EXPERIMENTAL BEHAVIOR OF SINGLE AND DOUBLE MASONRY PANELS

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ABSTRACT:

In this paper, the results of the experimental tests, carried out at the *Laboratory on Materials and Structures* of the University of *Roma Tre* to characterize masonry panels behavior are shown and discussed. 36 single and 12 double panels have been considered: 12 single panels are made of 80×160×330 mm^3 bricks with horizontal holes, 24 of 120×250×120 mm^3 half-full bricks with vertical holes and two different mortars and 12 double panels coupling the two previous types of simple panels.
The panels have been built with a level of accuracy similar to the one adopted in buildings therefore they are well done but not lacking some defects that unavoidably would be found in real constructive practice.
Compression tests in horizontal, vertical and diagonal directions were performed to evaluate their "constitutive relationships" in term of force-displacement diagrams and in particular their strength and elastic modulus.
Experimental tests also included the characterization of the bricks and of the mortar used to realize the panels.

KEYWORDS: masonry panels, infill

1. INTRODUCTION

Mechanical properties of masonry panels are very relevant for r.c. infilled frame structural analysis both in terms of frame strength and stiffness and in terms of failure mechanisms. This paper focuses on some results of experimental tests performed on single and double infill panels at the *Laboratory on Materials and Structures* of the University of *Roma Tre*. The experimental study includes characterization of both brick and mortar components and infill specimens. First, two different kinds of mortar (in the following *type 1* and *type 2* mortar) and two of bricks (in the following *hollow* and *half-full* bricks) have been chosen after a careful selection among available basic materials and their mechanical characteristics identified by experimental tests. Then, a total of 48 walls (36 single and 12 double panels) have been built with these bricks and mortars: 12 single panels using hollow bricks and type 1 mortar, 12 single panels using half-full bricks and type 1 mortar, 12 single panels using half-full bricks and type 2 mortar, 12 double panel walls combining the previous types of brickwork both realized with type 1 mortar.
A more detailed discussion of the experimental activity performed are given in A. V. Bergami (2008).

2. BASIC COMPONENTS

2.1. Characteristics of the Basic Components

Two kinds of bricks are considered (Figure 2.1): 80×160×330 mm^3 bricks with an apparent weight density of 7.57 kNm^{-3} and horizontal holes and a hollow percentage $\varphi > 55\%$ (named *hollow* bricks) and 120×250×120 mm^3 bricks with an apparent weight density of 9.21 kNm^{-3} and vertical holes and a hollow percentage $\varphi = 49\%$ (named *half-full* bricks). Two kinds of mortars are selected: one to be realized on site with a specific mix (named *type 1* mortar) and the other pre-mixed (named *type 2* mortar). The composition of type 1 mortar is: 1 part of *Portland* cement (*CEM II/B-M(L-S-V)32.5*), ¼ of 32.5 cement, ¼ of 12.5 cement, 4 parts of sand (granulometry between 1-4 mm), 0.5 water-cement ratio. Type 2 mortar is a pre-mix consisting of hydrated lime, Portland concrete with the following technical characteristics: specific weight in powder 1500 kg/cm^3, granulometry <3 mm, paste water 18 %.

Figure 2.1 Hollow bricks (left) and half-full bricks (right)

2.2. Tests on Mortar

Three points bending tests (support span 100±5 mm) on 3 prismatic 40×40×160 mm^3 specimens (Table 2.1) and compression tests on 9 cylindrical specimens (100×200 mm^2) were carried out in order to characterize the mortars (Table 2.2).

Table 2.1 Bending tests results on mortars (f_{mt}=tensile strength)

Mortar	Type 1		Type 2	
Prism	F_{max} [N]	f_{mt} [MPa]	F_{max} [N]	f_{mt} [MPa]
Sample 1	2009	4.94	1924	4.78
Sample 2	1872	4.61	1946	4.83
Sample 3	1992	4.90	1542	3.83
μ		4.82	1750	4.35
σ		0.18		0.87
f_{mtk}=0.7 f_{mtm}		3.37		4.45

Table 2.2 Compression tests results on mortars (f_m=compressive strength)

Mortar		Type 1			Type 2	
Cylinder	f_m [MPa]	E_m [MPa]	ν_m [-]	f_m [MPa]	E_m [MPa]	ν_m [-]
Sample 1	22.15	-	-	12.83	16049	0.20
Sample 2	19.48	15157	0.163	12.12	16208	0.21
Sample 3	24.81	15197	0.181	10.68	16887	0.21
Sample 4	26.01	18638	0.196	11.22	15405	0.21
Sample 5	24.09	16900	0.207	12.52	17421	0.23
Sample 6	26.50	18269	0.207	12.54	16026	0.20
Sample 7	28.73	17605	0.202	11.05	16113	0.21
Sample 8	17.96	-	-	10.80	15714	0.24
Sample 9	21.71	-	-	-	-	-
μ	23.49	16961	0.193	11.72	16228	0.21
σ	3.47	1504	0.017	0.87	1504	0.01

During the compression tests, according to indications provided by *UNI EN 1015-11:1999*, before reaching the maximum load, elastic cycles have been performed in order to guarantee perfect adhesion between the press and the sample. Table 2.2 illustrates the compressive strength f_m, the elastic modulus E_m and the Poisson coefficient ν_m determined by each test and the correspondent average values. The elastic modulus, in the absence of specific indications, has been determined with reference to the loading branch limited by 50% and 25% of the maximum load. Thus, type 1 mortar is classified as M20 (very high quality) and type 2 mortar as M5 (normal quality).

From the tests a substantially linear behaviour with a brittle failure as soon as the maximum stress is reached has been observed (Albanesi et al. 2008).

2.3. Tests on bricks

12 hollow and 12 half-full clay bricks have been tested: a half of each group (6 specimens) was tested in holes direction (called *strong direction* tests) and the other half (6 specimens) in perpendicular in-plane direction (called *weak direction* tests).
The compressive strength of the blocks f_b has been determined according to *UNI-EN 772-1:2000* prescriptions as total failure load-to-orthogonal gross area ratio. Test results are summarized in Table 2.3. In all the tests performed the bricks have an essentially linear behavior up to a brittle failure which occurs as soon as peak strength is reached; no stiffness decay due to micro-cracks occurs (Albanesi et al. 2008).

Table 2.3 Compression tests results on bricks (f_{bs}=compression strength in strong direction; f_{bw}=compression strength in weak direction)

Brick	hollow		half-full	
	f_{bs} [MPa]	f_{bw} [MPa]	f_{bs} [MPa]	f_{bw} [MPa]
Sample 1	10.94	4.04	21.27	6.29
Sample 2	10.11	3.71	24.01	4.84
Sample 3	9.34	5.04	25.42	4.40
Sample 4	12.89	6.48	22.80	4.32
Sample 5	7.56	4.83	23.63	4.14
Sample 6	11.57	5.73	23.21	6.65
μ	10.4	4.97	23.39	5.11
σ	1.85	1.03	1.37	1.09

3. TESTS ON MASONRY PANELS

3.1. Specimens

Same kinds of bricks and mortars previously described were used to build 48 square infill panels (Figure 3.1) having 5÷10 mm thick mortar layers: in particular, with type 1 mortar 12 walls (1010×1010×800 mm^3) using hollow bricks with horizontal holes (named *hollow panels*), 12 (770×770×120 mm^3) using half-full bricks with vertical holes (named *half-full panels*) and 12 (1010×1010×260 mm^3 including a 60 mm air space in depth) coupling the previous walls (named *double panel* walls). Other 12 walls (770×770×120 mm^3) of half-full panels have been built with type 2 mortar (Table 3.1).

Table 3.1 Tested panels

Panels	Type 1 mortar	Type 2 mortar
Hollow bricks	12	-
Half-full bricks	12	12
Double	12	-

Panels have been realized by an expert workman with a level of accuracy that can be compared with the procedure of building sites, with same low defects in disposal and planarity as usually happens in real practice. Loading surfaces have been coated in order to create smooth and horizontal surfaces by means of high strength mortar layers. Panels were tested in compression, both in horizontal and vertical directions, and in the diagonal one. The vertical direction is the strong one for half-full panels while it is the weak one for hollow panels.

Figure 3.1 Hollow (left), half-full (center) and double (right) panels

3.2. Test Equipment

A load-control testing machine (3000 kN Metrocom) was used to carry out compressive monotonic tests up to panel failure: the loading rate was 1.60 kNs-1 (in-plane tests) and 0.80 kNs-1 (diagonal tests). Applied load was monitored by an external 1000 kN Tedea loading cell equipped with a spherical joint in order to avoid accidental loading eccentricities. Two stiff HEB 300 steel trusses have been used for in-plane tests to achieve a uniform load distribution on the panel; in diagonal compression tests, two supporting steel angle plates were used to apply corner loads and to avoid local stress concentration. Test equipment and an example of panel after failure are shown in Figure 3.2 to 3.7 for compression tests in all directions and for all the typologies of panel.

Displacement transducers (linear potentiometer with ±50 mm stroke) have been placed with hinged-ends connected to steel bars embedded in mortar layers to acquire panel deformations. Measure base is so long (678 mm for hollow panels, 523 mm for half-full ones) as to include at least 3 mortar layers in hollow direction. Data acquisition was performed at a frequency rate of 10 data per second.

Figure 3.2 Hollow panels with mortar type 1: compression test results in strong, weak and diagonal directions

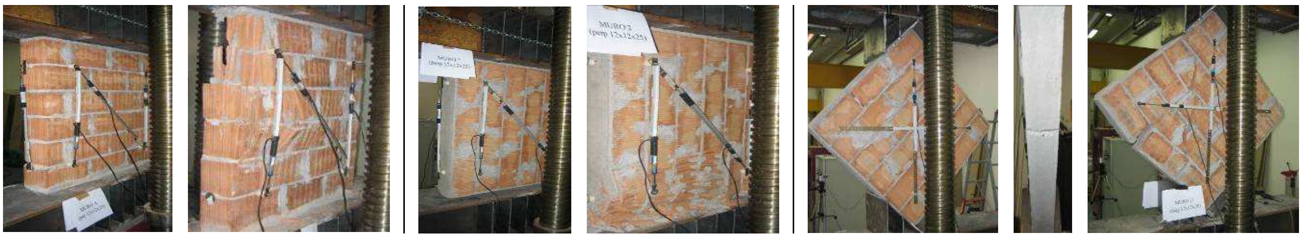

Figure 3.2 Half-full panels with mortar type 1: compression test results in strong, weak and diagonal directions

Figure 3.3 Double panels with mortar type 1: compression test results in strong, weak and diagonal directions

Figure 3.4 Half-full panels with mortar type 2: compression test results in strong, weak and diagonal directions

3.3. Test results

The test results presented in the following have been obtained referring to the deformations imposed by the press: parameters obtained using deformation values measured by the transducers installed directly on the wall will be declared. In Table 3.2 to Table 3.9, test results are summarized in terms of maximum load *F*, maximum strength *f* and elastic modulus *E* (E_i if determined from the internal transducers) as well as their average values.

Table 3.0 Hollow panels with mortar type 1: compression test results in strong, weak and diagonal directions

Direction	Strong			Weak			Diagonal		
Specimen	*F* [kN]	*f* [MPa]	*E* [MPa]	*F* [kN]	*f* [MPa]	*E* [MPa]	*F* [kN]	f_{vo} [MPa]	f_{vko} [MPa]
1	229.63	2.84	761	70.69	0.87	1013	34.94	0.31	0.21
2	277.39	3.43	567	189.20	2.34	1040	62.22	0.54	0.38
3	193.27	2.39	429	224.20	2.77	986	26.39	0.23	0.16
4	304.19	3.76	683	128.96	1.60	751	37.87	0.33	0.23
σ	251.12	3.11	610	153.26	1.90	948	40.35	0.35	0.25

Table 3.0 Half-full panels with mortar type 1: compression test results in strong, weak and diagonal directions

Direction	Strong			Weak			Diagonal		
Specimen	*F* [kN]	*f* [MPa]	*E* [MPa]	*F* [kN]	*f* [MPa]	*E* [MPa]	*F* [kN]	f_{vo} [MPa]	f_{vko} [MPa]
1	590.17	6.41	1287	335.54	3.61	1091	118.32	0.91	0.63
2	846.29	9.22	2149	286.23	3.12	759	136.51	1.02	0.71
3	739.88	8.02	1984	252.88	2.71	734	131.21	1.03	0.72
4	753.91	8.21	1470	269.08	2.92	756	137.74	1.02	0.71
σ	732.56	7.92	1723	285.93	3.09	835	130.95	0.99	0.69

Table 3.0 Double panels with mortar type 1: compression test results in strong, weak and diagonal directions

Direction	Strong			Weak			Diagonal		
Specimen	*F* [kN]	*f* [MPa]	*E* [MPa]	*F* [kN]	*f* [MPa]	*E* [MPa]	*F* [kN]	f_{vo} [MPa]	f_{vko} [MPa]
1	381.80	1.89	361.21	1185.90	5.87	803.46	211.38	0.75	0.52
2	488.97	2.42	744.86	433.66	2.15	289.30	124.49	0.44	0.31
3	399.69	1.98	688.57	730.68	3.62	850.08	316.67	1.12	0.78
4	581.11	2.88	667.98	399.98	1.98	356.45	177.27	0.63	0.44
σ	462.9	2.29	615.7	687.6	3.40	574.8	207.5	0.73	0.51

Table 3.0 Half-full panels with mortar type 2: compression test results in strong, weak and diagonal directions

Direction	Strong			Weak			Diagonal		
Specimen	*F* [kN]	*f* [MPa]	*E* [MPa]	*F* [kN]	*f* [MPa]	*E* [MPa]	*F* [kN]	f_{vo} [MPa]	f_{vko} [MPa]
1	431	4.66	3425	186	2.01	2340	162	1.24	0.87
2	557	6.03	5757	268	2.91	5291	186	1.43	1.00
3	588	6.37	8699	285	3.08	4237	147	1.12	0.79
4	379	4.11	14511	254	2.75	3889	81	0.62	0.43
σ	489	5.28	8098	248	2.69	3939	144.06	1.10	0.77

Table 3.9 Elastic modulus determined from internal transducers

	hollow brick-type 1 mortar		half-full brick-type 1 mortar		half-full brick-type 2 mortar	
	strong	weak	strong	weak	strong	weak
Sample	E_i [MPa]	E_i [MPa]	E_i [MPa]	E_i [MPa]	E_i [MPa]	E_i [MPa]
1	4250	4400	11927	9507	3425	2340
2	4018	7053	10203	3542	5757	5291
3	2867	3349	11390	2937	8699	4237
4	6167	4415	7151	3567	14511	3889
σ	4326	4804	10168	4888	8098	3939

Lacking specific indications, *E* has been calculated referring to the linear loading branch included between 25% and 50% of the failure load. In diagonal test f_{vo} is the shear strength defined as failure load-to-gross area perpendicular to loading direction ratio. In this case the characteristic value is conventionally evaluated as a percentage of the average value: $f_{vko}=0,7\times f_{vo}$.

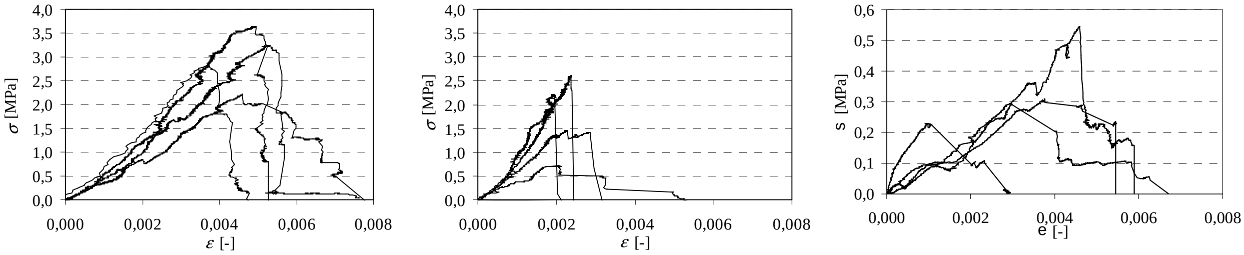

Figure 3.8. Hollow panels with mortar type 1: σ-ε curves in (a) strong, (b) weak, (c) diagonal direction tests

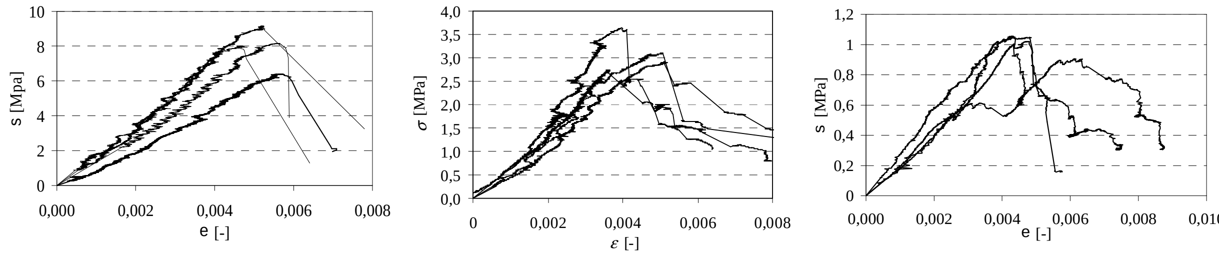

Figure 3.9. Half-full panels with mortar type 1: σ-ε curves in (a) strong, (b) weak, (c) diagonal direction tests

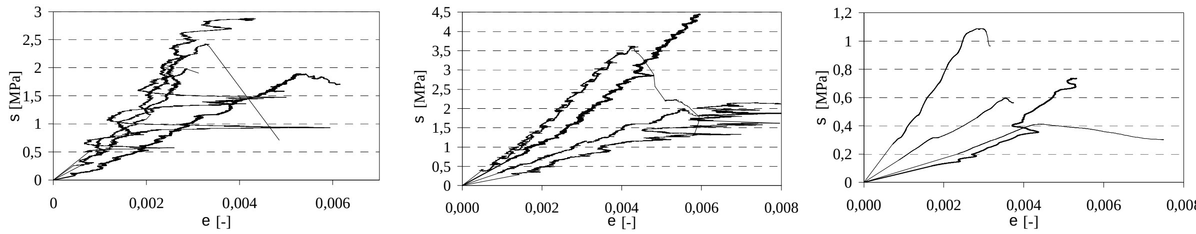

Figure 3.10. Double panels with mortar type 1: σ-ε curves in (a) strong, (b) weak, (c) diagonal direction tests

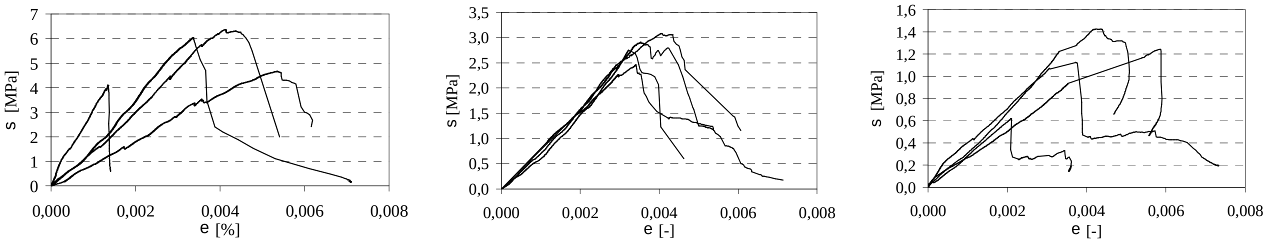

Figure 3.11. Half-full panels with mortar type 2: σ-ε curves in (a) strong, (b) weak, (c) diagonal direction tests

In Figure 3.8 to Figure 3.11 global stress-strain curves are shown, i.e. stress is load-to-gross cross section area ratio and strain is measured in terms of relative displacement between press plates: therefore measures include initial sliding between loading machine and specimen thus reproducing actual behaviour of an infill panel when a gap exists with surrounding r.c. frame; in order to linearize the elastic branch, this initial sliding is disregarded.
In hollow panels (mortar type 1) failure, typically occurs due to external shell out-of-plane local instability, due to tensile failure of perpendicular internal brick webs or to compressive crush of bed face bricks caused by stress concentration due to incipient out-of-plane global instability. In diagonal tests, failure occurs for shear limit: generally a pseudo-vertical crack crosses the panel from one corner to the other. In some cases two parallel vertical cracks have been observed: in these cases a central compressive strut forms due to steel angle plates confinement and failure is not a pure shear one. Panel behavior is essentially linear and shows a sudden brittle failure at peak strength. Stiffness response in strong and weak directions is similar, but peak strength and strain in strong direction are almost 50% higher than those in weak direction (Figure 3.8 a, b). In diagonal shear tests (Figure 3.8 c), one result is very different to the others with lower critical load and higher stiffness. This fact seems to be related to perfect contact between specimen and steel angle plates; furthermore an evident crack (or two parallel ones) suddenly spreads at lower nominal load than in the other tests. This test result can be disregarded due to its unavailability respect to real behaviour in an r.c. frame. Another topic is that all specimens show noticeable peak strength differences that depend on panel fragility. Such differences in peak strength are not related to differences in corresponding stiffness.
Half-full panels (mortar type 1 and type 2) show a linear behavior up to a brittle failure which occurs as soon as the peak strength is reached; differently from previous cases, a residual capacity is observed due to different geometrical characteristics of bricks and to a minor out-of-plane local instability tendency (Figure 3.9). This residual capacity can be related to contribution of mortar penetration into vertical brick holes and grip holes: for this reason inner brick web are less prone to tensile failure and global behavior is more resistant and less fragile. Obviously this effect is more significant in strong direction tests rather than in weak ones. So force-displacement responses, both in strong and weak directions, are almost equal in terms of strain but strong strength is about 60% higher than weak one. Panel failure typically occurs due to external shell failure; in strong direction tests this mechanism is sudden and yields to a pure fragile response; in weak direction this phenomenon takes place only after a linear strength decay due to progressive cracking of internal brick webs. In diagonal shear tests failure occurs for lower load and in a more brittle manner. Compared with equivalent cases of hollow panels, peak strength values, both in (strong and weak) compression and shear, are more homogenous: half-full panel behavior is thus less dependent on global panel slenderness and stress concentrations at the edges of specimen.

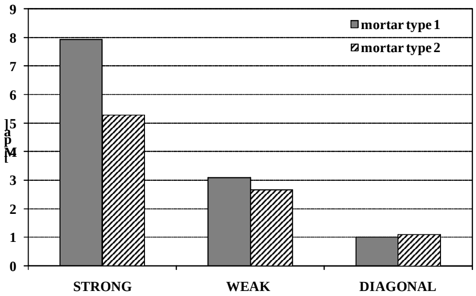

Figure 3.12. Mortar effect on half-full bricks panels strength in (a) strong, (b) weak, (c) diagonal direction tests

Mortar type influences strength only (Figure 3.9 vs Figure 3.11): stronger mortar yields to stronger panels. This effect is much more relevant in strong direction (near 40%) than in weak one (about 15%) (Figure 3.12). This result can be related to the higher fluidity of type 2 mortar that, even though less resistant, falls in greater quantity within the brick holes. The relevance of this “holes filling” effect has been already pointed out in weak compression tests: also in this case it improves wall strength much more than what the sole mortar strength could do.
Coupled single panels have opposite holes directions: half-full bricks hole direction is named the strong one.
Differently from single panels, an important residual resistance is found (Figure 3.10); this phenomenon is

rather clear for strong direction tests in which, due to different strengths offered by the panels (hollow bricks panel loaded in weak direction resists approximately 70% less than the half-full brick panels loaded in strong direction, Figure 3.8b vs Figure 3.9a), the half-full brick panel remains substantially integral even after the collapse of the hollow brick one; therefore, the residual resistance coincides with the capacity of a slightly damaged half-full brick panel. This phenomenon can be neglected in weak direction tests: in this case, single panels offer similar resistances (Figure 3.8a vs Figure 3.9b) and the collapse involves both single walls that, at the end of the test, don't offer a relevant residual resistance. From the previous considerations, we can understand why in the weak compression tests where the weakest direction of the strongest panel is loaded, the greatest resistance is reached. Weak strength is more than 30% higher than strong strength, deformation to collapse is however similar for both tests. Strength from diagonal compression tests, as previously observed for single panel walls, is much lower than the others: from experimental observation the wall resists with a compressed strut mechanism and the strut has more or less the same dimensions on both of the panels even though collapse is due to hollow brick panel. The compressive strength in all loading directions is lower than that of half-full brick panels and slightly higher than the hollow brick ones.

4. CONCLUSIONS

Experimental tests pointed out both a strong influence of brick quality on global behavior of panel specimens and a panel failure mode dependence on masonry arrangement and handwork accuracy. So, pre-cracked bricks could trigger off a sudden failure at a specimen corner as well as a light non-planar shape could produce out-of-plane buckling. These uncertainties are particularly relevant in the case of hollow panels since they are usually assembled without procedures which could guarantee geometrical and mechanical regularity. As shown above, in case of half-full panels much more regular and planar walls can be obtained, due to brick regularity and compact geometry: regular horizontal and vertical mortar layers and low imperfections and pre-cracking in brick unities can be detected. Thus more homogenous strength values and similar failure mechanisms are observed with low fragile behavior.

Mortar type influences the behaviour of panels: roughly speaking stronger mortar yields to stronger panels. This effect is much more significant in strong direction than in weak one, probably due to the relevance of the "holes filling" effect which improves wall strength much more than what the sole mortar strength could do.

Test results on double panels show that bricks disposals in coupling single panels might play a relevant role in determining both the strength of the panel and its failure mechanism. The compressive strength in all loading directions is lower than that of half-full brick panels and slightly higher than the hollow brick ones. Finally, differently from single panels, an important residual resistance is detected.

All these factors highlight the complexity of infill panel modeling and make very difficult to define an efficient approach to r.c. infilled frame analysis.

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