FAÇADE SANDWICH PANEL FOR ENERGY RETROFITTING OF EXISTING BUILDINGS

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INTRODUCTION

In 2010 residential and commercial buildings were responsible of about 40% of the total energy consumption in Europe, 70% of this energy being used for heating[1]. To reduce this consumption, Standards introduce limits to guarantee energy saving in new buildings, but also the energy retrofitting of existing buildings has to be considered because of their large impact on the phenomenon.

The European project EASEE[2] - Envelope Approach to improve Sustainability and Energy Efficiency in existing multi-storey multi-owner residential buildings - acts along this perspective. 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. 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. The solution proposed by the consortium consists in a prefabricated façade sandwich panel characterized by an internal insulation layer, made of expanded polystyrene, and by two external layers in textile reinforced concrete. The panels designed in the project have been applied to a test façade realized at Politecnico di Milano, campus Leonardo (**Figure 1**). A sketch of the proposed solution is shown in **Figure 2a**.

TRC is a composite cement-based material reinforced with alkali-resistant glass fabrics which allows designers to obtain thin and lightweight structures[3, 4] thanks to the high tensile resistance. The use of TRC guarantees to significantly reduce the thickness of the layers if compared to traditional sandwich panels. Furthermore, the fine-grained concrete used in TRC allows the producers to obtain good durability and finishing. Hegger et al.[5] previously proposed a sandwich panel with both the concrete layers made of TRC and pointed out the good mechanical behaviour of this solution; the panel exploits the advantages of a prefabricated sandwich solution while solving corrosion problems, improving the design possibility and obtaining the desired finishing.

The maximum size of the panel assumed in the project is 1.50 x 3.30 m^2 [60 x 130 $in.^2$]. The panel height is 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. The polystyrene layer is chosen to be 100 mm thick 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. Thermal bridges caused by the connectors are prevented by using the insulating material to transfer the shear between the two external TRC layers. In the panel just few connecting devices, active only in extreme conditions (e.g. fire), are provided to prevent the detachment between the two TRC layers. This approach to transfer the shear by means of the core material is commonly adopted for building sandwich panels characterized by polymeric or metallic external skins[6]. Nevertheless, several authors[7-11] proposed 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.

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 the higher 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[12]. The use of modified matrices and coatings can determine substantial improvements in TRC durability[12].

The proposed panel is also characterized by all the advantages related to precasting in terms of quality control and fast mounting. The use of TRC allows to keep the weight of the panel under 70 kg/m^2 [14.3 psf]; that means building site safety during panel handling and low building mass increment, particularly important in seismic areas.

In this paper the results of tests performed on full scale panels are shown.

EXPERIMENTAL INVESTIGATION

Two full scale panels (**Figure 2b**) were tested in bending by means of a distributed load. Two configurations were considered in order to simulate both wind pressure and wind suction loading condition.

Cross-section and materials

The panel solution is characterized by two external layer 12 mm [0.47 in.] thick made of textile reinforced concrete (TRC) and by an internal insulation layer 100 mm [3.94 in.] thick in expanded polystyrene (EPS), **Figure 2c**. TRC 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 [0.08 in.]. 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_{cc}) equal to 78.9 MPa [11,444 psi] (STD=12.2% on 14 specimens) at 7 days and to 87.7 MPa [12,720 psi] (STD=15.6% on 10 specimens) at 28 days; these mechanical properties were determined according to EN 196 Standard for mortar[13]. The mix design is summarized in **Table 1**.

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.

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 [36.26 psi] and by a thermal conductivity equal to 0.034 W/mK [0.236 BTU in./ft^{2}hr.°F] (properties guaranteed by the producer according to UNI EN 13163[14]).

Considering e.g. a typical existing wall made of external plaster, brick masonry 120 mm [4.72 in.] thick, air cavity, brick masonry 80 mm [3.15 in.] thick and internal plaster, its thermal transmittance U is estimated to be 1.16 W/m^{2}K [0.204 BTU/ ft^{2}hr.°F]; the addition of a layer of EPS250 100 mm [3.94 in.] thick leads to a significant reduction of the thermal transmittance down to 0.26 W/m^{2}K [0.046 BTU/ ft^{2}hr.°F]. This value is lower than the one specified for external walls by the Italian standards currently in force.

Tests on beams characterized by the same stratigraphy of the panel were previously performed by the authors[15] in order to investigate the cross-sectional behavior and the failure modes of the sandwich solution; in particular, small (550 x 150 mm^2 [21.65 x 5.91 in.^{2}]) and large (1200 x 300 mm^2 [47.24 x 11.81 in.^{2}]) sandwich beams were tested according to a four-point load scheme. Further details can be found in the paper of Colombo et al.[15]

Small beams were also tested after the exposure to freezing-thawing cycles in order to investigate the durability of the interface in sandwich panels. 8 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^2 [31.33 psf] and cracks for that condition were not detectable by visual inspection. The temperature ranged between +4°C [39.2°F] to -18°C [-0.4°F], with the bottom TRC face completely immersed in water; the number of cycles for the 8 specimens were respectively 150 (2 samples, un-cracked - "U150") and 500 (6 specimens, 3 un-cracked - "U500" - and 3 pre-cracked - "C500"). No specific damage and layer delamination was observed directly on the specimens and looking at the load-stroke response (**Figure 3**)[16]. All the details can be found in the thesis of Colombo[16]. The same freezing-thawing cycles were applied to TRC specimens (400 x 70 x 6 mm^3 [15.74 x 2.76 x 0.24 in.^{2}]) then tested in uniaxial tension; also in that case a good durability was noticed[17].

Full scale specimen geometry and test set-up

The size of each tested panel is 1.50 x 3.03 m^2 [60 x 120 in.^{2}] and the stratigraphy is as described above. The fabric warp is aligned with the longitudinal direction of the panel. The detail of the four edges is visible in **Figure 2c**; the choice of this geometry is related to the requirement of a staff bead on all the corners in order to avoid damages 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.

The insulation layer is used to transfer the shear forces between the external TRC layers; however, in order to prevent the layer detachment in extreme conditions (e.g. fire), the panel is equipped with four stainless steel AISI 310S bent bars (ϕ5 [0.20 in.]) embedded in both the longitudinal panel edges at the upper and lower ends, **Figure 2b**.

A vertical formwork was used to cast the specimens 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.

During the test, the 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 x 2.5 m^2 [51.2 x 98.5 in.^{2}]. The distributed load is applied on the upper surface by filling a pool with water and is measured by a flow-meter. A picture of the test set-up is shown in **Figure 4**.

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. 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 5a**).

According to the test set-up, the panels were tested in horizontal position. In order to account the real panel boundary conditions, the position of the anchoring systems in the tests reproduced the situation of the panel once placed in the vertical position on the façade, if the friction on the bottom supports is neglected. In particular, the two anchoring systems placed on the side that will correspond to the bottom part of the panel (S1 and S2, **Figure 5b**) were directly in contact with the panel edge. On the contrary, the steel arms placed on the side that will corresponds to the upper part of the panel (S3 and S4, **Figure 5b**) showed an eccentricity of 15 mm [0.59 in.] with respect to the panel edge.

Figure 5 shows the instrumentation adopted to measure the panel displacements. 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 (δ_{S1}, δ_{S2}, δ_{S3} and δ_{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 (δ_1, δ_2 and δ_3). Finally, a displacement transducer was placed on the bottom surface of the panel astride the mid-span with a gauge length equal to 450 mm [17.72 in.] and was instrumental at measuring the crack opening displacement (COD).

Displacements δ_{Si} (i=1,4) and COD were measured through inductive full bridge type transducers, with a nominal displacement equal to 10 mm [0.39 in.], while δ_j (j=1,3) were measured using potentiometric transducers, with a nominal displacement equal to 150 mm [5.91 in.]. The data acquisition was performed by using an electronic measurement system SPIDER8 by HBM.

EXPERIMENTAL RESULTS AND DISCUSSION

The test results are summarized in **Figure 6** for both the tests.

In particular, in **Figures 6a** and **6b** the distributed load vs. mid-span vertical displacement curves are collected respectively for the wind pressure and wind suction test. The mid-span displacements measured (δ_1, δ_2 and δ_3) are adjusted by deducting the average value of displacements (δ_{S1}, δ_{S2}, δ_{S3} and δ_{S4}) measured close to the supports.

Figures 6c and **6d** show the distributed load vs. crack opening displacement (COD) curves respectively for wind pressure and wind suction test.

In **Figures 6d** and **6e** the curves of distributed load vs. vertical displacement measured at the supports (δ_{S1}, δ_{S2}, δ_{S3} e δ_{S4}) are plotted respectively for the wind pressure and wind suction test.

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 kN/m^2 [13.78 psf], which has to be added to the applied distributed load of **Figure 6**.

In all the graphs it is possible to observe some plateaus, corresponding to increments of the measured displacements or 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 each graph 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.

The crack pattern, clearly visible by visual inspection, is shown in **Figures 7a** and **7b**.

Taking as an example the Italian Standard "Nuove norme tecniche per le costruzioni"[18], at serviceability limit state a maximum wind pressure equal to 1.50 kN/m^2 [31.33 psf] 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 [17.72 in.], is equal to 135 µm [0.005 in.]

and 34 μm [0.001 in.] in the two cases. Considering that multi-cracking occurs in this region, it can be assumed that cracks are not visible to the naked eye (crack width lower than 50 μm [0.002 in.]), thus satisfying an important requirement for a façade panel.

The weak reduction of the COD in the suction test could be associated to a not symmetric crack pattern which involved, after cracking, a weak loss of stiffness in the measured region.

Looking at **Figures 6e** and **6f** it is possible to observe that vertical displacements δ_{S1} and δ_{S2} are considerably lower than δ_{S3} and δ_{S4}, especially in the wind pressure test. This fact is related to the higher pin rotation observed in S3 and S4 with respect to that registered in S1 and S2; this higher rotation is due to the 15 mm [0.59 in.] lever arm introduced to reproduce the real pin layout of a panel applied on a vertical façade.

Looking at the crack pattern of **Figure 7** it is possible to note that, as expected, multi-cracking occurred in both panels. In the panel tested according to wind suction loading condition (**Figure 7b**) some longitudinal cracks were visible after test, with a crack width up to 0.2 mm [0.008 in.]. These cracks were visible before testing and were due to mortar shrinkage. In both the panels the crack width due to bending is always smaller than 0.20 mm [0.006 in.].

FURTHER RESEARCH

Two main further developments, crucial for the application of the panel in real buildings, are now ongoing in the European EASEE project:

- the investigation on the cyclic mechanical behavior of the sandwich panel, as the panel is mainly loaded by wind action;
- the investigation on the panel behavior when exposed to thermal cycles, thinking in particular to the sun radiation. Full scale panels exposed to real environmental conditions will be tested after 1 year of exposure and some tests on small sandwich beams are in progress controlling the temperature in the range 20 - 70 °C [68 - 158 °F].

For the production of the following panels, anti-shrinkage additive has been added to the mix design in order to avoid the presence of cracks due to mortar shrinkage.

In the framework of the EASEE project, the proposed technology will be applied, in addition to the test façade, also on some demo buildings and its thermal behavior will be monitored and compared to that of other technologies also applied on test façades and demos, such as a cavity wall insulation system and an insulating solution for the interior.

CONCLUSIONS

A multi-layer precast façade panel is proposed as a durable alternative to the exterior insulation and finishing system, usually adopted in the energy retrofitting of existing building. The solution, obtained combining expanded polystyrene and textile reinforced concrete layers, is characterized by a reduced weight and a high quality finishing, which can be customized. The good mechanical behavior of this panel has been experimentally proven. 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 EPS material is used not only with an insulation function, but also as a structural layer in order to transfer shear stresses between the external TRC faces.

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^{2}K [0.204 BTU/ ft^{2}hr.°F] to 0.26 W/m^{2}K [0.046 BTU/ ft^{2}hr.°F] can be achieved.

The production technique is sufficiently flexible to be used to produce panels for demo buildings.

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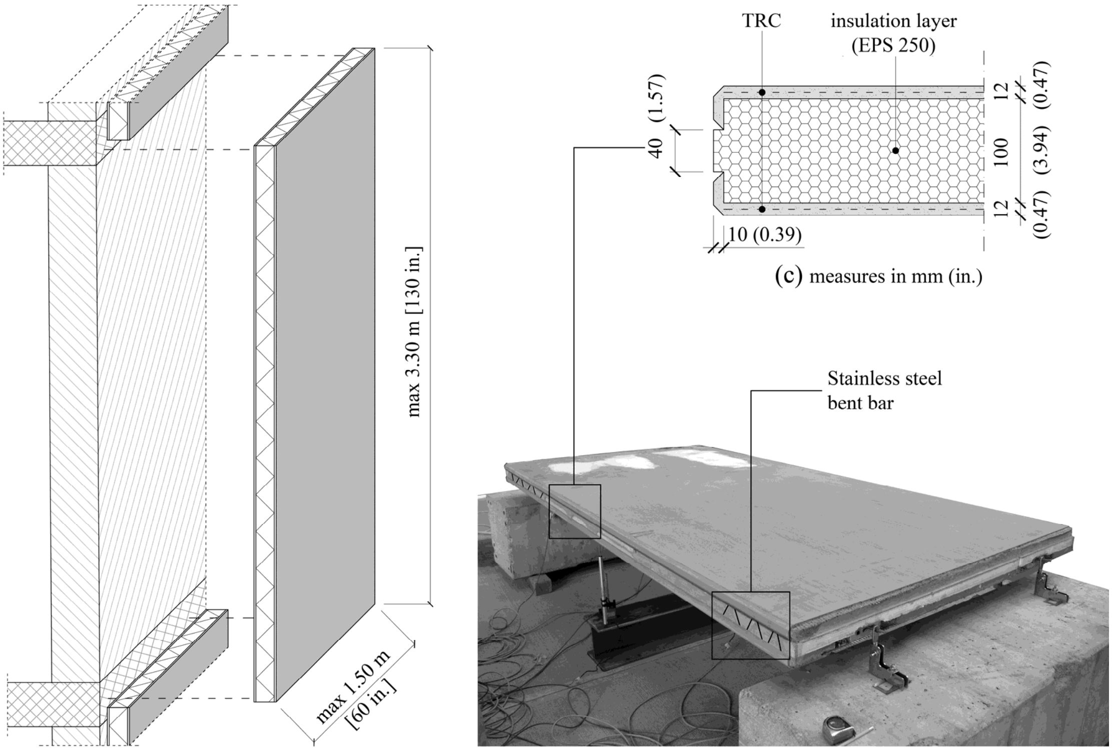
FIGURES AND TABLES


(a) (b)

Figure 1– Test façade at Politecnico di Milano: erection of the façade (a) and the completed façade (b).



(a) (b)

Figure 2– Sandwich panel solution proposed for the energy retrofitting of existing buildings: sketch (a), full scale panel fastened to concrete beams (b) and detail of the panel edge (c).

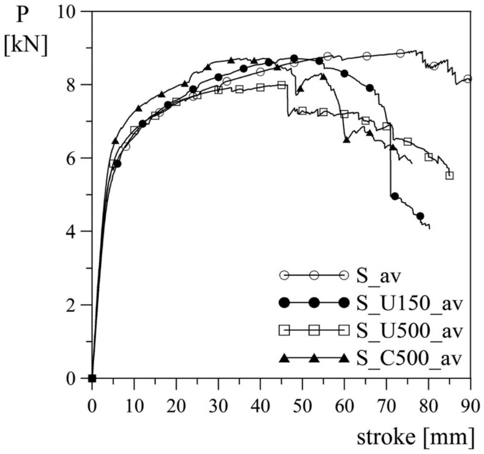
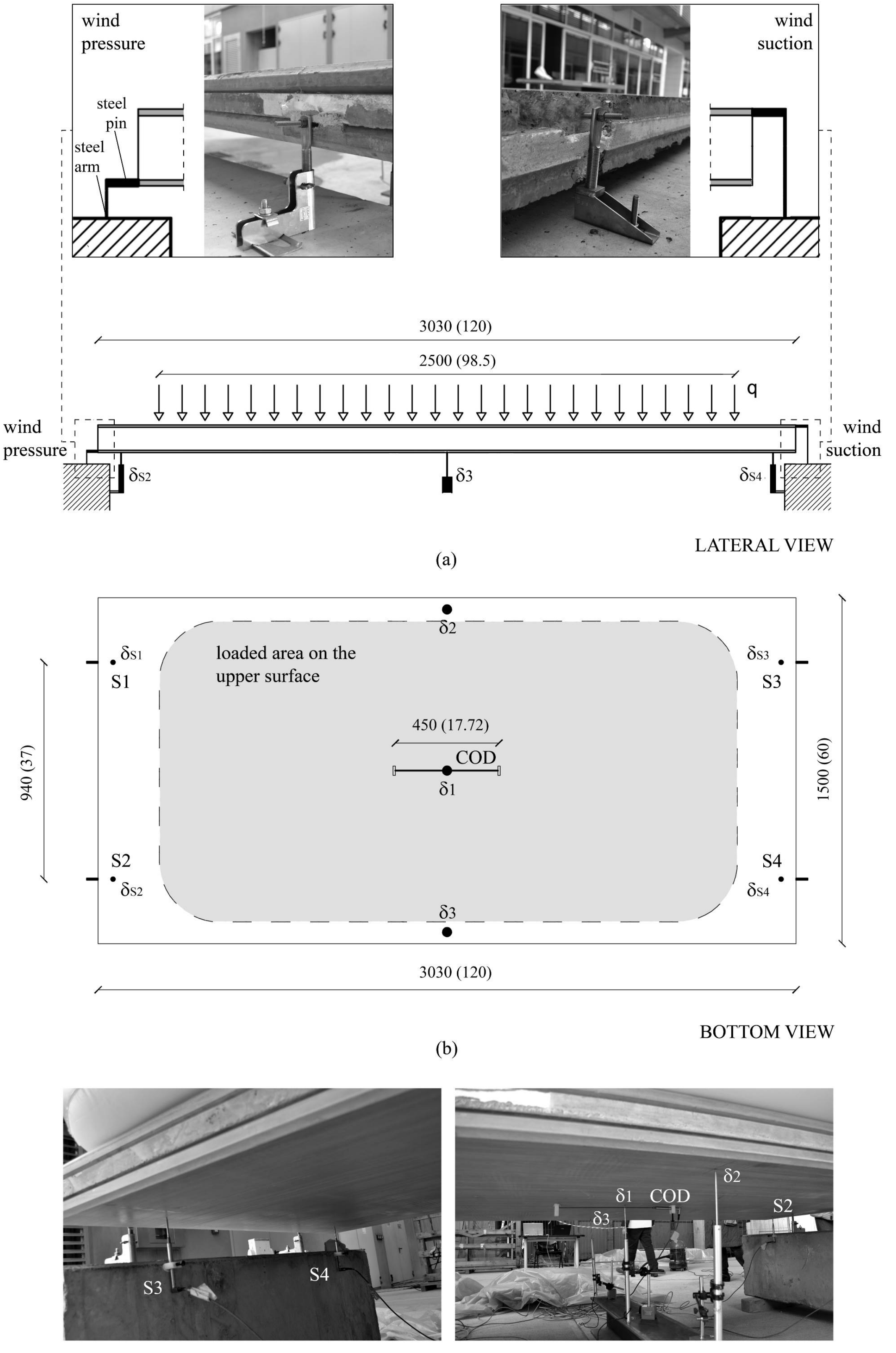


Figure 3– Small sandwich beams tested after the exposure to freezing-thawing cycles: comparison of load vs. stroke average curves [Colombo[16]].

Figure 4– Test on full scale panel (wind pressure).

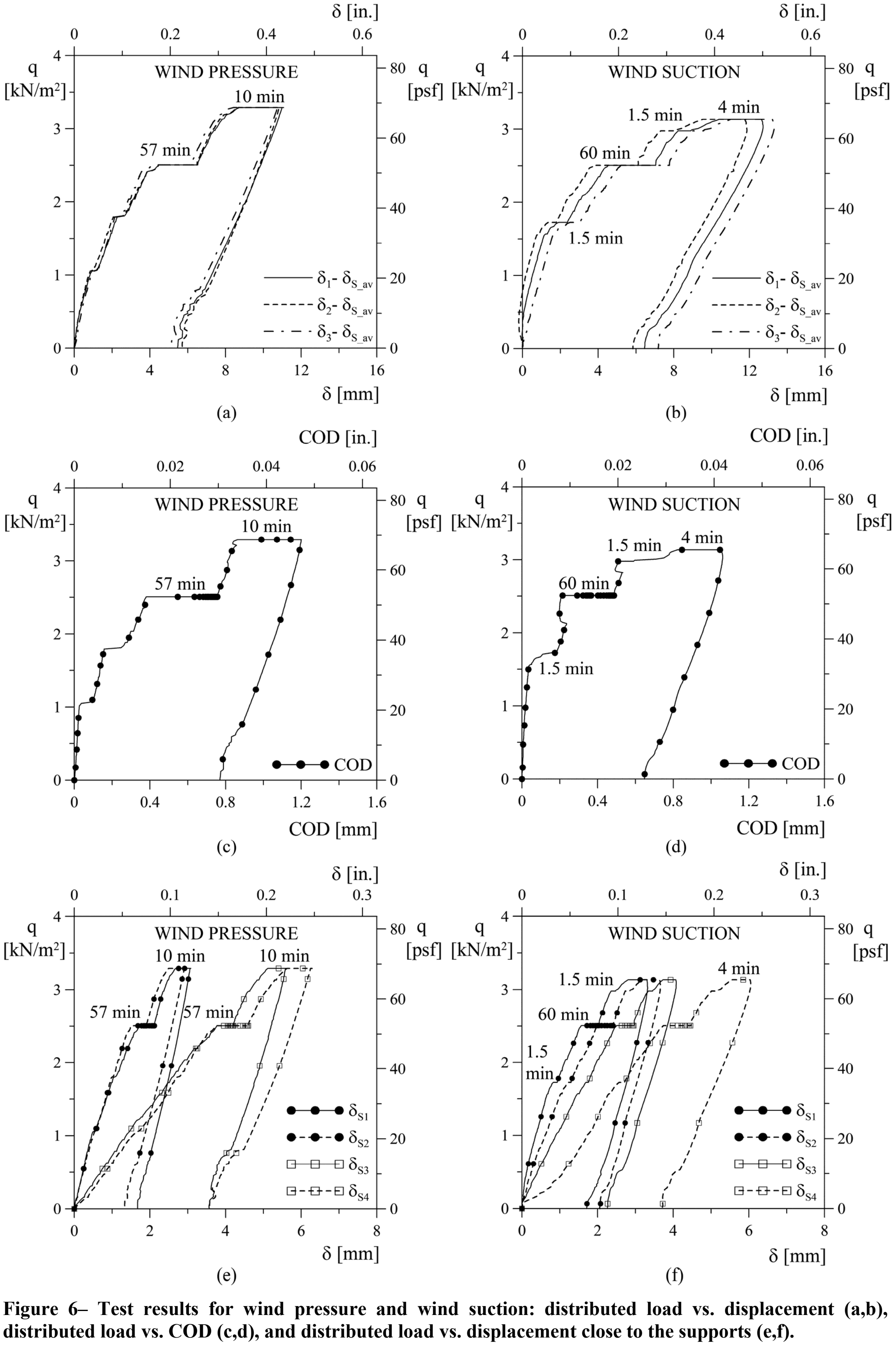


(a)

(b)

(c) (d)

Figure 5– Instrumented panel, measures in mm (in.): lateral view (a), bottom view (b) and pictures (c, d).

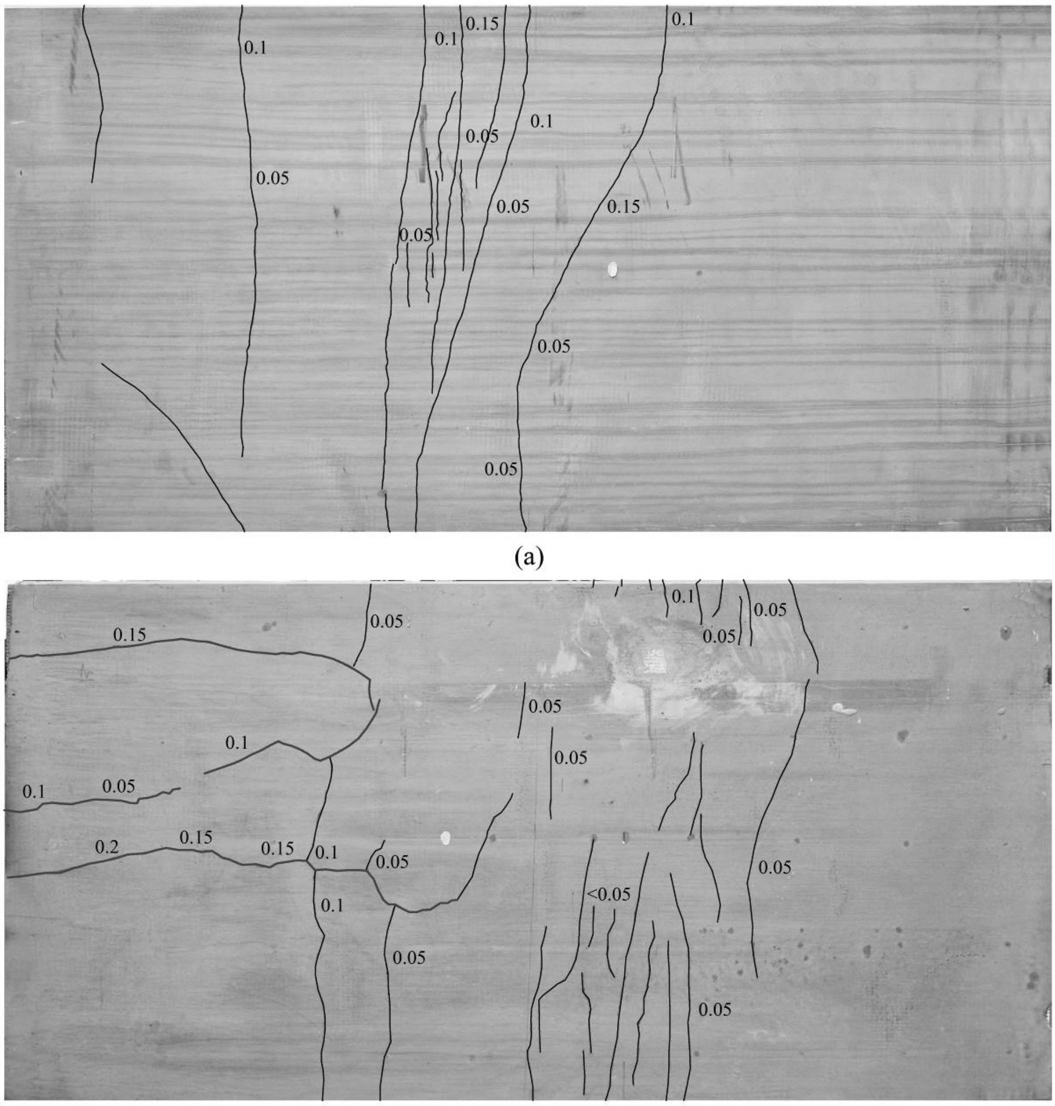


(a) (b)

(c) (d)

(e) (f)

Figure 6– Test results for wind pressure and wind suction: distributed load vs. displacement (a,b), distributed load vs. COD (c,d), and distributed load vs. displacement close to the supports (e,f).



(a)

(b)

Figure 7– Crack pattern after test for specimen loaded with wind pressure (a) and wind suction (b), measures in mm: 0.2 mm [0.008 in.]; 0.15 mm [0.006 in.]; 0.1 mm [0.004 in.]; 0.05 mm [0.002 in.].

Table 1–Mix design of the matrix

Component	Content
Cement I 52.5, kg/m^3 (pcf)	600 (37.46)
Quartz sand 0-2 mm [0-0.08 in.], kg/m^3 (pcf)	847 (52.88)
Water, l/m^3 (pcf)	207 (12.92)
Superplasticizer, kg/m^3 (pcf)	33 (2.06)
Slag, kg/m^3, (pcf)	500 (31.21)

Table 2–Characteristics of the fabric

Fabrication technique	Leno weave
Material	AR-glass
Coating	Water resin based on SBR[a]
Warp yarn spacing, mm (in.)	10.0 (0.39)
Weft yarn spacing, mm (in.)	14.3 (0.56)
Warp, Tex (Yield)	2 x 2400 (2 x 207)
Weft, Tex (Yield)	2 x 1200 (2 x 413)
Coating weight, g/m$^2_{\text{fabric}}$ (psf)	100 (0.02)
Maximum tensile load[b] on 70 mm [2.76 in.], kN (lb)	9.15 (2057.10)

[a] Styrene-Butadiene Rubber; [b] Average values of 10 tests