A PROCEDURE FOR TESTING MASONRY STRUCTURES: THE PILE-MODEL AND THE OPPOSITE PANEL SHEAR COMPRESSION TESTS.

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SUMMARY

A simple procedure to manage in situ mechanical tests on masonry walls is illustrated, to join economical aspect, ease of execution and significance of testing results.
The present proposal consider the use of the penetrometer PNT-G to perform on-site measurement of the compression strength of mortar joints, followed by extraction of block specimen to laboratory tests and a geometrical survey of the texture, to characterize in a wide zone of the building the components of the wall to arrange an analytical model organized in an appropriate procedure named "pile-model". Subsequently it is proposed a collapsing test on twin panels, to calibrate the above non destructive tests and predicting model, acting on the inferior part of window openings. Two different geometrical situations of panels are considered: large windows (2,20 – 3,00 m and more) to execute twin panels under the same opening, and normal window (1,10 – 1,50 m) to execute twin panels under consecutive openings. The vertical forces, simulating permanent loads, are combined with cyclic horizontal loads, pushing between the twin panels: the vertical forces are applied in a closed system of anchorage, while the horizontal force is not diffused outside the tested panels, avoiding improper stresses on the adjacent zones of building. The shear compressive test has been repeated on a consolidated masonry panel, to characterize the improvement due to the adopted reinforcement technique. The combined use of the *pile model* and the *opposite panel* experimental procedures permits mechanical evaluations of masonry structures in buildings.

INTRODUCTION

The availability of economical, simple and useful test methods to apply on masonry constructions is crucial to establish the most appropriate consolidation technique, mainly on seismic zone. In a wide range of case studies the costs of preliminary tests represent an obstacle to perform a complete analysis of the existing configuration: in absence of cognitive tests, the structural designer frequently performs consolidation strategies using high impact techniques (r.c. plates, injections, demolitions, steel frames etc.) avoiding to save existing masonry frameworks, with relevant structural costs, loss of historical features and sometimes adding uncertainness or achieving minor seismic properties, due to the difficult of evaluating the correct interaction between existing and new structures or bearing and no-load bearing elements.
It is well-known that the use of less-destructive techniques [de Vekey, 1988] [Noland & Atkinsons, 1983] [Tomazevic & Weiss, 1990] to study an existing masonry building permits

the analysis on extended zones, if accompanied by destructive tests on a few specific zones, where it can be possible to characterize the results obtained with the less-destructive ones. Moreover the possibility to manage destructive tests on no-disturbed specimen is precious for their calibration significance: test of minor impact, as the single or double flat jacks, are useful but with high costs and some uncertainness to furnish a correct stress-strain law [Gucci et al, 1995]; tests of higher impact, as Sheppard test or diagonal compressive test [Anthoine et al, 1995] [Chiostrini et al, 2000] [Turnsek & Sheppard, 1980], could induce damages on the adjacent zones of the specimen and need retaining frameworks to avoid the influence on the results due to nearby zones. The degree of destructivity and the remarkable costs of those experiments implies the necessity of caution to optimise their use only on representative area of the masonry features, to calibrate the less-destructive tests on wide areas, and in the meaning time with low structural risk for the building.
In the present paper it is briefly described the PNT-G penetrometer [Gucci et al, 1995], [Gucci & Sassu, 2002], consisting of a driller connected to an energy counter: the physical principle of the instrument is the relationship between the energy dissipated to execute a cavity of prescribed dimensions (diameter 4 mm, depth 5 mm) with the compressive strength of the mortar. Other gears can measure the on site strength of the mortar, as pull out or push-on methods [Ferguson & Skandamoorthy, 1994], or block properties [de Vekey, 1988], [Sassu, 2000], [Borri et al, 2002], [Turnsek & Cacovic, 1971].
Anyway The PNT-G instrument has been cross correlated with a pull out method [de Vekey & Sassu, 1997], achieving the best results in case of weak mortar, where the grains glued by the lime are separated without further cracks. The characteristic compressive strength on site of mortar joints f_m furnished by PNT-G can be combined with the resistance of the blocks f_b of the wall (easily determined extracting sample blocks and testing on a laboratory) to deduce the corresponding resistance of the entire wall f_k with the consolidated formula (1) given by the Eurocode EN 1996 1.1.

$$f_k = K\ f_b^{\alpha}\ f_m^{\beta} \qquad (1)$$

A geometrical survey extended on proper zones can then individuate the texture of the walls, permitting in some cases to evaluate the thickness ratio between mortar and blocks, useful to a simplified pile-model simulation, referring to an Hillsdorf model of wall composed by elastic layers, cross-tested in a wide experimental campaign with double flat-jacks [Gucci et al, 1995].
Furthermore is illustrated the “opposite panels” destructive technique to test masonry walls on site. It is well known the opportunity to perform in-situ tests on wall panels, in order to determine the constitutive law avoiding the damages and the costs due to the removal and transport operations of the specimen into a laboratory.
The most on site techniques are the “Sheppard test” [Turnsek & Sheppard, 1980], the “shear-compression test” and the “diagonal compressive test” [Turnsek & Cacovic, 1971] [Anthoine et al, 1995]: all the above tests sometimes cause not neglegible damages on the walls involved in the trails; moreover is not simple to arrange shear-compressive tests varying the external force ratio.
The present procedure is an attempt to improve the above methods, acting independence between vertical and transverse loads, joined with easy of execution combined with low damages on vertical bearing walls.

THE PENETROMETER PNT-G AND THE PILE MODEL PROCEDURE.

The PNT-G driller (Figure 1 left), associating the compressive strength of the mortar to the energy dissipated on site to perform a small cavity on a mortar joint, permits a large number of measurements in short time for a statistical elaboration joined to a reduced level of destructiveness (Figure 1 right), similarly to the Smith Hammer test on concrete.
The relationship (see Figure 2) between the mortar compressive strength f_m and the units of energy dissipated P_g to execute a cylinder of 4 mm diameter and 5 mm height can be furnished by

$$f_m=(P_g+22)/134 \quad [\text{MPa}], \qquad (2)$$

in the range of best performances of the instrument ($f_m < 4$ MPa): in that case (lime with low resistance) only the connections of the grains are broken (see Figure 3 left).

Figure 1. The penetrometer PNT-G (left) and the effect on a mortar joint (right)

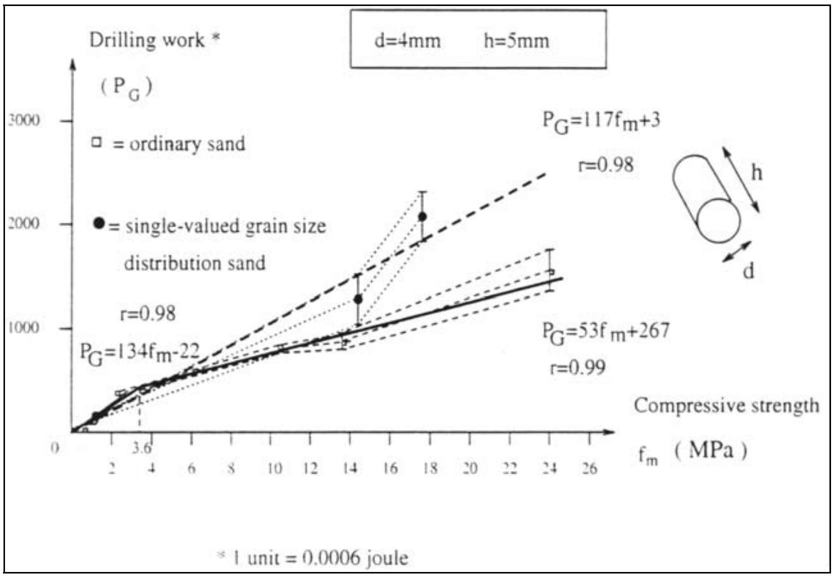

Figure 2. Relationship between drilling work (P_g) and mortar compressive strength (f_m)

In case of strong mixture of lime or cement, the energy dissipated by the driller is also addressed to destroy the grains (see Figure 3 right) and the relationship is less efficient, furnishing results comprised between the limits related on figure; an acceptable indication could be anyway represented by

$$f_m = 4 + (P_g - 512) / 20 \quad [\text{MPa}]. \tag{3}$$

In above cases, although less crucial in the applications rather than mortar with low resistance, the use of alternative instruments (i.e. helix pull-out test [de Vekey & Sassu, 1997]) to detect the strength on site is preferable.

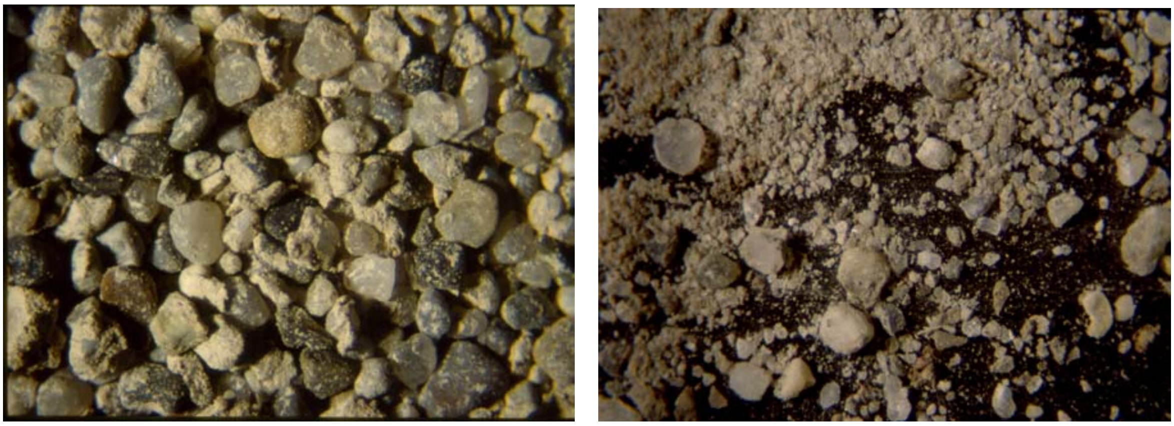

Figure 3: microscopic view of residues after cavities (left-weak mortar; right-strong mortar)

Specific laboratory tests on blocks can determine the compressive resistance $f_{b,}$ and the Young modulus E_b while for the Young modulus E_m of the mortar joint can be used the equation (4) given also by Eurocode EN 1996 1.1.

$$E_m = 1000 \, f_m \tag{4}$$

The Pile-Model procedure consider a masonry wall as an ideal set of elastic layers of alternating blocks and mortar, following the well known Hillsdorf model. A geometrical survey on prescribed "wall-windows", removing the plaster on both faces (at least 2.0 m^2) and measuring the thickness of blocks (s_b) and mortar joints (s_m) on at least three vertical lines, furnishes average and variance values of [s_b , s_m] and the parameter r,

$$r = s_b / s_m \tag{5}$$

as the ratio of the mean values of the thickness of block and mortar layers.
According to the Pile Model, the mean load state on masonry panel on the plane x-y due to a vertical pressure σ_y is governed by equilibrium conditions (6) along vertical (y) and horizontal (x) directions of the corresponding normal tensions on mortar (σ_{xm}; σ_{ym}) and brick (σ_{xb}; σ_{yb}) layers

$$\begin{gathered} \sigma_{ym} = \sigma_{yb} = \sigma_y \\ \sigma_{xm} \, s_m + \sigma_{xb} \, s_b = 0 \end{gathered} \tag{6}$$

with the congruence condition (6) between transverse deformations of mortar ε_{xm} and brick ε_{xb}

$$\varepsilon_{xm} = \varepsilon_{xb} \qquad (7)$$

The apparent Young modulus of masonry *E*, useful for the structural analysis [Magenes & Calvi, 1997] [Mc Nary & Abrams, 1985], could be easily deduced by the classic constitutive linear elastic equations on the block and mortar layers

$$E = E_b (1 + r) / (n + r) \qquad (8)$$

where the *n* dimensionless parameter is

$$n = E_b / E_{m.} \qquad (9)$$

The transverse stresses acting on blocks and mortar layers could be moreover evaluated through

$$\sigma_{xm} = \alpha\, \sigma_y\, r \quad ; \quad \sigma_{xb} = -\, \alpha\, \sigma_y \qquad (9)$$

where the α dimensionless parameter is

$$\alpha = (n\, \nu_m - \nu_b)/(1 + n\, r). \qquad (10)$$

Values of Poisson modulus ν_b could be managed through laboratory tests while indications on ν_m are quoted in [Noland & Atkinson, 1983].

Figure 4. PNT-G test on a masonry wall

THE TECHNIQUE OF THE OPPOSITE PANELS.

The main idea of the technique, named “opposite panels” from the strategy of loading a couple of identical panels with two identical opposite horizontal forces, implies to test, as masonry specimen, the inferior parts of the window openings. In most cases the structural features are the same of the adjacent vertically loaded panels and it is possible to arrange collapse tests without risks for the gravity loads acting on the masonry structures. Moreover the idea to test twin panels with horizontal forces mutually constrained can avoid any transverse loadings on the adjacent bearing structures. In case of large windows (2,20 –3,00 m and more) the couple of identical panels can be obtained under the same window; in case of ordinary openings (1,10-1,50 m) the twin specimen are to be involved in two consecutive windows (see fig.5).

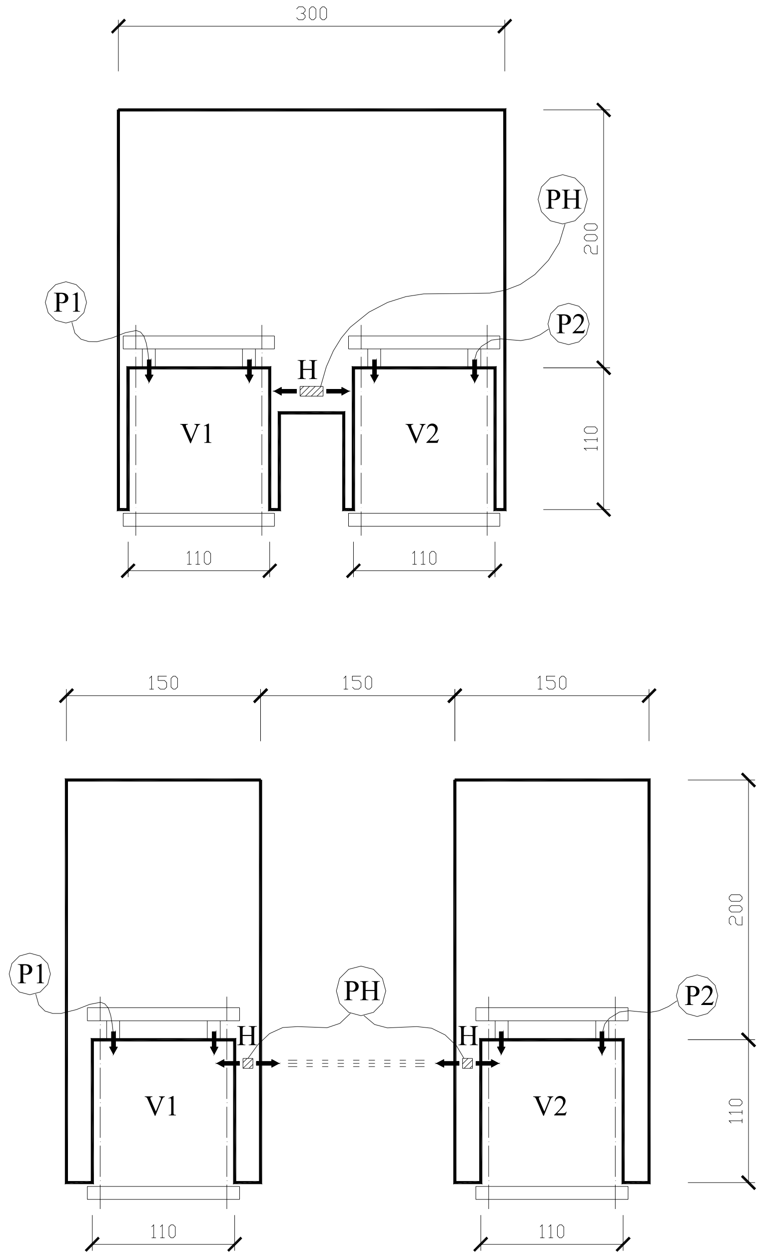

Figure 5. Scheme of the technique of opposite panels: large (up) and ordinary (down) opening.

The vertical forces are applied with two independent jacks governed by separated pumps connected to manometers detecting the vertical forces; the horizontal action is applied by a single or a couple of identical transverse jacks connected to the same pump, to apply the same opposite horizontal force on both panels. The vertical forces could be applied in a closed system of steel anchorage, to avoid any damage on the foundation, while the opposite horizontal forces are in self-equilibrium conditions, avoiding stress diffusion outside the tested panels and damages on the adjacent zones of the building.
It is possible to apply prescribed vertical force, i.e. simulating permanent or frequent loads, and in the meaning time to perform cyclic horizontal loads pushing between the twin panels, i.e. simulating an equivalent static seismic action, establishing a prescribed static time histories. It has been moreover possible to repeat the test reproducing a consolidation on the panels, to characterize the improvement due to the desired reinforcement technique.
A pilot test of the above technique has been performed on a large masonry panel made of irregular stones and clay units on twin rectangular panels 100x100x48 cm as in figure 6, acting vertical forces up to 250 KN (left) and 125 KN (right), combined with a variable horizontal force up to 80 KN: the vertical jacks are restrained by steel anchorages while the horizontal is self supported by the twin panels.

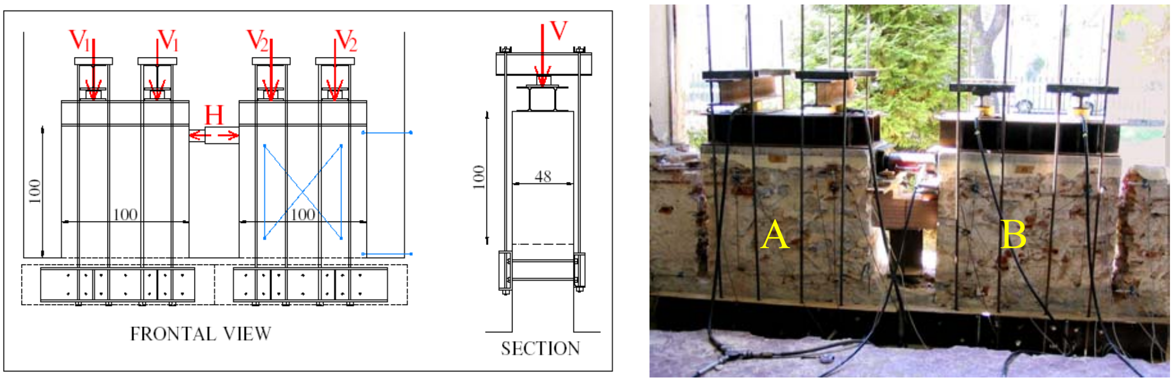

Figure 6. Scheme of the load apparatus and view of the test.

Preliminary load histories has been executed to calibrate the load system, consisting of a two couple of vertical independent oil jacks and a single horizontal one; a system of inductive transducers (1/1000 mm precision) to measure the horizontal displacements of base and top of both panels is applied, joined with four diagonal and four vertical transducers (two couple on each face) to detect the several in-plane deformations of the specimen. A series of main load tests has been then established: three tests of simple vertical loads, four tests of combined vertical-horizontal forces up to the collapse of panel B, three tests of combined vertical-horizontal forces after the consolidation of panel B, with concrete plaster and transverse steel connectors, up to the collapse of panel A.
The compressive stress on panel A has been systematically double value respect to panel B, acting rocking collapse on panel B due to minor normal stress σ, confirming the well known Eurocode EN 1996 1.1. equation (11) of the tangential limit stress τ

$$\tau = \tau_0 + 0.4\,\sigma \qquad (11)$$

Examples of diagrams and images from the several series of proofs are in Figures 8 and 9.

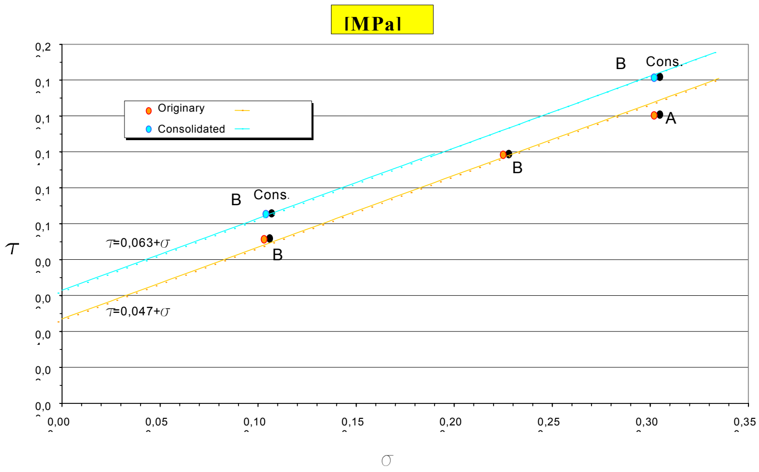

Figure 7. Diagram of σ–τ limit stress (experiment and Eurocode rule).

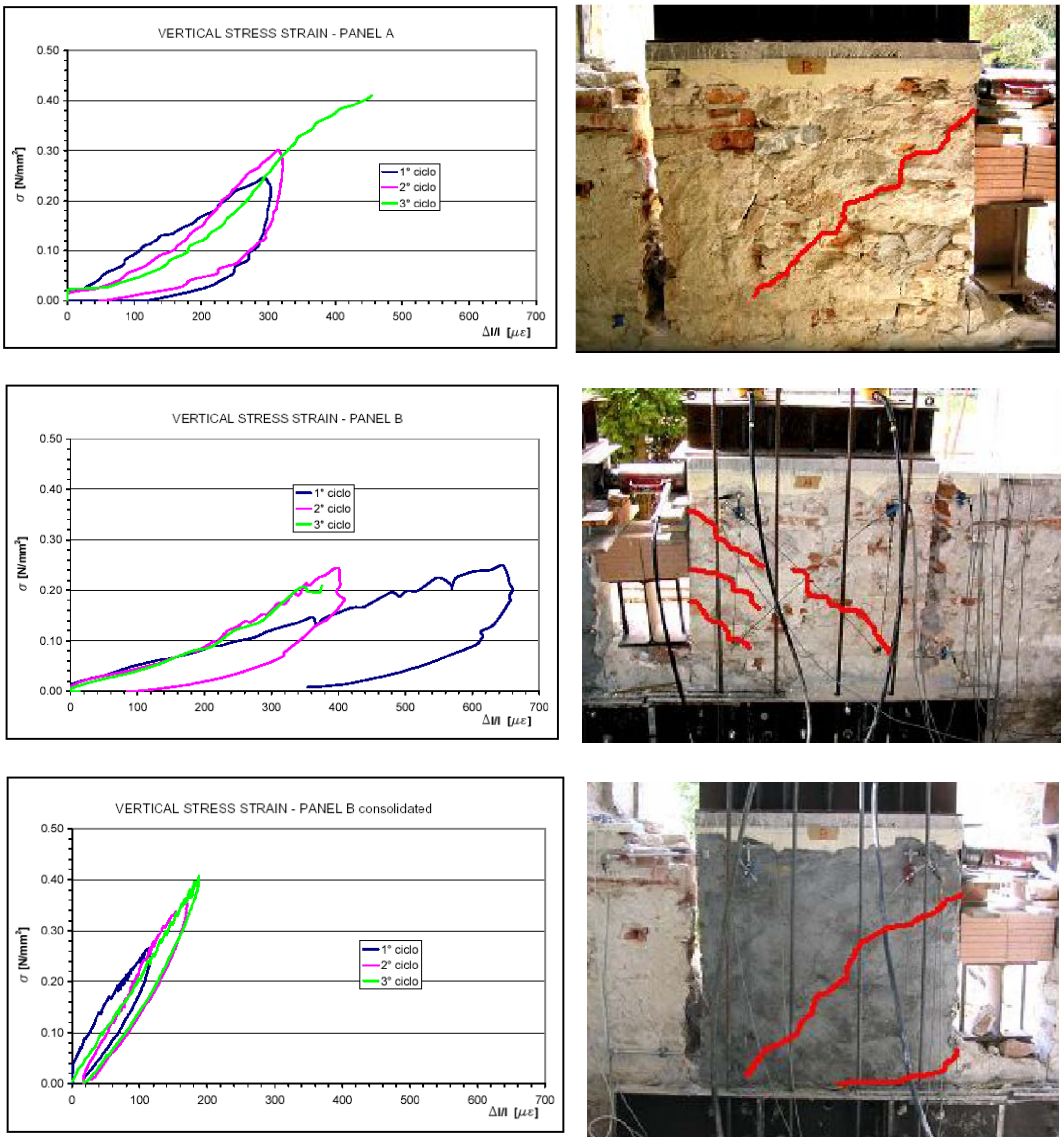

Figure 8. Test results on panels A, B and B consolidated (vertical stress-strain and cracks on collapse conditions)

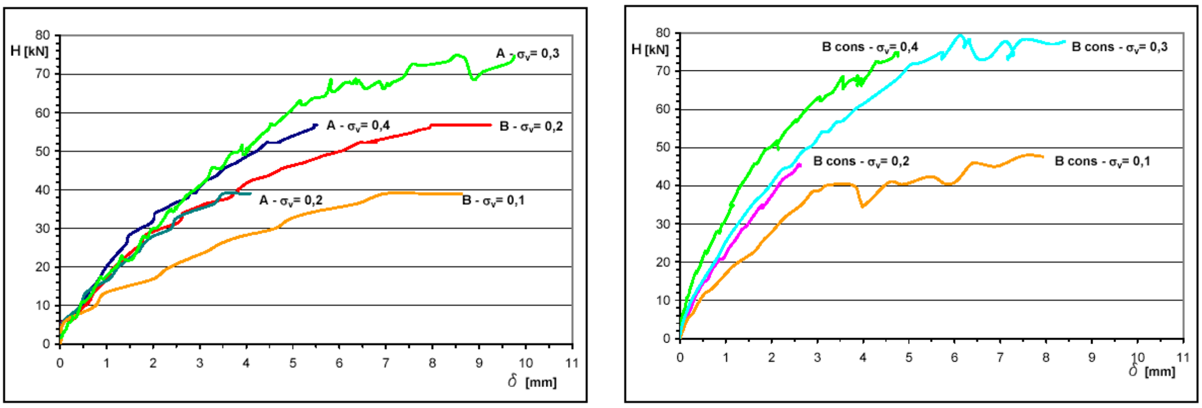

Figure 9. Test results on panels A, B and B consolidated (horizontal force-displacement)

E [MPa]	Panel A	Panel B	Panel B cons
1° cycle	793	379	1943
2° cycle	1363	831	2557
3° cycle	1286	733	1996

Table 1. Medium values of apparent Young modulus of masonry from tests.

From the experiments medium values of the apparent Young modulus are in Table 1.The Pile Model furnishes the following average characteristic values:

$$f_m = 0{,}92\ MPa\ ;\ E_m = 920\ MPa\ (mortar);\ f_b = 8{,}5\ MPa\ ;\ E_b = 4000\ MPa\ (block);$$
$$r = s_b/s_m = 3{,}0\ ;\ \mathrm{E} = 2177\ \mathrm{Mpa}.$$

CONCLUSIONS

The combination of less destructive (PNT G penetrometer – tests on blocks – geometrical survey) and destructive measurements (opposite panels shear compressive tests on basement of windows) can furnish mechanical evaluations on masonry strictures in existing buildings: the entire technique, illustrated on an applicative example, is easily reproducible on several geometrical situations and with different textures of the wall panels. The pile model results of the example are in accordance only with the B consolidated panel; it is then reasonable to deduce that the Hillsdorf mechanism, involving the containing effect due to the congruence between blocks and mortar, is ensured only by the concrete reinforcement plaster and the transverse connectors, acting a considerable improvement, in this sense, of the structural performances of the wall.

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