DEVELOPMENT OF MULTIFUNCTIONAL SANDWICH PANELS FOR INTEGRATED REHABILITATION OF RC-BUILDINGS: CHARACTERIZATION OF THE COMPONENTS

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Abstract

This research work deals with the development of a sustainable multifunctional composite sandwich panel for reinforced concrete (RC) frame buildings built in Portugal until the mid-1980s, which require structural and thermal-comfort rehabilitation. The sandwich panel, aimed specifically for interventions on building envelopes (refurbishment of building facades), is characterized by three main components: (i) thin outer concrete layers reinforced with recycled steel fibres (from post-consumed tyres), which fulfils the strength, ductility and durability requirements of the panel; (ii) a lightweight core layer made of polystyrene, which accomplishes thermal insulation requisites; and (iii) internal glass fibre reinforced polymer (GFRP) connectors that join the different layers of the panel, providing an adequate structural behaviour of the composite solution. The present paper focuses on the assessment of the relevant mechanical properties of the different components of the rehabilitation solution that is being developed, namely: (i) the Recycled Steel Fibre Reinforced Micro-Concrete (RSFRMC) developed specifically for this application; (ii) the GFRP connector; and (iii) the core material. After characterization of each individual component, additional tests are conducted on small specimens that are representative of the sandwich panel solution under development in order to assess the overall composite performance in shear and compression loading. The experimental work is described, and the most relevant results are presented and discussed.

Keywords: Building facades, Polystyrene, Pushout tests, Recycled steel fibres, Rehabilitation of RC-buildings, Sandwich panel

1 Introduction

The activities of rehabilitation and conservation of the built patrimony constitute a very relevant issue for modern societies, not only due to the natural aging and deterioration of civil engineering structures, but also because modern design codes involve higher requirements that a significant portion of existing buildings cannot cope with. In relation to the retrofit of the existing housing stock, the main interests of the research community are nowadays focused on three different research areas: (i) structural rehabilitation, in view of the safety of buildings and protection of their inhabitants (e.g. buildings that exhibit structural vulnerabilities under seismic actions); (ii) energetic refurbishment, mostly due to the targets defined by the European Union regarding energy efficiency, indoor comfort condition of buildings, reduction of carbon emissions and use of on-site renewable energy sources; and (iii) use of sustainable resources in civil engineering structures in view of society's environmental and economic benefits. This research work aims to address the referred research topics through the development of a sustainable precast concrete sandwich panel solution for both structural and thermal rehabilitation of existing RC-frame buildings (refurbishment of building facades), built in Portugal during the 1960-80 decades.

Waste management of used pneumatic tyres is nowadays still a major environmental challenge worldwide, being both the reuse of tyres and the recovery of constituent materials sustainable options for disposing of post-consumed tyres (Pilakoutas *et al.*, 2004). At the same time, in the field of civil engineering, due to a growing interest regarding innovative and recycled materials for sustainable building construction, research efforts have been made towards building concrete structures resorting to different by-products obtained from the recycling of waste tyres (e.g. granulated rubber and steel fibres). The addition of small fractions of recycled steel fibres to the concrete during mixing is one example of such strategy, with research studies on this topic reporting favourable effects on concrete structures in terms of structural efficiency: it can decrease the brittleness of the concrete matrix in tension, enhancing its toughness and post-cracking resistance (Aiello *et al.*, 2009; Centonze *et al.*, 2012; Zamanzadeh *et al.*, 2015; Caggiano *et al.*, 2017). The sustainability of the studied rehabilitation solution is hence to be addressed by using steel fibres resulting from the tyre recycling industry as discrete reinforcement of the outer concrete layers of the sandwich panel (described next), also known as *wythes*.

In order to combine structural and thermal efficiency, sandwich panel solutions are characterized by an insulation layer that separates the outer load-bearing layers. For insulated precast concrete sandwich panels, rigid foam insulation plates are frequently used, such as polystyrene plates. More specifically, expanded polystyrene (EPS) and extruded polystyrene (XPS) are amongst the most common insulation materials. In the context of structural design, sandwich panels are usually categorized as fully, partially or non-composite, according to the degree of composite action between concrete wythes. This is known to be highly dependent on the connection between wythes, typically provided by shear connectors or solid concrete regions (Lameiras *et al.*, 2013; Tomlinson *et al.*, 2016). However, available literature has shown that the insulation layer can also contribute for the panel's composite action depending on its mechanical and surface properties (Frankl *et al.*, 2011; Choi *et al.*, 2015). This difference is mainly dependent of the adhesion between the insulation and the surrounding concrete layers.

The research reported in this paper focuses on the experiments that were conducted in the scope of the development of a multifunctional sandwich panel intended to be used on the refurbishment of building facades, namely for structural and thermal rehabilitation. At this stage of the research program, the experiments are restricted to (i) material characterization tests of the different individual components that form the referred sandwich panel - external Recycled Steel Fibre Reinforced Micro-Concrete (RSFRMC) layers, Glass Fibre Reinforced Polymer (GFRP) connectors and polystyrene core layer -, and (ii) tests of representative sandwich panel samples subjected to shear and compression loads. The former tests, described in Section 2, aimed to collect relevant information about the properties of the constituent materials. The latter experiments, described in Section 3, were conducted for the selection of the insulation material to be adopted for the sandwich panel, in view of the influence that different insulation typologies can produce on the overall composite behaviour of the panel, assessed through pushout and compression tests. All the tests presented in this paper were conducted in the Structural Laboratory from University of Minho (LEST), except the tests concerning the characterization of the RSFRMC, which were performed at the CiviTest company.

2 Material characterization tests of the sandwich panel components

2.1 Recycled steel fibre reinforced micro-concrete

The RSFRMC was specifically developed for the production of thin concrete layers to be adopted as wythes of precast sandwich panels. The final mix composition of the RSFRMC is shown in Table 1. Taking into account the adopted thickness for the concrete layers of the studied sandwich panel, defined as 25 mm (based on preliminary numerical simulations and geometric restrictions imposed by anchoring the GFRP connectors), a nominal maximum aggregate size of 9 mm was adopted, therefore justifying the "micro-concrete" designation that was attributed to the concrete composition.

Table 1
Mixture composition of RSFRMC (kg/m^3)

Cement	Fly ash	Crushed granite	River sand	Fine sand	Water	Superplasticizer	Fibres
400	200	597.24	734.7	147.47	173	7.2	70

The recycled steel fibres used for this research were obtained through a shredding process applied to post-consumed truck tires. The separation of the steel fibres from the rubber matrix is achieved through an electromagnetic extraction system. The fibres obtained from this process are characterized by having different diameters, lengths and shapes. The average values that characterize the fibres, provided by the supplier, are as follows: length (l_f) of 20 mm, diameter (d_f) of 0.15 mm, aspect ratio (l_f / d_f) of 133, and tensile strength equal to 2850 MPa. The fibres added to the concrete mixture composition constitute the only steel reinforcement of the concrete layers (*i.e.* no continuous steel reinforcement was adopted), resulting in a concrete with recycled steel fibre volume content of 0.89%.

The modulus of elasticity and compressive strength of the RSFRMC was assessed at the age of 28 days by testing cylinders with 150 mm of diameter and 300 mm of height according to standards EN 12390-13 (CEN, 2013) and EN 12390-3 (CEN, 2009), respectively. The average values obtained for the modulus of elasticity and compressive strength were equal to 27.25 GPa and 54.03 MPa, respectively. The post-cracking behaviour of the RSFRMC was assessed, at the same concrete age, by performing direct tensile tests on notched dog-bone shaped specimens. The test setup, depicted in Fig. 1a, includes a servo-controlled direct tensile testing machine with a 50 kN capacity actuator and load cell, and two ribbed grips that secured the specimen on both ends. Additionally, four displacement transducers (LVDT) were installed at the lateral, front and back faces of the specimen, near the notch tip, in order to measure the crack mouth opening displacement (CMOD), which was determined by the average value of the displacements registered by the LVDTs. The geometric configuration of the specimens, which had a thickness of 30 mm, is presented in Fig. 1b. The tests were performed by imposing a displacement rate of 0.1 mm/min to the top grip of the equipment. Fig. 1c presents the envelope and corresponding average tensile stress vs. CMOD relationships obtained in these tests. At crack initiation and at peak load average tensile stresses of 3.38 MPa and 3.78 MPa were obtained, respectively. The post-cracking behaviour can be characterized by residual tensile strengths of 3.51 MPa and 1.72 MPa at CMOD = 0.5 mm (service limit state) and CMOD = 2.5 mm (ultimate limit state), respectively.

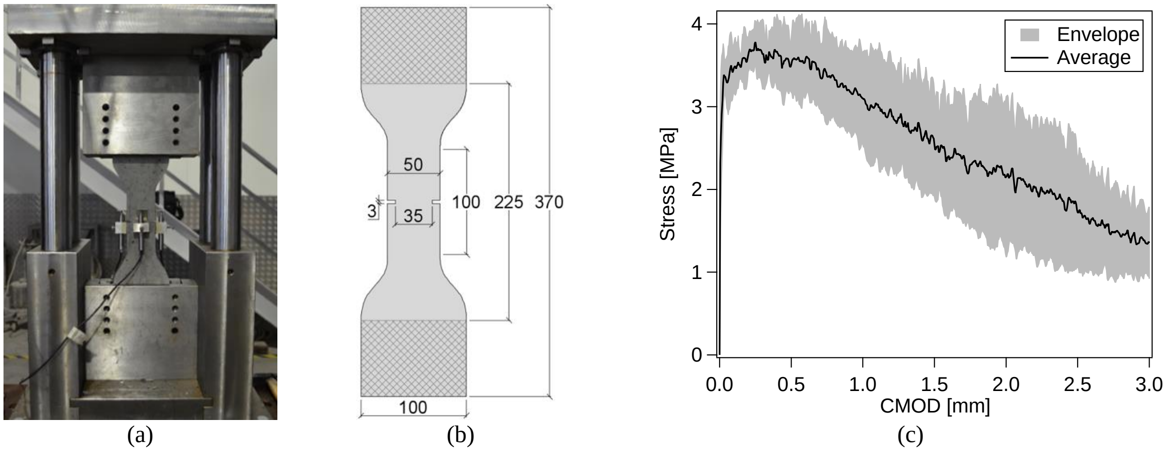


Fig. 1 Tensile tests of RSFRMC: Test setup (a); Specimen geometry [mm] (b); Load *vs.* CMOD curves (c).

2.2 GFRP connectors

The GFRP connectors are specifically designed for the production of sandwich panels in precast concrete industry, namely to provide connection between the outer concrete wythes and the inner polystyrene layer (for typical concrete/polystyrene/concrete sandwich panel configurations). The adopted connector was the one developed to be incorporated in a sandwich panel with a total thickness of 100 mm, external concrete wythes with 25 mm of thickness each and a 50 mm thick core insulation layer (see dimensions in Fig. 2a). Fig. 2b presents a 3D representation of the connector, highlighting its two main peculiarities: (i) the ends of the connector have a particular shape to provide better anchorage conditions to the parts that will be embedded in the RSFRMC wythes, and (ii) the connector has a protruding thicker section in the upper concrete/insulation transaction, which works like a stopper, for an easier assembly process (to provide higher quality control regarding the position of the insulation layer and the thickness of the external RSFRMC layers). According to the data provided by the supplier (RIA-Polymers GmbH, 2012), the GFRP material of the connectors has a tensile modulus of 10.10 GPa and a tensile strength of 91.00 MPa. These properties were confirmed experimentally by performing uniaxial tensile tests (see test setup in Fig. 2c) on the supplied GFRP connectors (see results in Fig. 2d): the obtained average tensile modulus and strength were 10.40 GPa and 95.59 MPa, respectively.

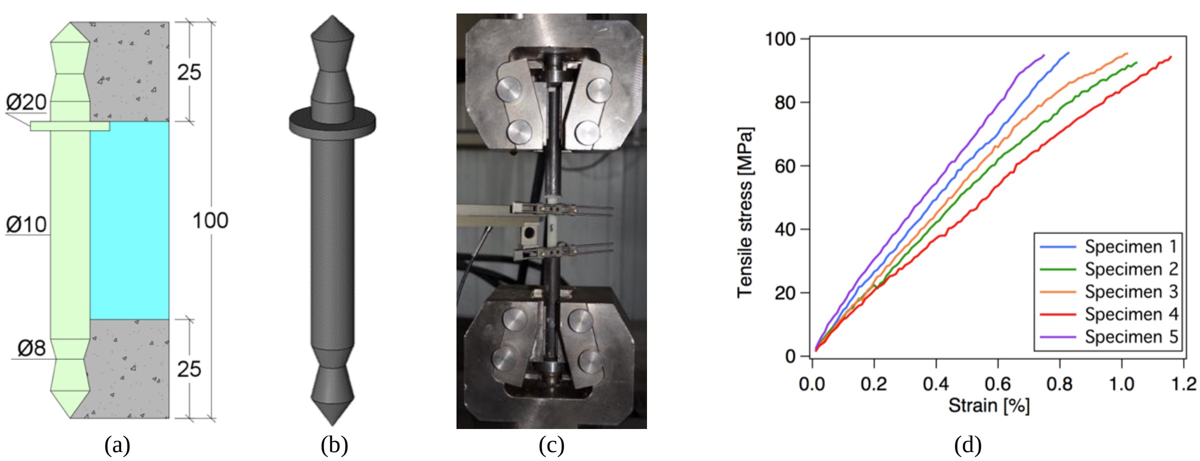
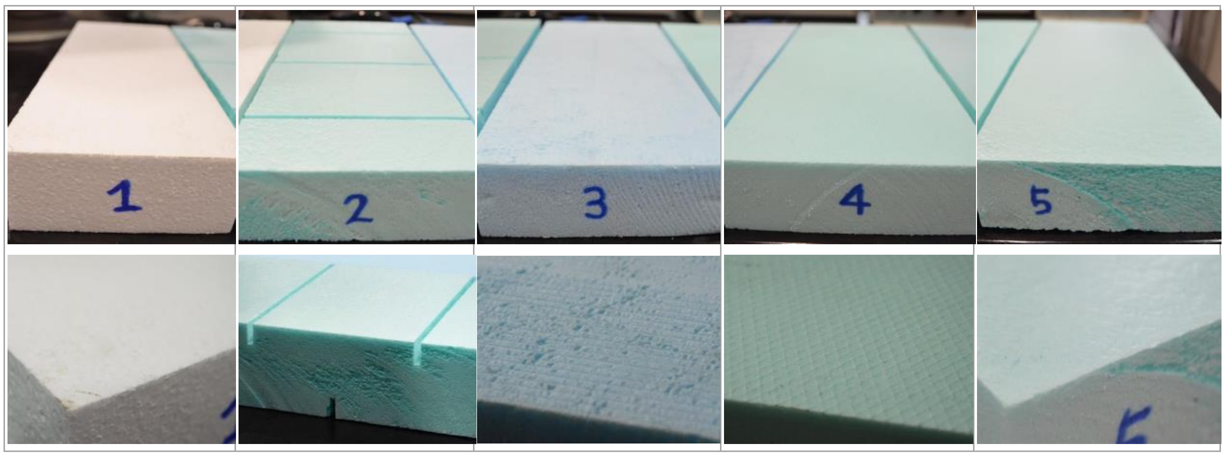


Fig. 2 Tensile tests of GFRP connectors: Geometry [mm] (a); 3D view (b); Test setup (c); Stress-strain curves (d).

2.3 Polystyrene

To assess the influence of the interface between the RSFRMC wythes and the core layer when subjected to shear and compression forces, different types of polystyrene panels were considered for this experimental program. The main objective was to understand the dependence of the adhesion between RSFRMC and polystyrene on the type of polystyrene and on its surface finishing. In view of this, the tests encompassed five different types of commercially available polystyrene plates: (i) expanded polystyrene (EPS-1, Fig. 3a); (ii) extruded polystyrene with smooth surface, with parallel notches cut on both sides, with spacing of 100 mm, depth of 12.5 mm and thickness of 3 mm (XPS-2, Fig. 3b); (iii) extruded polystyrene with rough/irregular surface (XPS-3, Fig. 3c); (iv) extruded polystyrene with diagonally ribbed wafer-like surface (XPS-4, Fig. 3d); and (v) extruded polystyrene with smooth surface (XPS-5, Fig. 3e).



(a) (b) (c) (d) (e)

Fig. 3 Studied polystyrene typologies: EPS-1 (a); XPS-2 (b); XPS-3 (c); XPS-4 (d); XPS-5 (e).

The material properties of the aforementioned polystyrene typologies (data provided by the suppliers) are detailed in Table 2. There is a clear difference between the properties of EPS and XPS, with XPS presenting, as expected, higher density, elastic modulus and compressive strength, and lower thermal conductivity.

Table 2
Material properties of the tested polystyrene typologies

Material	**Density [kg/m^3]**	**E-modulus [MPa]**	**Compressive strength at 10% deformation [kPa]**	**Thermal conductivity [W/mK]**
EPS-1	15	[4 - 6]	90	[0.038 - 0.040]
XPS-2	32	[18 - 20]	300	[0.034 - 0.036]
XPS-3				
XPS-4				
XPS-5				

3 Tests of sandwich panel assemblies

3.1 Pushout tests

3.1.1 Experimental setup and procedure

For these experiments, 300 × 300 mm^2 samples of the investigated sandwich panel configuration were adopted. The geometry of the specimens is presented in Fig. 4. It can be seen that the polystyrene layer does not cover the whole extent of the specimen plan area: it is placed only in a 150 mm wide central portion of the specimen. This is due to the need for free space in the peripheral areas of the specimen, in order to ensure proper support/anchoring of the bottom RSFRMC layer to the test fixture. It should also be mentioned that the GFRP connector is placed vertically, in the geometrical centre of the specimen, bridging the three layers of the specimen (as depicted in Fig. 5a). The test setup adopted to evaluate the pushout shear behaviour of the specimens is shown in Fig. 5a (front view) and 5b (top view), where the aforementioned anchoring issue can be more clearly understood: the bottom RSFRMC layer is firmly fixed to a metallic frame with four steel plates (one near each corner), whereas the upper RSFRMC layer is fixed to an actuator with 50 kN capacity, which was used to impose shear loading to the specimen. The tests were performed under displacement control at a rate of 5 μm/s up to 20 mm of imposed displacement (assessed by an LVDT with ± 0.25 μm precision, which measures the relative deformation between RSFRMC wythes). The pushout tests comprised a total of fourteen specimens, with two specimens being considered for the tests with EPS and three specimens being tested for each one of the four XPS typologies.

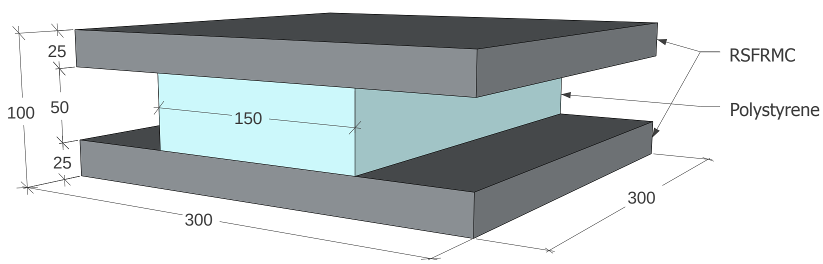
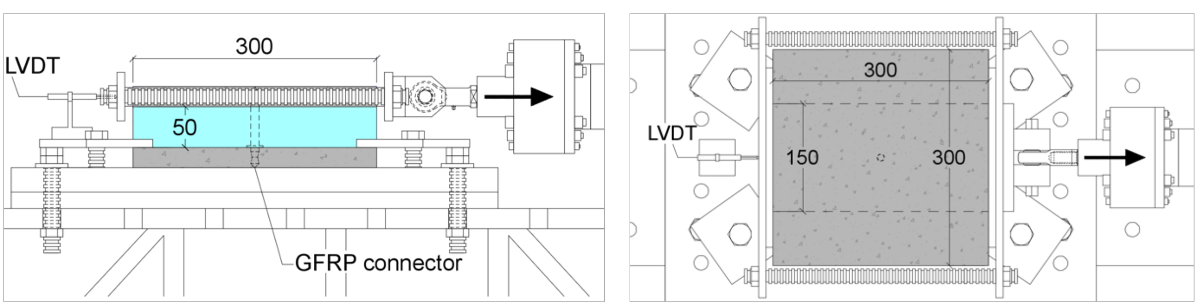


Fig. 4 Specimen geometry adopted for pushout and compression tests [mm].



(a) (b)

Fig. 5 Experimental setup for pushout tests [mm]: Front view (a); Top view (b).

3.1.2 Results and discussion

Fig. 6a, 6b, 6c, 6d and 6e present the load *vs*. relative deformation (horizontal) curves obtained for specimens with typologies EPS-1, XPS-2, XPS-3, XPS-4 and XPS-5, respectively. One specimen of series XPS-2 was disregarded due to a problem related to the test setup at the time of testing. The comparison between all the test series is presented in Fig. 6f, which depicts the average curves for each type of investigated sandwich panel configuration. In general, the structural behaviour of the specimens under shear loading can be described by four main phases: (i) linear behaviour until approximately [0.5-1.5] mm of relative deformation between wythes; (ii) beginning of non-linearity, with stiffness reduction followed by a load decrease (more abrupt for polystyrene typologies that afford better adhesion to the RSFRMC wythes), when the debonding process between the bottom RSFRMC and its contacting polystyrene is initiated; (iii) hardening phase characterized by a gradual increase in load due to friction in the RSFRMC-polystyrene transition that takes place during the continuing debonding process; and (iv) softening phase, initiated after failure of the GFRP connector at the bottom RSFRMC-polystyrene interface (see details presented in Fig. 8) that takes place between approximately 10 and 12 mm of relative deformation, until full debonding of the bottom RSFRMC-polystyrene interface occurs.

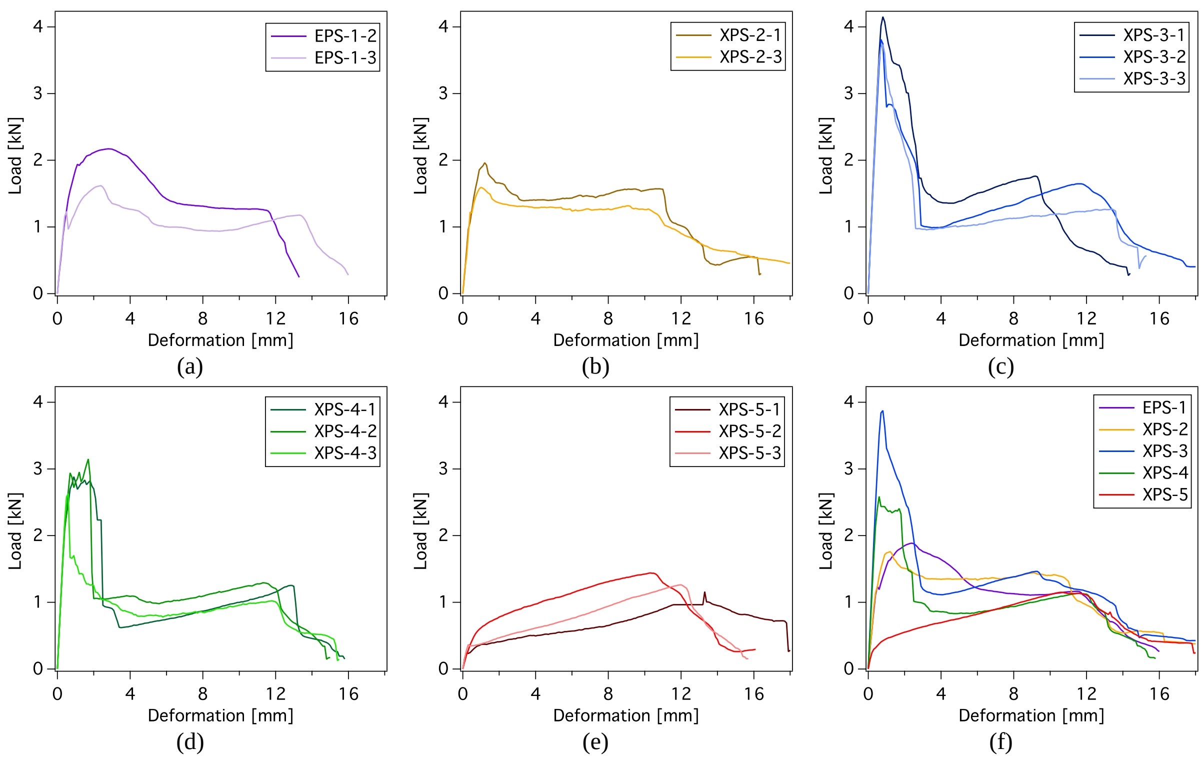


Fig. 6 Pushout tests – load *vs.* deformation curves: EPS-1 (a); XPS-2 (b); XPS-3 (c); XPS-4 (d); XPS-5 (e); Average curves (f).

Fig. 7 shows a more detailed insight of the tests performed on all the specimens, presenting a collection of images taken before, during and after testing, providing a more individual analysis of the different specimen typologies. Particular disparities were observed in case of typology XPS-5, for which the linear/non-linear transition point was reached for a significantly lower load (less than 1 kN) and was followed by a load increase in the above-mentioned second phase, rather than a decrease. Also, for specimens with EPS, only partial debonding occurred (in approximately half of the RSFRMC-polystyrene interface extension), with actual shear failure taking place in the polystyrene layer itself, near the interface, which is visible in Fig. 7c (a small portion of EPS remains attached to the bottom RSFRMC layer). It can be seen that the specimens with core layer type XPS-3 ensured the highest load carrying capacity until approximately 3 mm of lateral deformation, with an average peak load of 3.94 kN. The lowest performance was provided by specimens XPS-5 (XPS with smooth surface finishing). It is also worth highlighting that among the two most commonly used polystyrene solutions - specimens EPS-1 and XPS-5 - EPS provided significantly higher (+ 50%) shear strength to the composite solution.

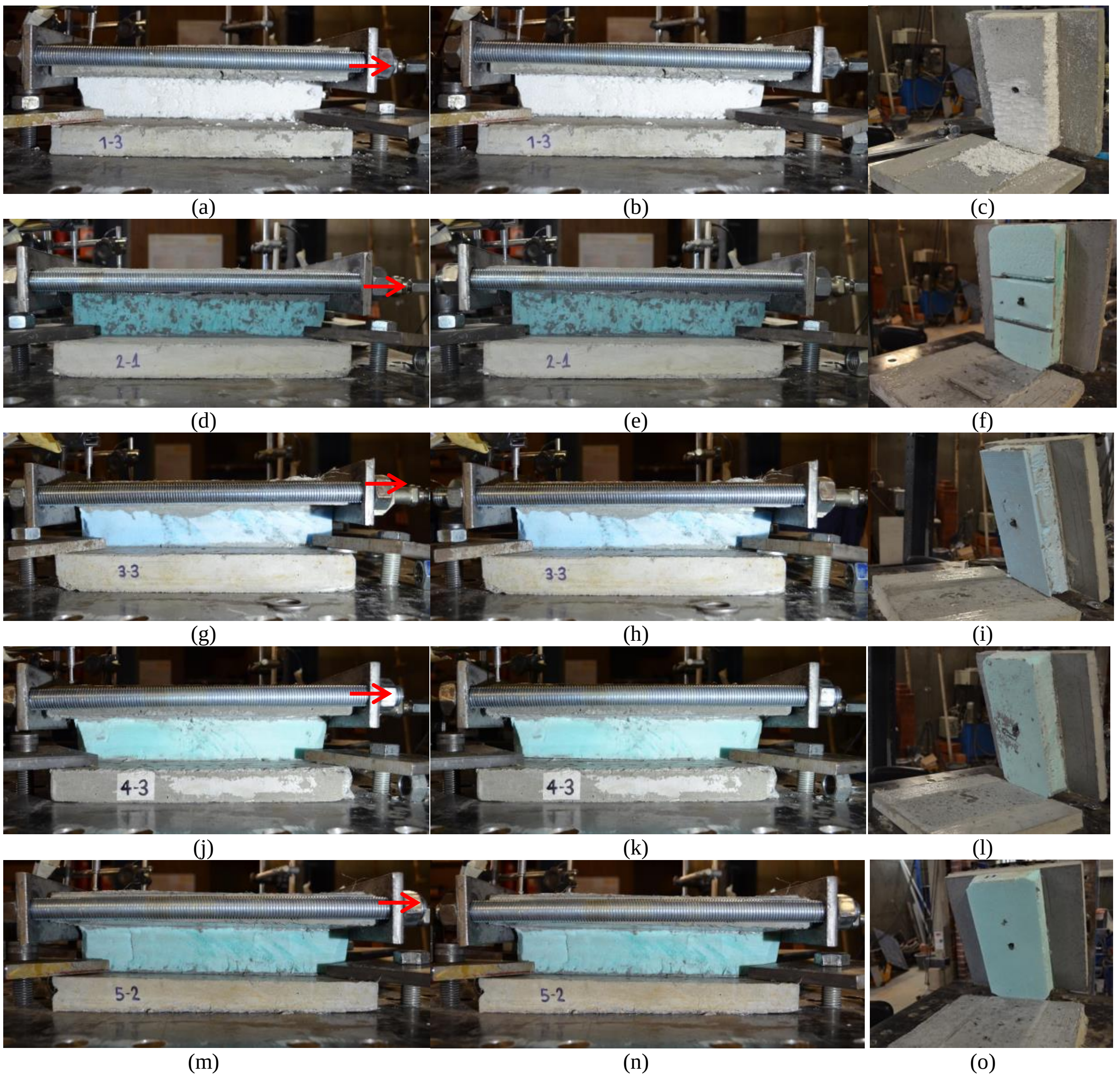


Fig. 7 Pushout tests – specimens before (left), during (centre) and after testing (right): EPS-1 (a,b,c); XPS-2 (d,e,f); XPS-3 (g,h,i); XPS-4 (j,k,l); XPS-5 (m,n,o).

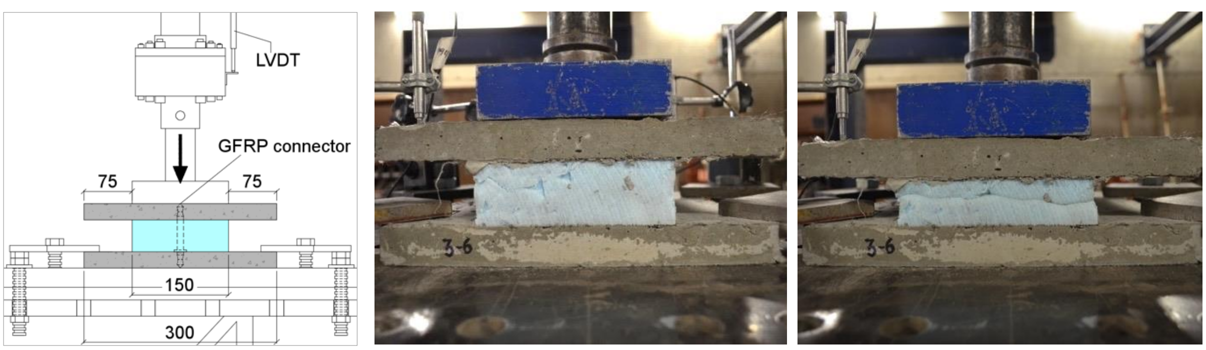
(a) (b) (c) (d) (e)

Fig. 8 Pushout tests – details of failure mode (bottom RSFRMC-polystyrene transition: EPS-1 (a); XPS-2 (b); XPS-3 (c); XPS-4 (d); XPS-5 (e).

3.2 Compression tests

3.2.1 Experimental setup

For the compression tests, the same specimen configuration was used, as depicted in Fig. 4. The test setup adopted to evaluate the behaviour of these specimens under compression loading is shown in Fig. 9a. The load is applied vertically, by an actuator with 50 kN capacity, and transmitted to the specimen through a metallic plate that covers the central area of the specimen, which includes the insulation layer (300 x 150 mm^2). The tests were performed under displacement control at a rate of 30 μm/s (assessed by an LVDT with ± 0.5 μm precision, which measures the vertical displacement of the actuator), up to a maximum imposed displacement of 15 mm, which corresponds to a vertical deformation of 30% of the polystyrene layer. The tests under compression comprised a total of fourteen specimens, as for the pushout tests (two specimens for tests with EPS and three specimens for each one of the XPS typologies).



(a) (b) (c)

Fig. 9 Compression tests on sandwich panel specimens: Front view [mm] (a); Specimen at beginning of test (b); Specimen with 15 mm of deformation (c).

3.2.2 Results and discussion

The results obtained for all specimens of test series EPS-1, XPS-2, XPS-3, XPS-4, and XPS-5 are shown in Fig. 10a, 10b, 10c, 10d and 10e, respectively. Also, as an example, pictures taken before and after performing one of these tests can be seen in Fig. 9b and 9c, respectively. The highest average results in terms of maximum applied compressive stress were attained for polystyrene typology XPS-5

(485.5 kPa), closely followed by XPS-2 (473.9 kPa). In both cases, the peak load was reached for an average vertical deformation of 5.18 mm. The results obtained for the different specimen typologies are compared in Fig. 10f, which presents the average curves for each type of core. It can be seen that all specimens with XPS as core layer behaved similarly, reaching a maximum compressive stress higher than 425.0 kPa in all cases. Among specimens with XPS, a slight disparity can be pointed out for test series XPS-3, where the peak load was reached earlier, for an average vertical deformation of approximately 3.00 mm; and test series XPS-4, for which a more premature stiffness reduction occurred (for an applied compressive stress of approximately 225.0 kPa – see Fig. 10f). Fig. 10f also shows that the lowest average compressive strength was obtained in EPS specimens (163.3 kPa, at an average vertical deformation of 4.00 mm), which corresponds to approximately 1/3 of the compressive strength obtained in XPS specimens. For both EPS and XPS specimens, the maximum compressive stresses are significantly higher than the compressive strength values reported in the manufacturers' technical sheets, respectively 90.0 kPa and 300.0 kPa at 10% deformation (*cf*. Table 2). To some extent, this may be due to the load distribution between the insulation foam and the GFRP connector.

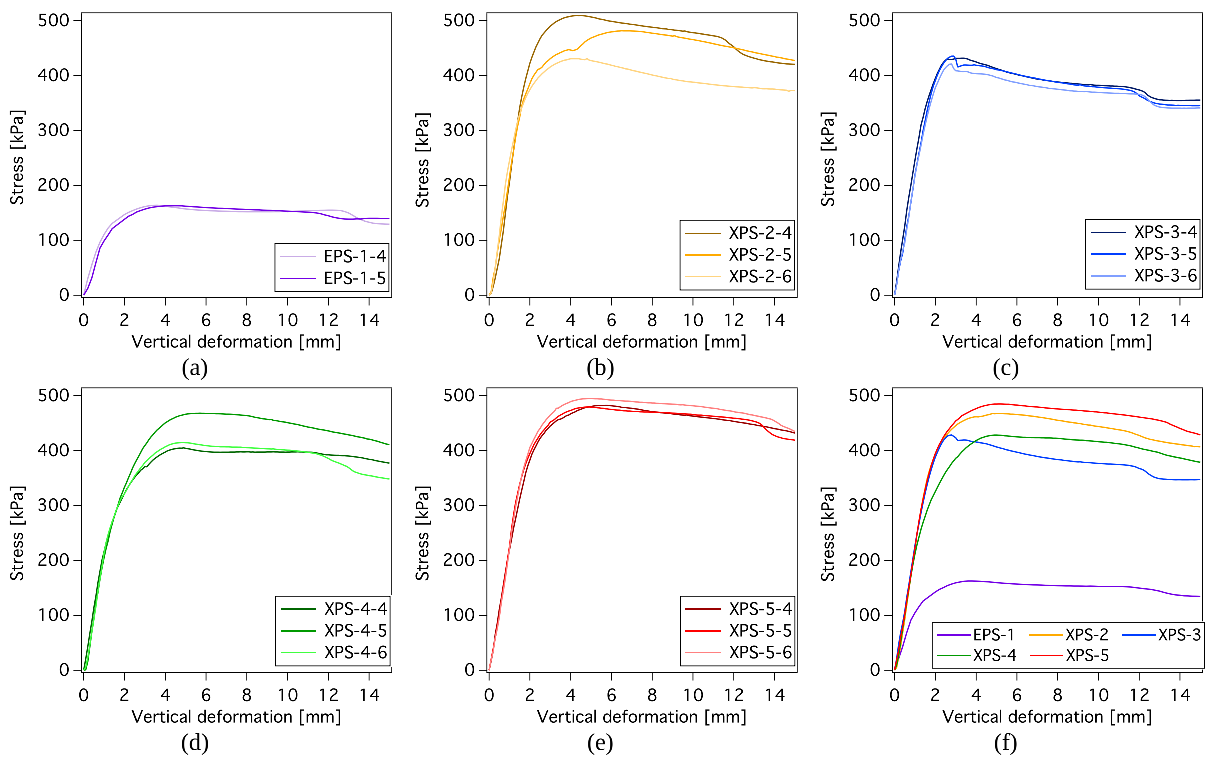


Fig. 10 Compression tests – compressive stress *vs.* vertical deformation curves: EPS-1 (a); XPS-2 (b); XPS-3 (c); XPS-4 (d); XPS-5 (e); Average curves (f).

4 Conclusions

In this study, a sandwich facade panel concept comprising external recycled steel fibre reinforced micro-concrete layers, a polystyrene insulation layer and glass fibre reinforced polymer connectors was proposed. The referred sandwich panel concept, intended for the integrated rehabilitation of multi-storey RC-frame buildings, was studied by experimentally testing the behaviour of its individual components and by performing tests on sandwich panel samples, under shear and compression loading conditions. Based on the experimental results obtained in this study, the following conclusions can be drawn:

1) The RSFRMC used in the wythes exhibits satisfactory results in terms of compressive (54.0 MPa) and stress at crack initiation (3.38 MPa) and, more importantly, relatively high post-cracking tensile capacity, exhibiting a residual tensile strength of 3.51 MPa and 1.72 MPa for CMODs of 0.5 mm and 2.5 mm, respectively. These results indicate that the use of recycled steel fibre reinforced concrete for the production of facade panels can constitute a viable solution as a material to be employed for structural rehabilitation of RC-frame buildings (e.g. buildings presenting seismic vulnerability), while contributing to a more sustainable rehabilitation sector.

2) The pushout tests performed for the selection of the type of insulation layer to be used in the panels showed that, although this component is regarded almost exclusively as being responsible for providing thermal insulation to the composite panel, indeed it provides non-negligible contribution to the structural performance of the panel. The experimental program revealed clear differences between the tested specimen typologies, highlighting the influence of the adhesion between RSFRMC and polystyrene on the overall structural performance of the sandwich panel solution under shear loading conditions. Based on the obtained results, the XPS-3 (of rough surface) was the selected polystyrene typology for the production of the sandwich panel prototype envisaged for this research work. Specimens with XPS-3 core presented the highest in-plane shear capacity up to a relatively large sliding (3 mm). EPS specimens, although having the lowest mechanical properties among all tested polystyrene typologies, performed better under shear loading when compared to the ones containing XPS with smooth surface finishing (XPS-5) – this fact can also be associated to the different adhesion between the sandwich panel layers due to the polystyrene surface treatment.

3) XPS specimens with different surface finishing presented similar performance under compression loading, whereas specimens with EPS yielded at significantly lower compressive stress values. This behaviour of the sandwich panel samples under compression can be directly related to the different compressive strength of these polystyrene layers, as reported by the manufacturers.

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