

## **MECHANICAL CHARACTERIZATION OF TRC PRECAST FAÇADE SANDWICH PANEL FOR ENERGY RETROFITTING OF EXISTING BUILDINGS**

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### **ABSTRACT**

Residential and commercial buildings are responsible of a large energy consumption, both for the heating in winter and the air conditioning in summer. Standards have introduced severe limits to guarantee the energy saving in new buildings; however, there is a significant need of retrofitting existing buildings, because of their large impact on the real estate in continents like Europe.

In the framework of a FP7 European project, a multilayer prefabricated façade panel is proposed as an outdoor solution. It is characterized by an internal EPS layer, 100 mm thick and by two external layers made of textile reinforced concrete (TRC), 12 mm thick. The insulating material is also used to transfer the shear between the external TRC layers. The maximum size of the panel is 1.50 x 3.30 m<sup>2</sup>; the panel height is properly chosen in order to fasten it to the frame concrete beams. In the paper the design of the panel and the results of tests performed on full scale panels are resumed. The panels were punctually fastened on the corners through suitable anchors and were loaded by means of a distributed load (considering wind pressure and suction as the main load acting on the panel). The panels were also tested according to a 4 point-bending set-up up to collapse to check their ultimate limit state on full-size prototypes.

**Keywords:** façade retrofitting element, sandwich panels, textile reinforced concrete, mechanical behavior.

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## 1. INTRODUCTION

Sandwich structures have been applied primarily in aircraft, missile and spacecraft industry since 1940s (Vinson, 1999); their use has been extended to other fields, such as building industry, since 1960s, when a worldwide boom in prefabricated building elements favoured the diffusion of these sandwich products (Davies, 2001).

Two main kind of sandwich panels are used in buildings: metallic face panels and R/C cladding sandwich panels.

Panels characterized by both the inner and the outer faces formed of metal sheets usually act compositely with a relatively low-strength core (with suitable insulating and stiffening properties). The bond between components can be obtained through a line forming process, by using adhesive or through mechanical fastenings. According to Davies (2001), these sandwich solutions are designed in such a way that they act as a composite load-bearing unit for the expected working life.

Pre-cast R/C cladding sandwich panels are generally made of two external reinforced concrete layers connected through the insulation layer by means of various type of shear connectors (Einea et al., 1991). Those panels are not designed in order to behave as composite panel, exploiting the adhesive bond; depending on the strength and stiffness of the shear connectors used, a sandwich behaves as fully-composite, partially-composite or non-composite panel (Salmon et al., 1997; Benayoune et al., 2008, Naito et al., 2011). With respect to metallic face panels, their weight is considerably higher as the thickness of each concrete layer is never smaller than 40 mm.

Hegger and Horstmann (2009) proposed a lightweight panel with both the concrete layers made of textile reinforced concrete (TRC). The use of TRC guarantees to significantly reduce the thickness of the layers if compared to traditional panels. Furthermore, the fine-grained concrete used in TRC allows to obtain good durability and finishing, features that are very important for façade elements. Finally, exploiting adhesive bond it is possible to limit or to completely prevent the use of shear connectors, thus avoiding thermal bridges. In real applications, they introduced connecting devices in order to guarantee a proper sandwich action and a durable connection between the TRC layers. Shams et al. (2014) studied the influence of shear connectors on the behavior of these TRC panels.

Colombo et al. (2008), Dey et al. (2015), di Prisco et al. (2012), di Prisco and Zani (2012), Ferrara et al. (2008) and Müller et al. (2012) also studied cement based sandwich elements in which advanced cementitious composites are used for the external layers and the connection between the layers is obtained only through the bond between the insulating material and the cementitious layer, without any connector.

In the framework of the European project EASEE - Envelope Approach to improve Sustainability and Energy Efficiency in existing multi-storey multi-owner

residential buildings - a TRC sandwich panel is proposed for the energy retrofitting of existing building (EASEE, 2012-2016). Targets of the project are multi-storey multi-owner residential buildings, dated before 1975, characterized by reinforced concrete frame structures and hollow-core brick walls.

One of the main project objectives is the design of a technological solution representing a valid and more durable alternative to the exterior insulation and finishing system (EIFS), which is usually used for the energy retrofitting of existing buildings. The main advantages of the solution, if compared with the thermal coating (EIFS system), are: the lower impact on occupant life (no scaffolding required), the possibility to obtain the desired finishing in terms of surface roughness, color, pattern (including the reproduction of the original façade), the increase in impact resistance, the higher quality of finishing and an higher expected durability. The latter aspect is particularly important, especially considering a residual expected building life of at least 30 years. Aesthetic and durability aspects are directly related to the use of a high strength fine-grained concrete in TRC.

Durability problems could occur mainly in the EPS/TRC interface and in both the materials (TRC layers and EPS), because of temperature conditions correlated to freezing and thawing cycles in winter and sun radiation in summer. Moreover, alkali-resistant glass fabric could be affected in the time by some degradation, resulting in a loss in strength of the TRC composite: in previous tests performed on cementitious materials reinforced with AR-glass fibers, a loss in strength of about 20% was detected after 10 years (Purnell et al., 2006). The use of modified matrices and coatings can determine substantial improvements in TRC durability (Purnell et al., 2006).

The proposed panel is also characterized by all the advantages related to pre-casting in terms of quality control and fast mounting. The use of TRC allows the producer to keep the weight of the panel under 80 kg/m<sup>2</sup>; that means building site safety during panel handling and low building mass increment, requirement that plays a key role in seismic areas.

This paper is focused on the mechanical characterization of full-scale panels.

## **2. TRC PRECAST FAÇADE SANDWICH PANEL**

The final solution proposed by the EASEE consortium consisted in a prefabricated façade sandwich panel characterized by an internal insulation layer 96 mm thick, made of expanded polystyrene (EPS 250) and by two external layers 14 mm thick in textile reinforced concrete (Figure 1).

The maximum size of the panel was 1.50 x 3.30 m<sup>2</sup>. The panel height was properly chosen in order to fasten it to the frame concrete beams by means of four connectors placed near to the corners on the short edges: the two upper connectors are aimed at resisting only the wind pressure acting on the panel, while the two

connectors placed at the bottom are loaded both by wind pressure and the self-weight of the panel.

When the panel is applied to a façade, the anchoring system connects the internal TRC layer to the bearing structure of the building. When the wind pressure acts on the external surface of the panel, the load is transferred from the outer to the inner TRC layer through the insulation layer and from the inner TRC layer to the bearing structure through the anchors. A proper anchoring system, which is not discussed in this paper, has been developed by the consortium of the European EASEE project in order to properly transfer the stresses from the panel to the bearing structure and to resist the wind load and the panel self-weight.

The thickness of the polystyrene layer is chosen in order to guarantee a proper thermal insulation, significantly reducing heat losses of the building.

In order to correct the out of plumb of the existing façade, an air cavity is left between the panel and the wall (Figure 1a).

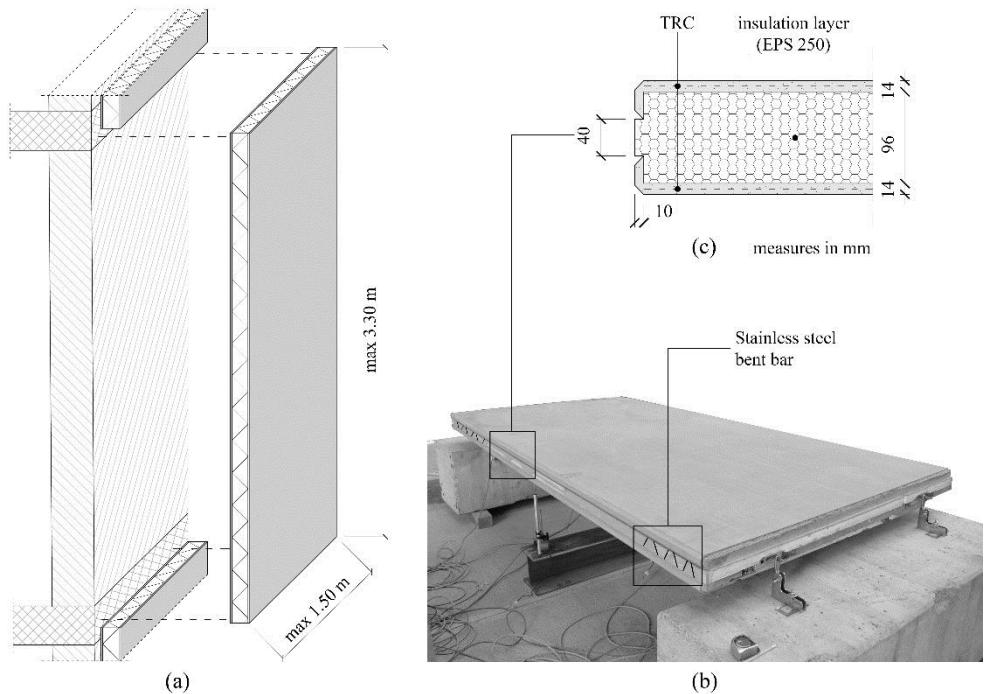


Figure 1 – EASEE sandwich panel: sketch (a), full scale panel fastened to concrete beams (b) and detail of the panel edge (c), (Colombo et al., 2015c).

Thermal bridges caused by the connectors are prevented by using the insulating material to transfer the shear between the two external TRC layers. However, in order to prevent the outer layer detachment in extreme conditions (e.g. fire), the panel is equipped with four stainless steel AISI 310S bent bars ( $\varnothing 5$ ) embedded in both the longitudinal panel edges at the upper and lower ends (Figure 1b).

The fabric warp is aligned with the longitudinal direction of the panel. The detail of the four edges is visible in Figure 1c; the choice of this geometry is related to the requirement of a staff bead on all the corners in order to prevent any damage during handling and to guarantee an adequate aesthetic finishing of the joints. Furthermore, the mortar corner, together with a proper elastomeric joint, protects the insulation layer from the atmospheric agent attack.

A vertical formwork is used to cast the panels in order to guarantee a proper thickness of the concrete layers, minimizing the presence of voids in the mortar and ensuring an adequate level of finishing.

The panels designed in the project have been applied on a test façade at Politecnico di Milano and on three demo-buildings respectively in Gdynia (Poland), Madrid (Spain) and Cinisello Balsamo (Italy). The last one in Cinisello Balsamo is a full demo-building, which was completely retrofitted by applying the EASEE panels. It is a four storey building (ground floor for the basement plus three floor of apartments) characterized by a reinforced concrete load-bearing structure with central concrete columns and external reinforced concrete walls. Pictures of the test façade and of the Italian demo building are shown in Figure 2.

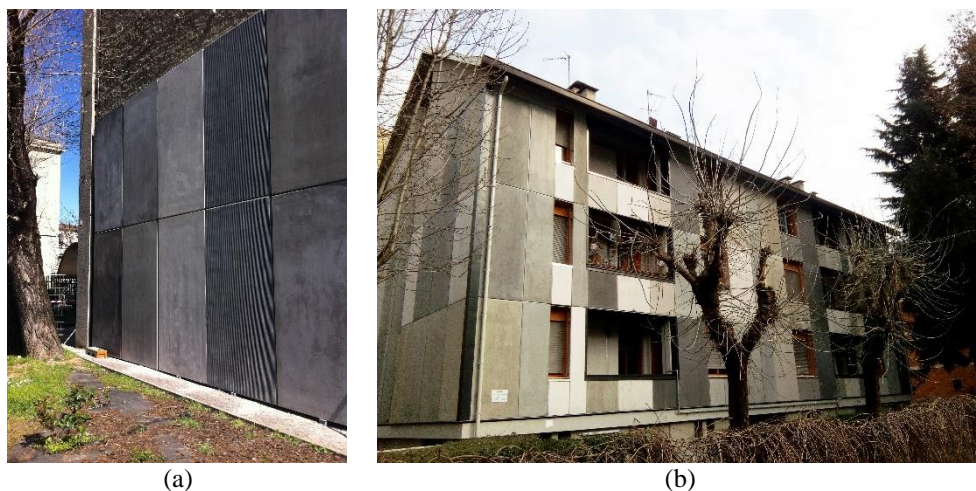


Figure 2 – Application of the EASEE sandwich panels: test façade at Politecnico di Milano (a) and full scale demo building in Cinisello Balsamo (b).

### 3. MATERIALS

#### 3.1. Textile reinforced concrete

Each TRC layer is obtained reinforcing a high strength fine grain mortar with one alkali-resistant glass fabric.

The matrix used is characterized by a water to binder ratio equal to 0.19 and by a superplasticizer to cement ratio equal to 5.5%. The maximum aggregate size selected is equal to 2 mm. These properties guarantee a high flowing capability that means good matrix-fabric and matrix-EPS bond. The mortar is characterized by a cubic compressive strength ( $f_{cm,cube}$ ) equal to 78.9 MPa (STD = 12.2% on 14 specimens) at 7 days and to 87.7 MPa (STD = 15.6% on 10 specimens) at 28 days; these mechanical properties were determined according to EN 196-1 (2005). The mix design is summarized in Table 1.

Table 1: mix-design of the matrix.

Component	Content
Cement I 52.5 ( $\text{kg/m}^3$ )	600
Quartz sand 0-2 mm ( $\text{kg/m}^3$ )	847
Water ( $\text{l/m}^3$ )	207
Superplasticizer ( $\text{kg/m}^3$ )	33
Slag ( $\text{kg/m}^3$ )	500

The fabric used as reinforcement, whose geometrical and mechanical characteristics are collected in Table 2, was selected after performing several investigations aimed at optimizing the performance in terms of TRC strength and ductility, the bond between matrix and fabric, and the internal filament slip.

Table 2: characteristics of the fabric.

Fabrication technique	Leno weave
Material	AR-glass
Coating	Water resin based on SBR <sup>a</sup>
Warp yarn spacing (mm)	10.0
Weft yarn spacing (mm)	14.3
Warp (Tex)	2 x 2400
Weft (Tex)	2 x 1200
Coating weight ( $\text{g/m}^2_{\text{fabric}}$ )	100
Maximum tensile load <sup>b</sup> on 70 mm (kN)	9.15 (STD = 4.7%)

<sup>a</sup> Styrene-Butadiene Rubber; <sup>b</sup> average values of 10 tests

### 3.1. Expanded polystyrene

The expanded polystyrene used is commercially known as EPS250 and is characterized by a compressive strength, at strain equal to 10%, of 0.25 MPa, by a thermal conductivity equal to 0.034 W/mK and by a density of 35 kg/m<sup>3</sup> (properties guaranteed by the producer according to EN 13163 (2009)).

Six nominally identical specimens with dimensions of 100 x 100 x 150 mm<sup>3</sup> were cut from a larger mat of EPS: three were tested in uniaxial compression and three in uniaxial tension by gluing their ends to the testing devices; all tests were performed using an electromechanical press INSTRON 5867 with a maximum load capacity of 30 kN. The tests were displacement controlled by imposing a constant displacement rate of the machine cross-head equal to 1e-3 mm/sec.

The compressive behavior obtained is elasto-hardening, while the uniaxial tensile behavior is elasto-brittle, with a higher strength in tension ( $\sigma_{t,av} = 0.392$  MPa, STD = 8.4%) rather than in compression ( $\sigma_{c,av} = 0.187$  MPa at the end of the linear branch, STD = 2.7%). The initial slope of the compressive  $\sigma$ - $\epsilon$  curve, equal to 13.7 MPa, gives an estimation of the elastic modulus in compression.

Three shear tests were performed on as many EPS specimens in order to determine the  $\tau$ - $\gamma$  shear constitutive law. A proper test set-up were adopted according to EN12090 (2013) following the prescriptions for the double test specimen assembly. The maximum shear stress measured is equal to 0.16 MPa (STD = 15.3%). An estimation of the shear modulus  $G$  can be defined as the initial slope of the experimental  $\tau$ - $\gamma$  curve and is equal to 5.04 MPa.

## 4. LAB-SCALE SPECIMENS

Four point bending tests were performed on sandwich beams with dimensions of 550 x 150 x 120 mm<sup>3</sup> and 1200 x 300 x 120 mm<sup>3</sup>. In both cases, the fabric warp was aligned with the beam longitudinal direction.

In this experimental campaign, the cross-section of the sandwich did not correspond to the final one: due to technical problems related to the production process, it was necessary to apply some changes during the project evolution.

In particular, the thicknesses of the layers differed from those of the final solution: TRC layers were 10 mm thick, and the EPS layer was 100 mm thick. Also the fabric used as reinforcement was not the same adopted in the final solution; it was characterized by a nominal strength in the warp direction of 820 MPa instead of 680 MPa.

All the results and an in-depth discussion of them can be found in Colombo et al. (2015a).

Despite differences, some main conclusions useful in understanding the TRC sandwich behavior can be drawn:

- the solution experienced a large ductility, due to both large compressive plastic strain in the EPS central core and multi-cracking pattern in the TRC layers;
- the multi-cracking pattern seems to be affected, especially in the small geometry, by the fabric position in the TRC layer thickness; nevertheless the different crack pattern does not affect the global response of the specimen;
- an important contribution to the global response is given by the large shear deformability of the EPS, that also causes the solution to behave as a partially composite sandwich;
- even if the non-linear global response is strongly driven by the EPS plastic compressive strains, the specimen failures are respectively related to the tensile failure of TRC for small specimens and to the EPS brittle cracking in case of bigger geometry;
- the transverse (z direction) behavior of the sandwich is less important for larger specimens.

Small beams (550 x 150 x 120 mm<sup>3</sup>) were also tested after the exposure to freezing-thawing cycles in order to investigate the durability of the interface in sandwich panels.

Eight tests were carried out considering both un-cracked and pre-cracked conditions; about cracked specimens, a rare SLS condition was considered: the equivalent load was 1.50 kN/m<sup>2</sup> and cracks for that condition were not detectable by visual inspection. The temperature ranged between +4°C to -18°C, with the bottom TRC face completely immersed in water; the number of cycles for the 8 specimens were respectively 150 (2 samples, un-cracked) and 500 (6 specimens, 3 un-cracked and 3 pre-cracked). No specific damage and layer delamination was observed directly on the specimens and looking at the load-stroke response.

All the details about this experimental campaign can be found in Colombo et al. (2016).

The same freezing-thawing cycles were applied to TRC specimens (400 x 70 x 6 mm<sup>3</sup>) then tested in uniaxial tension; also in that case a good durability was noticed (Colombo et al., 2015b).

## **5. FULL-SCALE PANEL BEHAVIOR**

### **5.1. Load controlled tests on full-scale panels anchored through the real anchoring system**

Two panels with dimension of 1.50 x 3.03 m<sup>2</sup> were tested according to a load controlled test set-up.

The characteristics of the panels are those described in Section 2, and the materials used in the production process are specified in Section 3. In this case the only difference between the tested panels and the final solution is the thickness of



the layers, which is 12+100+12 mm instead of 14+96+14 mm. The global thickness of the sandwich solution is unchanged and is equal to 124 mm.

The fabric warp is aligned with the longitudinal direction of the panel.

During the tests, each panel was fastened with four pin connections to two concrete supports and was loaded by means of a distributed load over an area of  $1.3 \times 2.5 \text{ m}^2$  (Figure 3 – measures in mm). The distributed load is applied on the upper surface by filling a pool with water and is measured by a flow-meter.

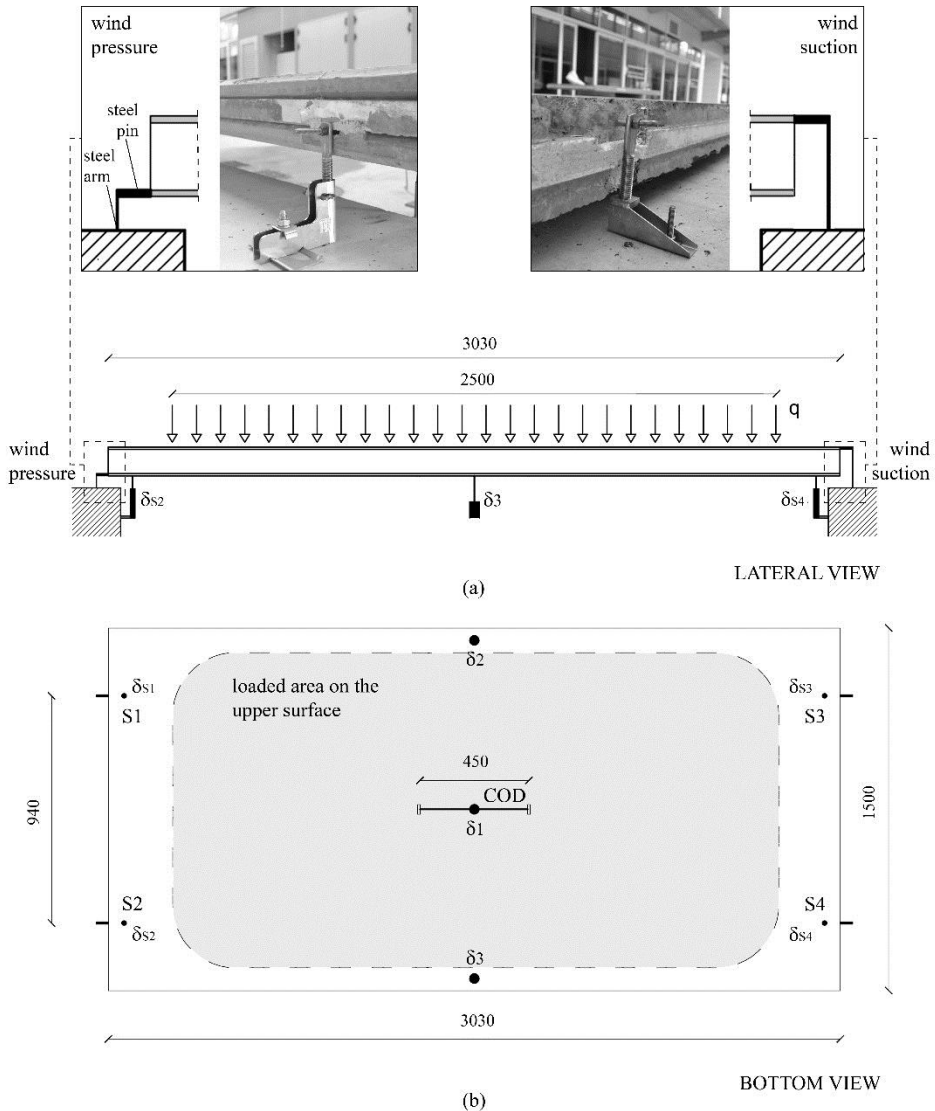


Figure 3 – Test set-up: lateral (a) and bottom (b) view (Colombo et al. 2015c).

In the experimental campaign, two configurations were considered: the first one simulates the wind pressure loading condition, while the second one simulates the wind suction loading condition (Figure 3).

All the details concerning the panel placement and boundary conditions during test and the instrumentation of the panel can be found in Colombo et al. (2015c).

### 5.1.1. Summary of main experimental results

All the test results are shown and discussed in detail in Colombo et al. (2015c).

In this Section, just the distributed load vs. crack opening displacement (COD) curve is shown in Figure 4 respectively for wind pressure and wind suction test.

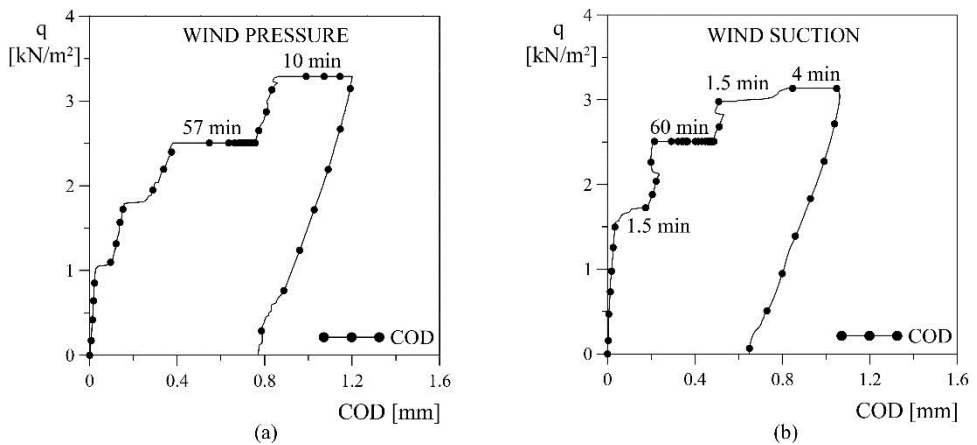


Figure 4 – Displacement controlled test results: distributed load vs. COD curves for wind pressure (a) and wind suction (b) case (Colombo et al. 2015c).

An important requirement for concrete façade elements during service life is that cracks should not be visible by visual inspection. That means that, at serviceability limit state, the crack width should be lower than 50  $\mu$ m.

Taking as an example the Italian Standard (NTC, 2008), at serviceability limit state a maximum wind pressure equal to 1.50 kN/m<sup>2</sup> could act on the panel (assuming a building 30 m tall, placed in an area characterized by unfavorable wind condition - zone 7). For this level of pressure, the COD measured over the mid-span, with a gauge length of 450 mm, is equal to 135  $\mu$ m and 34  $\mu$ m respectively for wind pressure and wind suction cases. Considering that multi-cracking occurs in this region, with a crack spacing close to the layer thickness, it can be assumed that cracks are not visible to the naked eye.

It is worth noting that the panel, placed in horizontal position according to the set-up, is bearing also the self-weight, equal to  $0.66 \text{ kN/m}^2$ , which has to be added to the applied distributed load of Figure 4.

In the graphs it is possible to observe some plateaus, corresponding to increments of the measured COD at a constant applied load. Taking into account the step load applied, these plateaus can be seen as the effect of the load sustained for some minutes and they are related to the applied test rate and to the consequent time of crack propagation. In both graphs the time of load permanence corresponding to these plateaus is specified. It is important to remind that the main load acting on the façade panel is the wind, whose gusts last seconds and not minutes.

When the tests were stopped (reaching of the maximum capacity of the loading pool) the panels were still able to carry the load (no failure occurred).

**5.2. Displacement controlled tests on full-scale panels**

The two panels already tested according to a load controlled test set-up were also tested up to failure according to a displacement controlled procedure. In this section, these panels are named V1 and V2 in order to indicate that they were cast by means of a vertical formwork.

In order to speed up the production, the panels applied in Cinisello Balsamo demo-building were produced not only by means of the vertical formwork, but also following a horizontal casting procedure. Two panels produced by means of this horizontal technique (H1 and H2) were also tested according to a displacement controlled test set-up. These full-size panels were 3.3m long and 1.5 m wide.

The materials used in the casting phase are those described in Section 3. At this stage of the project, the stratigraphy has been modified as specified in Section 2 (final solution), albeit keeping unchanged the global thickness (equal to 124 mm).

The adopted horizontal casting procedure allows maintaining staff beads on all the corners of the front face, while it does not allow the execution of the mortar corner on the panel edges. A detail of the edge is shown in Figure 5.

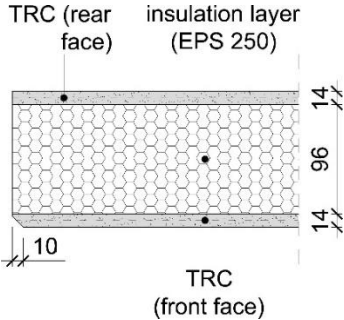


Figure 5 – Detail of the edge of horizontally cast panels (measures in mm).

5.2.1. Test set-up

The displacement-controlled bending tests were carried out by using a contrast frame equipped with an electro-mechanic actuator; a constant increase of stroke was imposed and the corresponding load measures were provided by a 1000 kN load cell. A displacement rate equal to 15  $\mu\text{m}/\text{sec}$  is applied. The displacement controlled test set-up is shown in Figure 6.

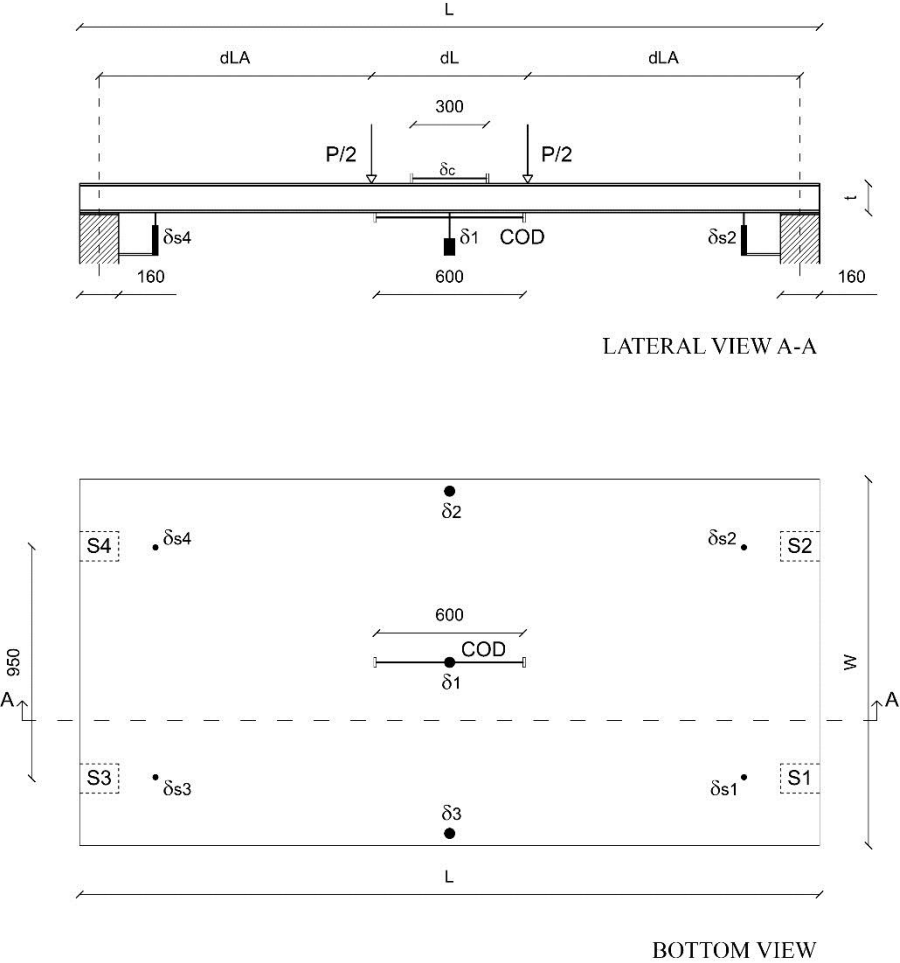


Figure 6 – Displacement controlled test set-up: lateral and bottom view (measures in mm).

In Table 3 the following information are provided for each panel:

- the name of the panel (V refers to a cast in vertical panel, while H refers to a cast in horizontal panel);
- the panel sizes;
- the applied loading condition (in case of wind in pressure the anchoring boxes are placed face-down, while for wind suction condition they are placed face-up);
- the nominal distances  $d_{Ln}$  (distance between the loading knives) and  $d_{LAn}$  (shear span) defined according to Figure 6.

Table 3: Panels tested according to a displacement controlled test set-up.

Panel	Dimensions L x W x t (mm <sup>3</sup> )	Wind	$d_{Ln}$ (mm)	$d_{LAn}$ (mm)
V1*	3030 x 1500 x 124	Pressure	640	1115
V2*	3030 x 1500 x 124	Suction	640	1115
H1	3300 x 1500 x 124	Pressure	640	1250
H2	3300 x 1500 x 124	Suction	640	1250

\* panel previously tested in serviceability conditions with real boundary conditions and distributed load (see Section 5.1)

The panels were simply supported on four points, under the anchoring boxes, resting on elastomeric bearing plates 120 mm wide and 10 mm thick. In Figure 7a a picture of panel V2 during test is shown, while the detail of the panel support on elastomeric plates is visible in Figure 7b.



(a)



(b)

Figure 7 – Panel V2 during test: global view (a) and detail of the supports (b).

The instrumentation adopted to measure the panel displacements is summarized in the following (see Figure 6). Four LVDTs were placed vertically on the bottom surface of the panel and were aimed at measuring the specimen vertical displacement next to the supports ( $\delta_{S1}$ ,  $\delta_{S2}$ ,  $\delta_{S3}$  and  $\delta_{S4}$ ). Three potentiometric transducers were placed in vertical position on the bottom surface of the panel and were aimed at measuring the specimen vertical displacement at mid-span respectively in the center and on the border of the panel ( $\delta_1$ ,  $\delta_2$  and  $\delta_3$ ). A displacement transducer was placed on the bottom surface of the panel astride the mid-span with a gauge length  $L_{COD}$  equal to 600 mm and was instrumental at measuring the crack opening displacement (COD). A displacement transducer was placed on the upper surface of the upper TRC layer between the loading knives (gauge length  $L_c$  equal to 300 mm) in order to measure displacement on the compressed side ( $\delta_c$ ).

Displacements  $\delta_{Si}$  ( $i=1,4$ ), COD (Crack Opening Displacement) and  $\delta_c$  were measured through inductive full bridge type transducers, with a nominal displacement equal to 10 mm, while  $\delta_j$  ( $j=1,3$ ) were measured using potentiometric transducers, with a nominal displacement equal to 150 mm. The data acquisition was performed by using an electronic measurement system SPIDER8 by HBM.

### 5.2.2. Experimental results

The experimental results are collected in Figure 8 in terms of load versus stroke and bending moment versus curvature curves.

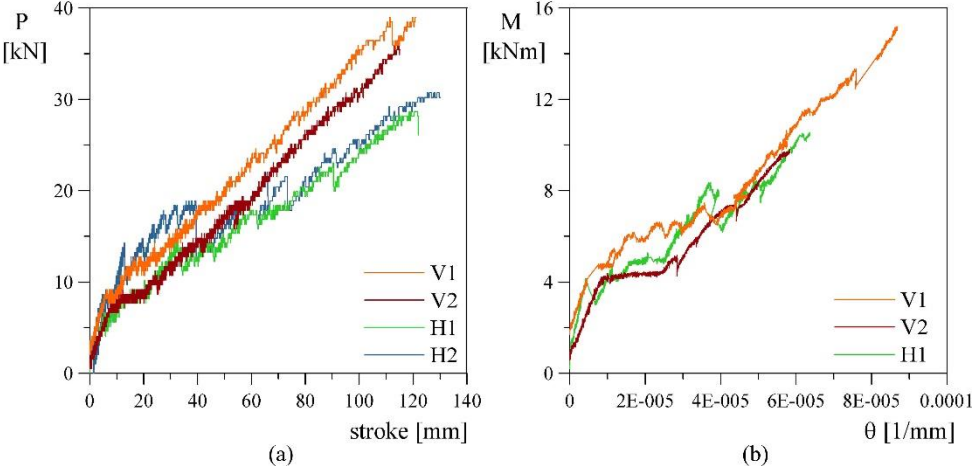


Figure 8 – Experimental results: load vs. stroke (a) and bending moment vs. curvature (b) curves.

The bending moments are obtained by multiplying the load acting on one knife for the lever arm, while the nominal curvature is defined as:

$$\vartheta = (\varepsilon_{\text{COD}} + \varepsilon_c) / t \quad \text{with} \quad \varepsilon_{\text{COD}} = \text{COD} / L_{\text{COD}} \quad \text{and} \quad \varepsilon_c = \delta_c / L_c .$$

Each instrument was not placed exactly on the specimen surface, but was located at a certain distance: this detail was taken into account in the detected measures, by correcting the measures by assuming a rigid rotation.

It is important to underline that each curve was stopped when one of the displacement transducers involved in the computation of the curvature reached its maximum displacement or when the instrumentation was removed; in both cases the ultimate failure of the specimens was not reached.

Unfortunately, data are not available for panel H2, because the instrument devoted at measuring COD did not register correct values.

The maximum bending moments reached are respectively 21.73 and 20.03 kNm for V1 and V2 and 17.92 and 19.19 kNm for H1 and H2.

In all cases, the failure is due to the reaching of the maximum tensile strength of the lower TRC layer, thus leading to the EPS failure and, hence, to the debonding between the EPS and the upper TRC layer (Figure 9).

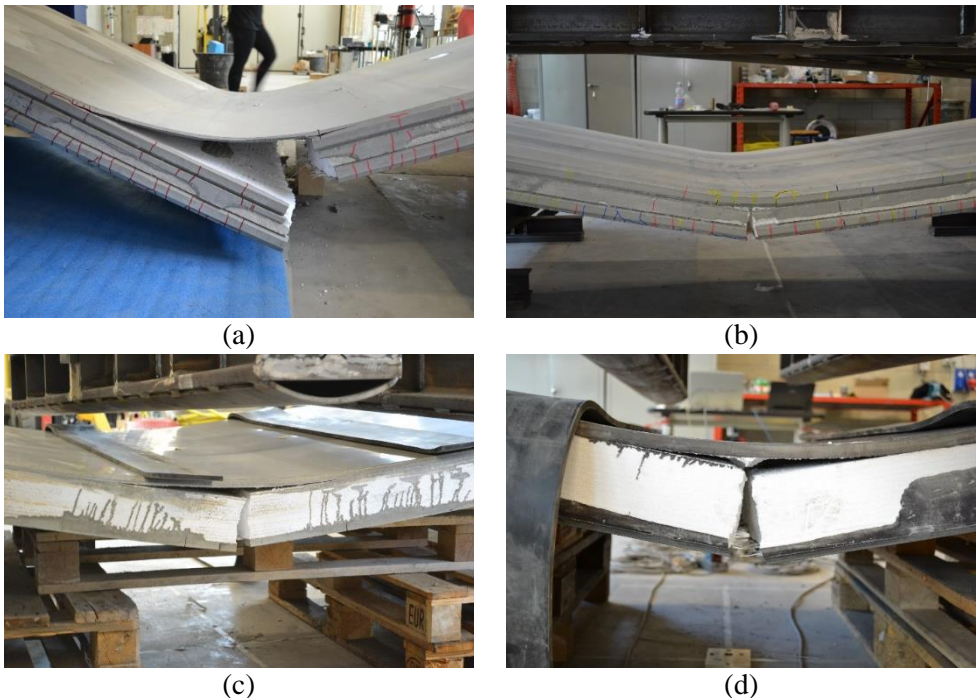


Figure 9 – Panel failure: specimen V1 (a), V2 (b), H1 (c) and H2 (d).

The crack pattern on the bottom surface at the end of each test is shown in Figure 10. It is worth noting that horizontally cast panels showed a higher crack distance and a lower maximum bending moment with respect to vertically cast panels due to the lower EPS-TRC bond related to the casting procedure.

## **6. CONCLUSIONS**

In the described European research project, a new prototype of light façade panel to improve the energy performance of existing buildings is proposed and checked.

The structural novelty is mainly related to the use of EPS material not only with an insulation function, but also as a structural layer in order to transfer shear stresses between the external TRC faces. The good mechanical behavior of this panel has been experimentally proven. The proposed solution guarantees a significant reduction of building heat losses; in particular, considering a typical existing hollow-core brick wall, a reduction of the thermal transmittance from 1.16 W/m<sup>2</sup>K to 0.26 W/m<sup>2</sup>K can be achieved.

The panel durability in winter environment has already been proven, while the effect of the sun radiation on the behavior of the composite is now under investigation. The production technique is sufficiently flexible to be used to produce panels for existing buildings as demonstrated in a full-size application implemented in Cinisello Balsamo village, in Milano outskirts.

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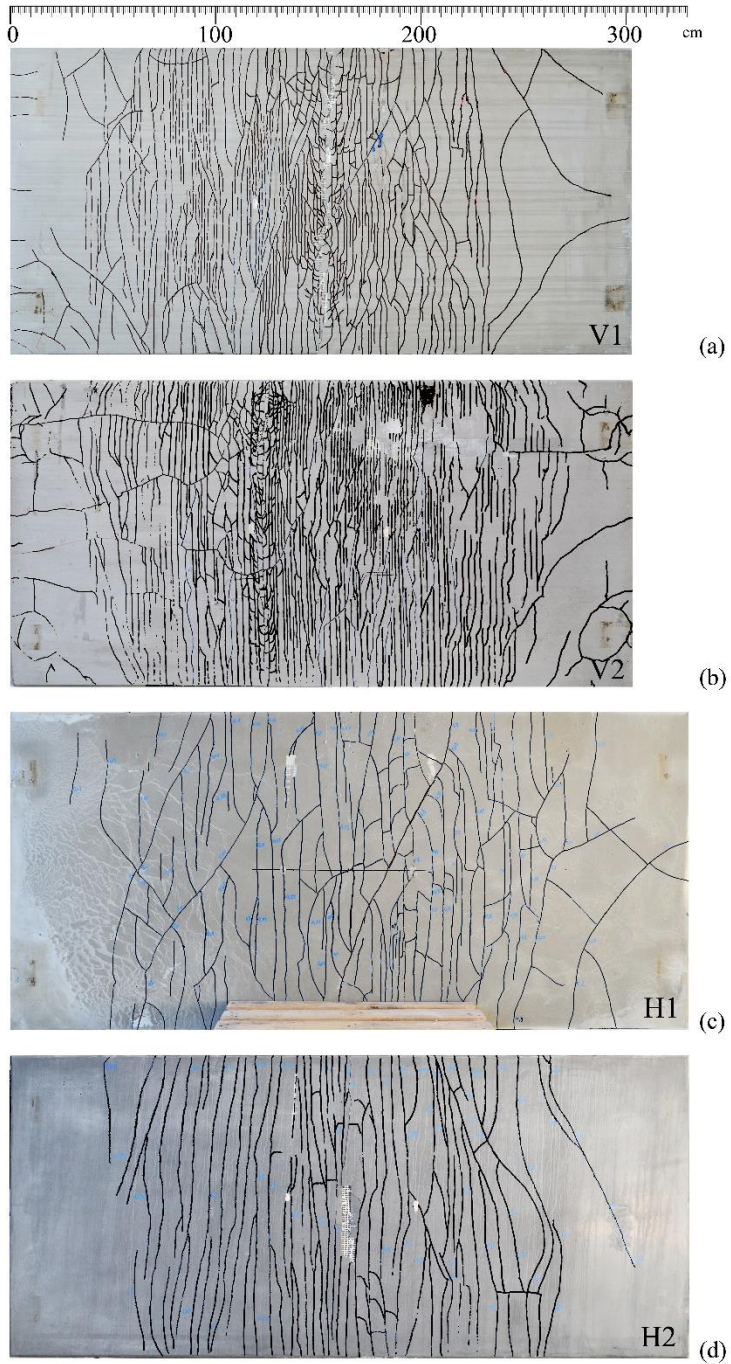


Figure 10 – Intrados crack pattern at the end of the test: specimen V1 (a), V2 (b), H1 (c) and H2 (d).

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