5 (see location on Fig. 2) have a range of ±25 mm and a linearity error of ±0.10%, whereas the LVDT2 and LVDT4 have a range of ±50 mm and the same linearity error. TML PFL-30–11-3L strain gauges (SG1) were used to monitor the FRC's strains at the mid-span, while strains in the top (SG2 and SG3) and bottom (SG4) face of the GFRP profile were measured using TML BFLA-5–3 strain sensors. The instrumentation also included one load cell of 200 kN capacity (±0.050% error) used to measure the applied force (F).

As it is shown in Table 2, a generic label X_Y_Z was adopted for each specimen, where X is the specimen's panel configuration (SP and TP – Single Panel or Two Panels), Y is the support system (SS – Simply supported, 1L, 2L and 2LA), and Z is a numeric value (1 or 2) to differentiate identical specimens.

2.4 Production of the Sandwich Panels

The production of the sandwich panels included two main stages: i) pultrusion of the composite sandwich (GFRP + PUR) and ii) FRC casting. The first stage took place at

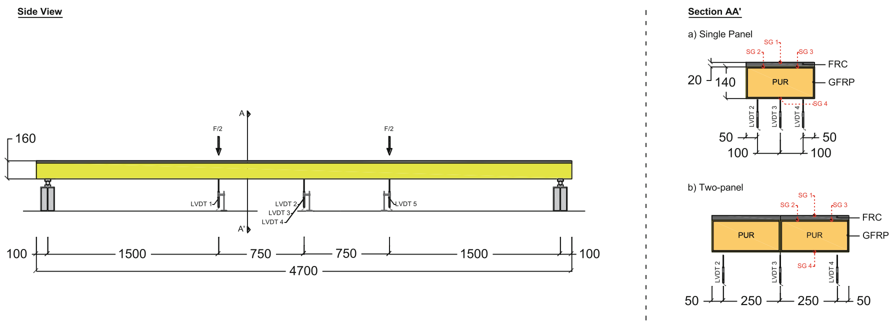


Fig. 2. Specimens' geometry and test set-up: (a) Single panel and (b) Two-panel configuration. Units in [mm].

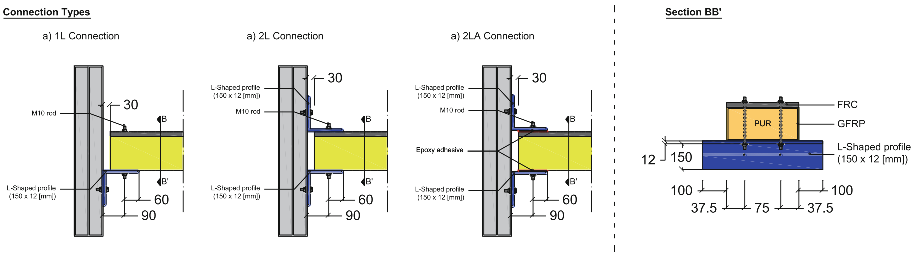


Fig. 3. Panel-to-wall connections: (a) 1L, (b) 2L and (b) 2LA. Units in [mm].

ALTO – Perfis Pultrudidos, Lda. while the second stage occurred at Civitest - Pesquisa de Novos Materiais para a Engenharia Civil, Lda.

In the production of the composite sandwich component by pultrusion, the core PUR foam blocks with the final dimensions (130 mm × 290 mm × 2000 mm) were introduced simultaneously with the unidirectional glass-fiber roving strands, fabrics and chopped strand mats (CSM) in the heated die. An unsaturated polyester resin was used as matrix of the GFRP and also to promote the bond between the PUR core and the GFRP component (see Fig. 4a).

Once the composite sandwich component has been produced, the top face sheet of the GFRP panel was slightly sanded and an epoxy adhesive (Sika 32 EF) was applied before pouring the fresh FRC, to improve the bond between both materials (see Fig. 4b).

2.5 Numerical Modelling

3D finite element modeling was developed to simulate the flexural tests using DIANA finite element software (version 10.3) [9]. Figure 5 shows the finite element mesh adopted to simulate the sandwich panels. Only half the slab was modelled due to its symmetry conditions. With an element size of 20 mm, all components of the panel (FRC, GFRP and PUR) were simulated with twenty-node solid elements (CHX60 elements according to Diana 10.3). The support conditions were modeled accordingly: i) for the simply supported conditions, only a vertical constrain (z axis) at the middle of the 50 mm support

Fig. 4. Production of the sandwich panels: (a) pultrusion process and (b) FRC casting

plate was imposed, thus allowing rotation and horizontal (x axis) displacement at the supports (see Fig. 5: Simply Supported - FEM_SS); ii) 1L connection uses a fixed 120 mm support (only compression stresses) and the two M10 bolts (see Fig. 2); iii) 2L connection with two 120 mm supports (only compression stresses) and the two M10 bolts; and iv) 2LA connection, identical to the 2L connection, but with the additional horizontal restriction, that results in a fixed support (see Fig. 5). Linear elastic behavior was assumed for all the materials. Therefore, average values of the elastic modulus (obtained from the material characterization) were adopted. Perfect bond was assumed between the different elements of the sandwich panel. It should be noted that the simplifications adopted in the numerical models, namely the non-linear behavior of the materials and the constraints adopted to simulate the support conditions, are known by the authors as factors that could be improved to better represent the experimental campaign. However, this type of approach were considered out of scope of this work.

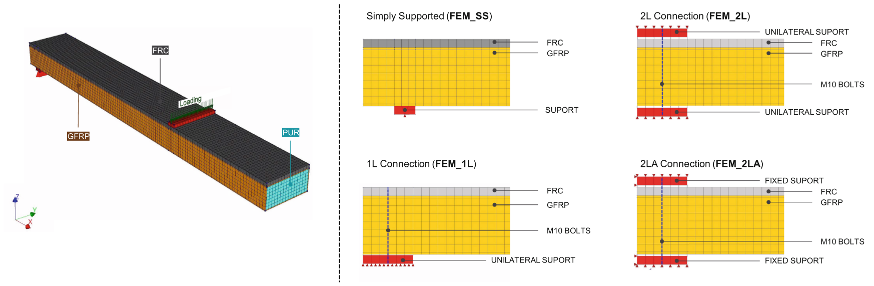


Fig. 5. Mesh of the 3D finite element model of the sandwich panel and detailed representation of the support systems.

3 Results and Discussion

The relationship between the applied force and the mid-span deflection is presented in Fig. 6. To facilitate a comparison between the experimental results, response of the

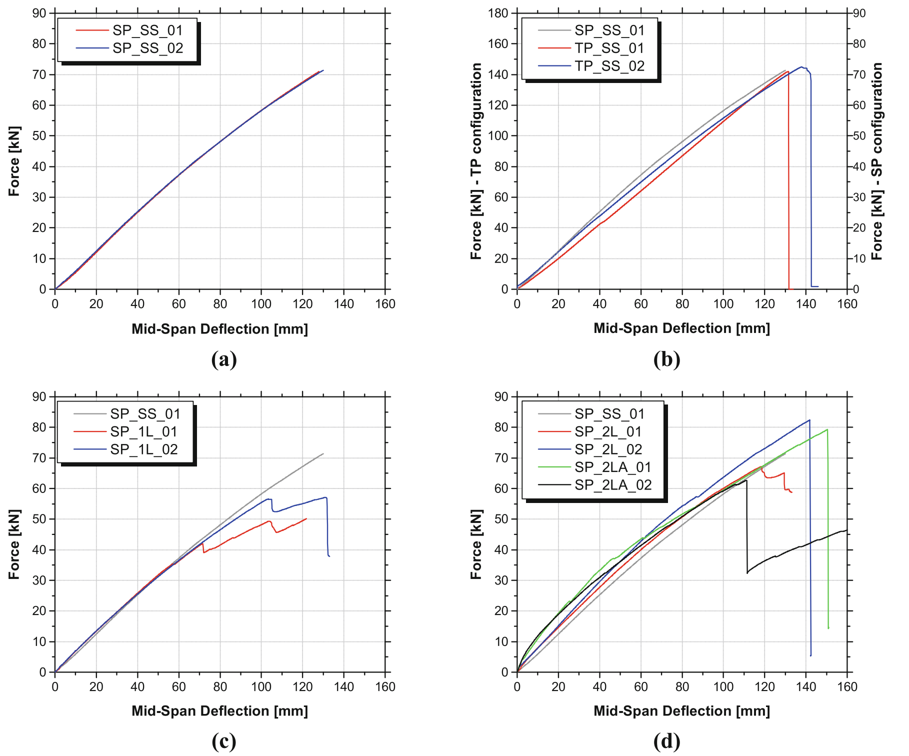


Fig. 6. Total force versus mid-span deflection: (a) simply supported SP specimens; (b) simply supported TP specimens; (c) specimens with 1L connection; and (d) specimens with 2L and 2LA connection.

specimen SP_SS_01 is presented in all graphs. Table 2 presents the main results of the flexural tests, namely the effective flexural stiffness ($K_{eff,exp}$), ultimate load (F_{max}) and corresponding mid-span deflection (δ_{max}), maximum strain in the bottom GFRP face sheet (ε_{max}). The effective flexural stiffness was computed between the interval of loads 5 kN – 15 kN. Table 2 also includes the flexural stiffness ($K_{eff,FEM}$) obtained from the numerical modeling – the values in parentheses (in percentage) are the differences between $K_{eff,FEM}$ and the mean value of $K_{eff,exp}$ for the corresponding series.

As depicted in Fig. 6a, single panels simply supported (SP_SS_01 and SP_SS_02) present identical force *versus* mid-span deflection response, with an effective flexural stiffness of 0.65 kN/mm. Figure 8a shows the comparison between the experimental and numerical results of SP_SS panels. From these results, linear behavior of the SP_SS panels was observed up to ~60% of the ultimate load. Considering the ultimate load obtained, it corresponds to a maximum load capacity of ~70 kN/m^2. Non-linear behavior (from ~60% up to the ultimate load) is mainly justified by the non-linear behavior of the FRC under the compressive stress state. Web local buckling due to transverse compression at the point loads triggered the failure of the SP_SS panels, followed by the FRC crushing.

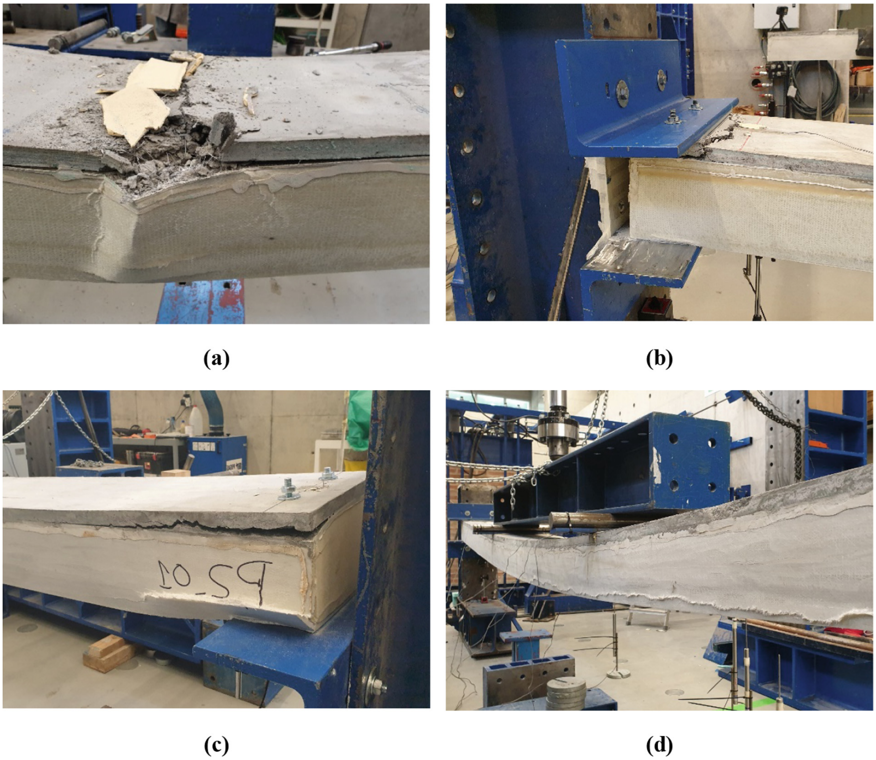


Fig. 7. Failure modes: (a) bucking on the side webs of the GFRP profile and FRC crushing observed on SP_SS_1; (b) tensile failure of FRC on SP_2LA_2; (c) FRP web crushing and debonding of the FRC layer, observed on SP_1L_1; and (d) FRP web/bottom face sheet rupture on the SP_2LA_2.

When comparing the response of the two simply supported panels (2 × SP_SS) with the two sided-bonded simply supported panels (TP_SS), similar behavior is observed (see Fig. 6b). Consequently, negligible beneficial synergic effects were obtained from the bonded-side solution. Moreover, series TP_SS presented failure modes similar to the ones observed in series SP_SS.

Three panel-to-wall connections were assessed using similar four-point bending configuration (two load points spaced 750 mm from the mid-span), using the 1L, 2L and 2LA connections, as presented in Fig. 3. These three connections present different support restrictions, which were observed in the service and ultimate stages of the flexural tests. As can be seen in Table 2, the flexural stiffness (K_{eff}) has increased with the level of restriction of the support system, with the lowest and highest values obtained in the 1L and 2LA connections, respectively, 0.65 and 0.91 (mean value per series, in [kN/mm]). The stiffness increase is also visible in Fig. 6. Figure 6c shows the slightly higher stiffness on series SP_1L connection during the first test stages (up to 20 mm of mid-span deflection), when compared with the SP_SS (grey line). The benefits of using two L-shaped steel profiles at service conditions is clearly identified in Fig. 6d, where the initial stiffness is much higher than in series SP_SS. The use of one L-shaped steel profile (series SP_1L) had deleterious effects at the ultimate capacity of these panels (when compared with series SP_SS). In fact, this type of connection led a premature failure (see details in Table 2), which yielded to a reduction on the load carried capacity of ~33%. In the case of using two L-shaped steel profiles (series SP_2L and SP_2LA), the ultimate load presented a marginal variation ~ 2.2% when compared with series SP_SS. Comparing the numerical simulations of series SP_2L and SP_2LA with the experimental results, despite the fact that the models could simulate properly the initial stiffness of the responses (see Fig. 8), they were not able to simulate further stages. The main reason for such differences rely on the limitations of the constitutive laws adopted for the materials (linear behaviour), while at early stages of the experimental tests, non-linear behaviour was observed in the FRC and GFRP at the support zones of the panels (Fig. 7 and Fig. 8).

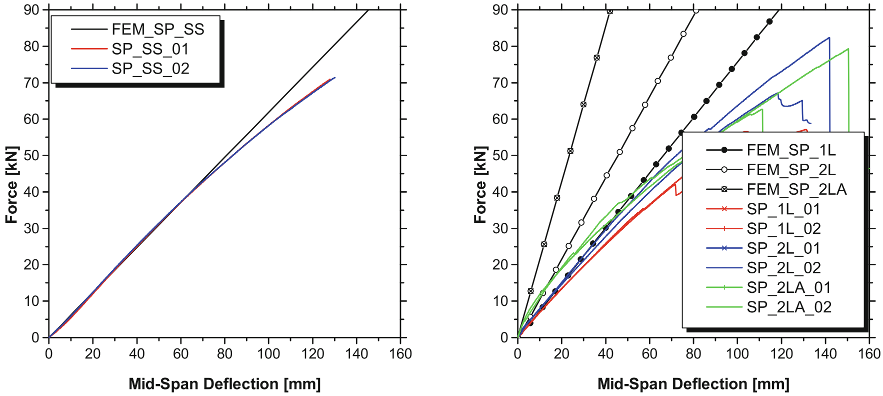
Table 2. Main results from the four-point bending tests.

Specimen	$K_{eff,exp}$ [kN/mm]	F_{max} [kN]	δ_{max} [mm]	ε_{max} [%]	$K_{eff, FEM}$ [kN/mm]	Failure Mode
SP_SS_01	0.65	70.9	127.9	0.25	0.62 (-5.6%)	Buckling of the webs followed by concrete crushing at the load point
SP_SS_02	0.66	71.6	129.9	0.27		Buckling of the webs followed by concrete crushing at the load point
TP_SS_01	1.22	142	131.4	0.26	1.24 (+3.6%)	Buckling of the webs followed by concrete crushing at the load point
TP_SS_02	1.17	145	137.9	0.27		Buckling of the webs followed by concrete crushing at the load point
SP_1L_01	0.65	50.1	121.8	0.24	0.76 (+14.5%)	Buckling of the webs and FRC deboding at support region
SP_1L_02	0.65	57.1	133.1	0.30		Buckling of the webs between the support and the load point

(*continued*)

Table 2. (*continued*)

Specimen	$K_{eff,exp}$ [kN/mm]	F_{max} [kN]	δ_{max} [mm]	ε_{max} [%]	$K_{eff,\,FEM}$ [kN/mm]	Failure Mode
SP_2L_01	0.68	67.1	133.3	0.23	1.12 (+37.1%)	Buckling of the webs and FRC failure at load point
SP_2L_02	0.73	82.4	142.5	0.28		Buckling of the webs and FRC failure at mid-span
SP_2LA_01	0.94	79.3	151.0	0.29	2.14 (+57.5%)	Buckling of the webs and FRC tensile failure at the support
SP_2LA_02	0.88	62.7	165.2	0.24		FRP web/bottom face sheet rupture and FRC tensile failure at the support



(a) (b)

Fig. 8. Experimental and numerical results of total force versus mid-span deflection: (a) simply supported SP specimens; (b) specimens with the connection 1L, 2L and 2LA.

4 Conclusions

The present work presents the flexural response of hybrid sandwich panels developed in the scope of the EasyFloor research project. The experimental programme included four-point bending tests i) on single supported panels, ii) on two panels side adhesively bonded and iii) on single panels with different connection solutions to the walls. Then, finite element models were developed for further understanding the test results. From the experimental and numerical work, the following main conclusions can be drawn:

- Single panels simply supported (SP_SS) presented a linear behaviour up to ~60% of the ultimate load. Considering the ultimate load obtained, it corresponds to a maximum load capacity of ~70 kN/m^2. Web local buckling and FRC crushing governeded the failure modes of these panels;
- The two-panel (TP_SS) configuration reached approximately twice the ultimate load and flexural stiffness of the single panel. The failure modes observed in the SP_SS were essentially similar to the ones observed in TP_SS;
- The results of the three panel-to-wall connections have shown an increase on the intial flexural stiffness (K_{eff}) with the lowest to highest values on the 1L to 2LA connections;
- Despite the higher K_{eff} on series 2LA and 2L, similar ultimate loads were obtained when compared to series SP_SS;
- The finite element simulations have shown good agreement with the experimental results for the stages when linear behavior is observed. Further work should be carried out, namely by conducting a non-linear (material and geometrical) finite element modelling of the tested specimens in order to predict the full response of the tested panels.

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