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TESTING ANALYTICAL MODELS FOR ASSESSING THE OUT-OF-PLANE CAPACITY OF INFILL MASONRY WALLS

André FURTADO[1], Mariano DI DOMENICO[2], Paolo RICCI[3], Hugo RODRIGUES[4], Maria Teresa DE RISI[5], António ARÊDE[6], Gerardo M. VERDERAME[7], Humberto VARUM[8]

ABSTRACT

The influence of masonry infills on the seismic behaviour of reinforced concrete buildings has been widely studied in terms of their strength and stiffness contribution in the in-plane direction while less studies have been carried out on their response in their out-of-plane (OOP) direction. OOP collapses were observed on recent earthquakes motivating experimental efforts to characterize this behaviour combined and not with previous damage due to in-plane loading demands. The present paper pretends to compare the test findings of two different experimental campaigns carried out on full-scale and scaled infill masonry panels under out-of-plane load. The main results of both experimental campaigns will be detailed and discussed to evaluate the key parameters that governed the infill panels OOP behaviour. The results will be presented in terms of force-displacement envelopes, energy dissipation and failure modes. Besides that, the second main goal of the manuscript is to present the comparison of the experimental results with the analytical models available in the literature.

Keywords: Infill Masonry Walls; Out-of-plane behaviour; Experimental testing; Analytical models

1. INTRODUCTION

The infill masonry (IM) walls are widely used for partition purposes and to provide thermic and acoustic insulation to the reinforced concrete (RC) structures. Usually the IM walls are considered non-structural elements and no special attention is given to them during the design process of new buildings and safety assessment of existing ones (Furtado et al. 2015; Furtado et al. 2016; Furtado et al. 2015). However, their strong influence on the seismic response of RC structures and their high level of damages observed in recent earthquakes alert the scientific community to give them a special attention (de la Llera et al. 2017; De Luca et al. 2014; Gautam et al. 2016; Hermanns et al. 2014; Romão et al. 2013; Vicente et al. 2012; Yatağan 2011). Their out-of-plane (OOP) vulnerability when subjected to transversal loadings which resulted on several number of collapses or extensive damages that in general increased significantly the risk to the population and the rehabilitation' costs of the buildings. The infill walls, due

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[1] PhD Student, CONSTRUCT-LESE, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal, afurtado@fe.up.pt

[2] PhD Student, Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples, Italy, mariano.didomenico@unina.it

[3] Assistant Professor, Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples, Italy, paolo.ricci@unina.it

[4] Senior Lecturer, RISCO – ESTG, Polytechnic Institute of Leiria, Portugal, hugo.f.rodrigues@ipleiria.pt

[5] Post-doctoral Research Fellow, Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples, Italy, mariateresa.derisi@unina.it (beneficiary of an AXA Research Fund Postdoctoral grant)

[6] Associated Professor, CONSTRUCT-LESE, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal, aarede@fe.up.pt

[7] Associate Professor, Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples, Italy, verderam@unina.it

[8] Full Professor, CONSTRUCT-LESE, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal, hvarum@fe.up.pt

to the interaction with the surrounding RC frame can develop a higher OOP strength through arching mechanism, which mainly depends on the panel' slenderness, masonry compressive strength and panel width support conditions. The risks associated to this behaviour can be increased due to constructive details aspects that nowadays are commonly adopted throughout the European Southern countries. Such for example no connection between the panel and the surrounding RC elements, no connection between the leafs in the case of double-leaf IM walls and insufficient width support of the panel can contribute to reduce to the IM walls OOP strength capacity and lead to fragile collapses. Results from experimental studies are of full importance to understand and increase the understanding regarding the OOP behaviour of the infill panels, especially for out-of-plane failure combined with prior in-plane damages.

The present manuscript pretends to present experimental results from an extensive experimental campaign of IM walls OOP tests. Quasi-static tests were carried out at the Laboratory of Earthquake and Structural Engineering (LESE) at the University of Porto and at the University of Naples in Full-scale and scaled specimens. The experimental tests carried out on URM infill wall panels at the Department of Structures for Engineering and Architecture of the University of Naples Federico II program is aimed at evaluating the influence of boundary conditions on URM infills' OOP response in terms of stiffness, strength and displacement capacity and then, for infills bounded along four edges at assessing the effects of IP damage on the OOP behaviour in terms of strength degradation, i.e., the IP-OOP interaction effects. Specimens' details and a brief description of the test setups will be provided. The main results of each experimental campaign will be provided as well as a global discussion and comparison between both testing campaigns. Finally, the efficiency of analytical models to predict the IM walls OOP capacity will be assessed. The analytical predictions of the specimens tested in both test campaigns will be carried out.

2. EXPERIMENTAL CAMPAIGN OF INFILL MASONRY WALLS OUT-OF-PLANE TESTS

2.1 Introduction

The present section will present the details of the tests carried out at the LESE Laboratory and at the University of Naples. The test setup and the experimental results will be presented (cracking pattern and force-displacement curves). The test campaign carried out at the LESE laboratory is composed by four full-scaled specimens that were subjected to OOP tests with airbags. The main objective of the test campaign was to evaluate the effect of the gravity load and the previous in-plane damage. The results of OOP pseudo-static tests carried out on URM infill wall panels at the Department of Structures for Engineering and Architecture of the University of Naples Federico II are presented. Single-wythe infill walls tested were equal to each other for geometrical properties, construction materials and workmanship but provided of different boundary conditions to the confining RC frames, which were 2/3 scaled and designed addressing seismic provisions given by the current Italian building code (NTC08 2008). A panel bounded along all edges to the surrounding frame was tested (Test OOP_4E), as well as a panel detached from the confining frame at the upper edge (Test OOP_3E) and a panel bounded to the confining frame only along the upper and lower edges (Test OOP_2E). Moreover, three infills bounded along four edges were first cyclically tested in the IP direction up to three different nominal drift levels (0.2% for test specimen IP+OOP_L, 0.4% for test specimen IP+OOP_M and 0.6% for test specimen IP+OOP_H) and then monotonically tested in the OOP direction.

2.2 Tests with uniform loading

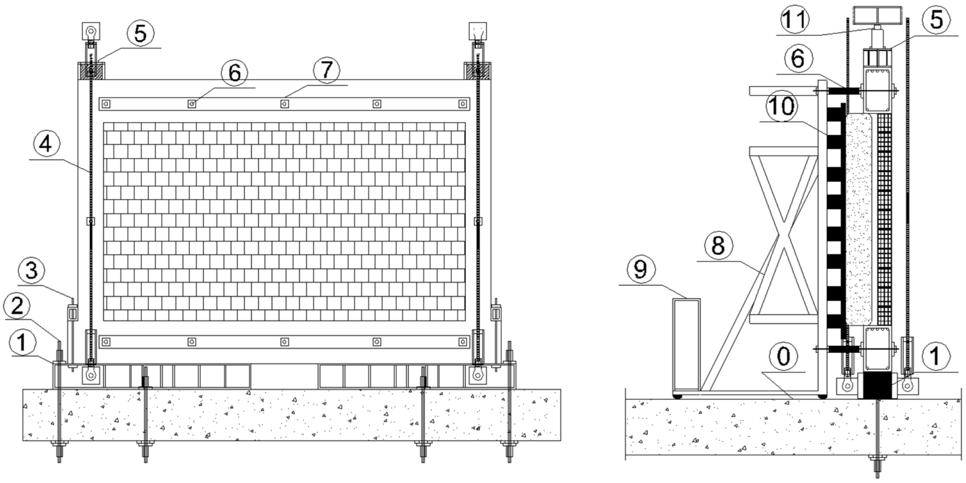
2.2.1 Specimens description and test setup

Four IM walls were built with the same geometric dimensions (4.20 x 2.30 meters length and height respectively) and made with hollow clay bricks (thickness equal to 0.15 meters), which is a solution typically adopted in the Southern Europe (Furtado et al. 2016). The mortar used to construct the specimens was an industrial pre-dosed M5 class ("Ciarga" type). No plaster was adopted. All the panels were built totally supported in the bottom RC beam. The contact between both specimens and the surrounding columns and the bottom beam was provided by approximately 1cm layer of mortar (full bedded joints). No gaps were introduced between the panel and the frame and no reinforcement was used. Regarding the contact between the top beam, half-brick and mortar are used to fill the gap that resulted from the IM wall construction. Specimen Inf_01 and Inf_04 were tested with the aim of evaluate the effect of the gravity load in the OOP response of the wall. Specimen Inf_01 was subjected to a monotonic OOP load and Inf_04 to a cyclic one. Specimen Inf_03 was first subjected to a previous in-plane drift of 0.5% and then subjected to a pure OOP cyclic load. The effect of the previous in-plane drift in the panel response was assessed. The reference specimen is Inf_02 that was tested only to cyclic OOP loading. The main characteristics of the four test specimens tested are summarized in Table 1.

Table 1 - Summary of the specimens' information: type of test, gravity load, mechanical and material properties.

Specimen	OOP Loading strategy	Type of test	Gravity load (kN)	Previous In-plane Drift	Infill panel support conditions	Masonry compressive strength (MPa)	Mortar compressive strength (MPa)	Mortar flexural Strength (MPa)
Inf_01	Airbag	Monotonic	270	No	Full Support	0.53	16.55	5.65
Inf_02		Cyclic	-	No	Full Support	0.53	5.66	2.11
Inf_03		Cyclic	-	0.5%	Full Support	0.53	13.40	4.27
Inf_04		Cyclic	270	No	Full Support	1.10	8.76	5.16

The OOP test consisted on the application of a uniform distributed pressure, throughout the entire panel under tested, through nylon airbags (Figure 1). The uniform load applied through all the infill panel is reacted against a self-equilibrated steel structure that is composed by five vertical and four horizontal alignments that are rigidly connected to the RC frame with steel re-bars in twelve previous drilled holes. The gravity load was applied in the top of each column through hydraulic jacks inserted between a steel cap placed on the top of the columns and an upper HEB 200 steel shape, which, in turn, was connected to the foundation steel shape resorting to a pair of high-strength rods per column. Hinged connections were adopted between these rods and the top and foundation steel shapes. In Figure 1 it can be observed the general view of the test setup.



a)

b)

Figure 1 – Tests with uniform loading: Test setup, a) Front View; b) Lateral view schematic layout.
0 - strong floor, 1 – foundation steel shape, 5 –steel cap, 6 - steel rods (ø20mm) connecting the RC frame and the reaction structure, 8 - self-equilibrated reaction steel structure, 9 – counterweight, 10 – wood bars, 11 - hydraulic jack (for axial load application).

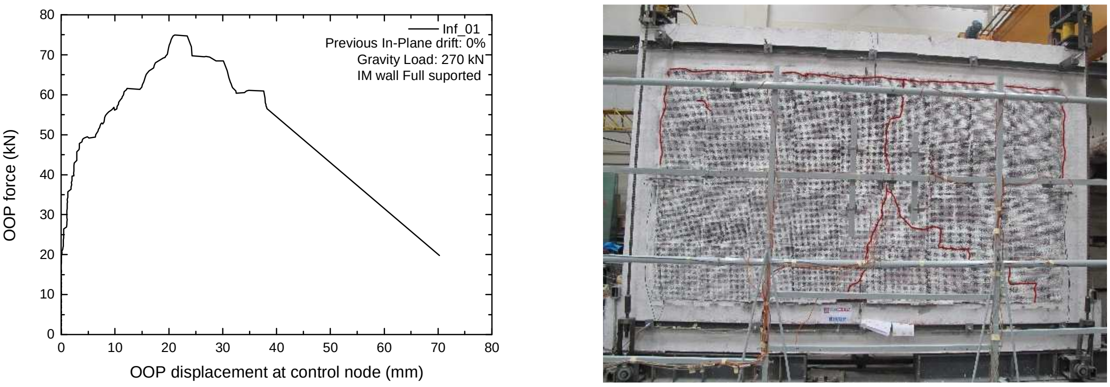
2.2.2 Test Results

From the OOP tests, different cracking pattern were obtained for each IM panel. Three different patterns were found, namely:

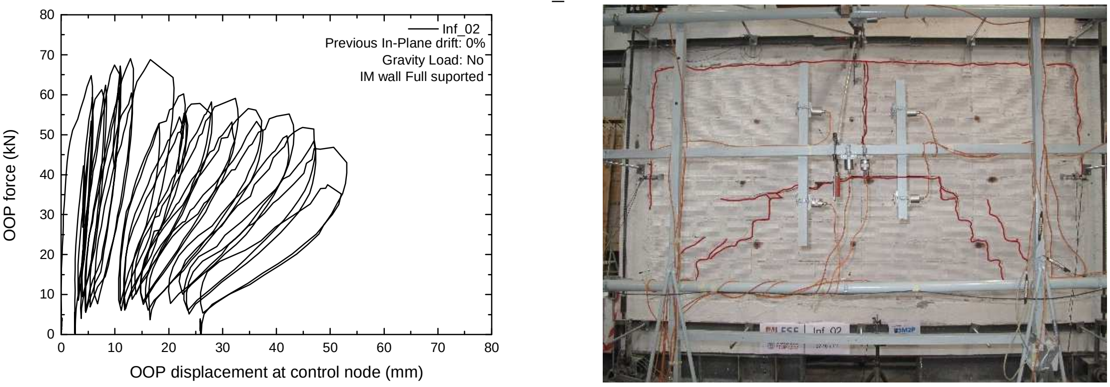
- Specimens with gravity load (Inf_01 and Inf_04): pure vertical cracking associated with the detachment of the top and bottom of the wall from the surrounding frame;

- Specimen with previous damage (Inf_03): no visible cracking, but it was observed that due to the existing detachment of the panel from the surrounding corner due to the previous in-plane test, it was observed a pure rigid body behaviour and the entire wall was mobilized to OOP;
- Specimen without previous damage and gravity load (Inf_02): trilinear cracking with the concentration of the OOP displacement in the center of the panel.

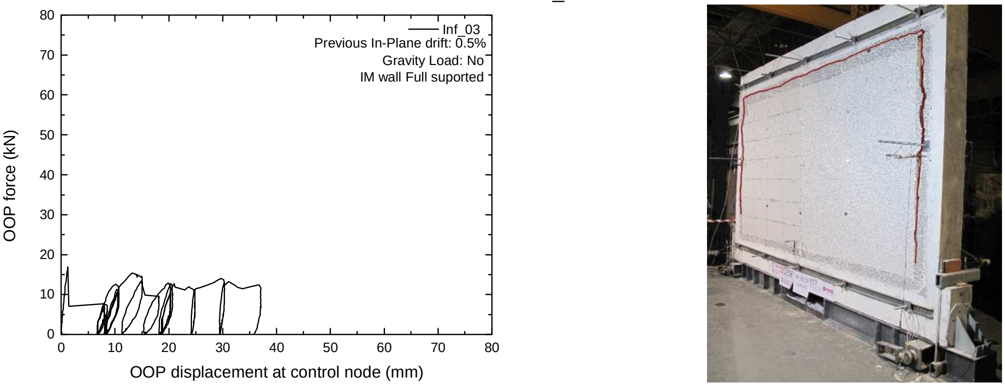
From the force-displacement curves (Figure 2 and Figure 3) it can be observed that the panels with gravity load achieved higher initial stiffness. The panel with previous in-plane damaged obtained the lower OOP force, about 30% of the reference specimen. A very fragile behaviour was observed, with the rupture of the panel occurring for lower OOP displacement demands. Regarding the specimens with gravity load, different responses were obtained. The panel Inf_01 reached the higher OOP force, about 75kN, which is 1.7 times higher than the maximum force obtained by the panel Inf_04. It was observed that the monotonic test maximum force occurred for an OOP displacement 30% larger than Inf_01.



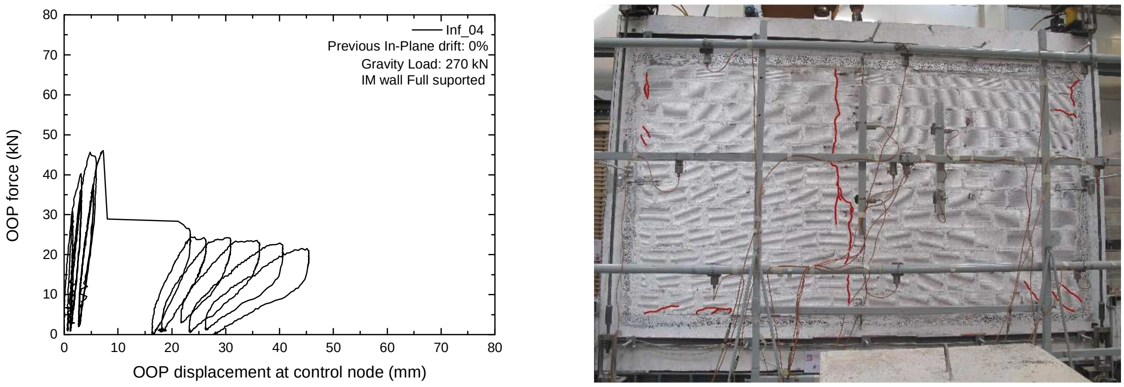
Inf_01



Inf_02



Inf_03



Inf_04

Figure 2 – Tests with uniform loading results: Force-displacement curves and Cracking pattern.

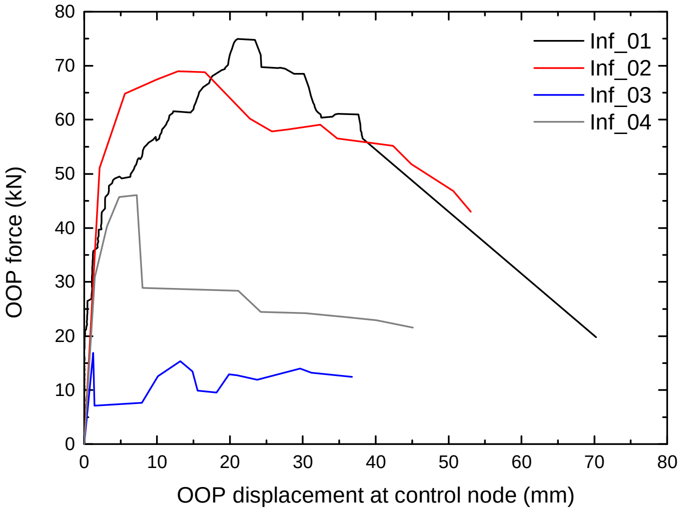


Figure 3 - Tests with uniform loading results: Global force-displacement envelope curves.

2.3 Tests with four points loading

2.3.1 Specimens description and test setup

The experimental tests herein described were carried out on 2/3 scaled infilled RC frames designed accordingly to the current seismic Italian building code. The RC frames were realized using class C28/35 concrete and steel reinforcement bars with nominal yielding stress equal to 450 N/mm^2. Construction drawings of the RC frame, with geometric and reinforcement details are reported in Figure 4. Infill walls with thickness t=80 mm were realized by using 25x25x8 cm^3 clay hollow bricks placed with horizontal holes and 1 cm thick horizontal and vertical courses of class M5 mortar. Infill walls had a width w equal to 2350 mm and a height equal to 1830 mm. Masonry mechanical properties are reported in Table 2.

The experimental setup was constituted by two parts. First, an OOP setup constituted by steel members and clamps aimed at preventing OOP drift of the RC frame during OOP tests and at functioning as reaction structure for the OOP hydraulic actuator. Second, an IP setup was realized. A cantilever vertical beam was used as reaction structure for the IP hydraulic actuator. IP cyclic loads were applied at one end of the RC frame beam. No axial load was applied on columns.

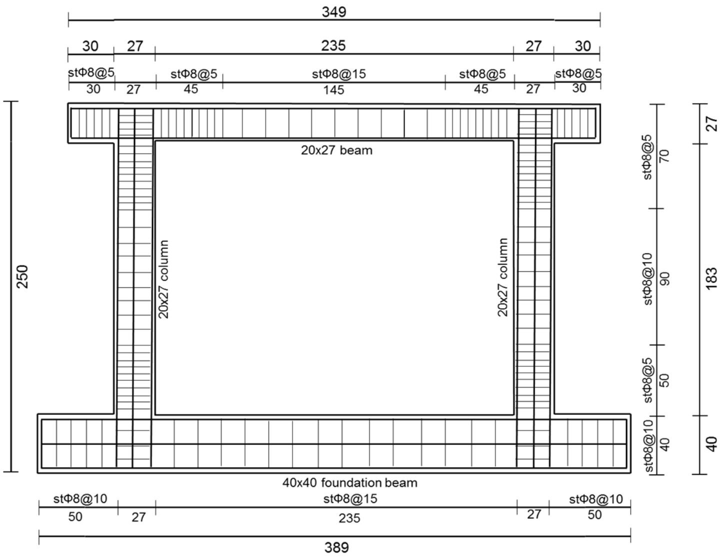


Figure 4 – Tests with four point loading: Construction drawings of the RC frame specimen.

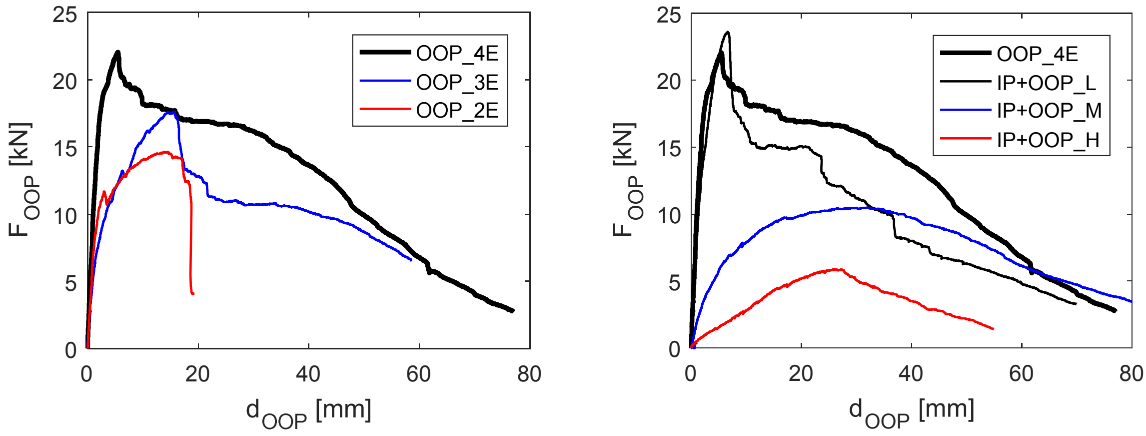
Table 2 - Masonry mechanical properties.

Masonry properties		Specimen	
		OOP_4E/OOP_3E	OOP_2E/IP+OOP (all)
Compressive strength // to brick holes	[N/mm^2]	2.21	2.45
Compressive strength ⊥ to brick holes	[N/mm^2]	1.80	1.81
Elastic modulus // to brick holes	[N/mm^2]	1188	1255
Elastic modulus ⊥ to brick holes	[N/mm^2]	1517	1080

2.3.2 Test Results

The overall response of test specimens is shown and compared in Figure 5. OOP_4E and OOP_3E responses are similar and characterized by five phases: I) pseudo-elastic behaviour until first macro-cracking; II) a linear response with reduced stiffness up to peak load, which occurs soon after first macro-cracking; III) a first softening branch with significant slope, similar to a load-bearing capacity drop; IV) a pseudo-plastic phase; V) a softening branch up to complete load-bearing capacity loss. OOP_2E had a different response, constituted by 3 phases: I) pseudo-elastic behaviour until first macro-cracking; II) a non-linear response up to peak load; III) a sudden drop in load-bearing capacity soon after peak load.

Test specimen IP-OOP_L exhibited an almost bilinear OOP behaviour, with a pseudo-linear response up to peak load and a steep softening branch up to the complete OOP resistance loss. A smother OOP response was observed for specimen IP-OOP_M, with a sort of pseudo-plastic phase over the attainment of peak load, while a nearly bilinear response was again observed for specimen IP-OOP_H. The strength, stiffness and displacement capacity reduction due to IP+OOP interaction is clearly visible from the comparison of the response curves shown in Figure 5. The OOP strength of IP damaged specimens is equal to 1.06, 0.48 and 0.27 times the OOP strength of the reference undamaged specimen for specimens IP+OOP_L, IP+OOP_M and IP+OOP_H, respectively. Cracking patterns at the end of tests for all test specimens are shown in Figure 6 and Figure 7.



(a) (b)

Figure 5 - OOP response of test specimen OOP_4E (reference specimen) compared with the OOP response of IP undamaged infills with different boundary conditions (a) and with the OOP response of IP damaged infills.

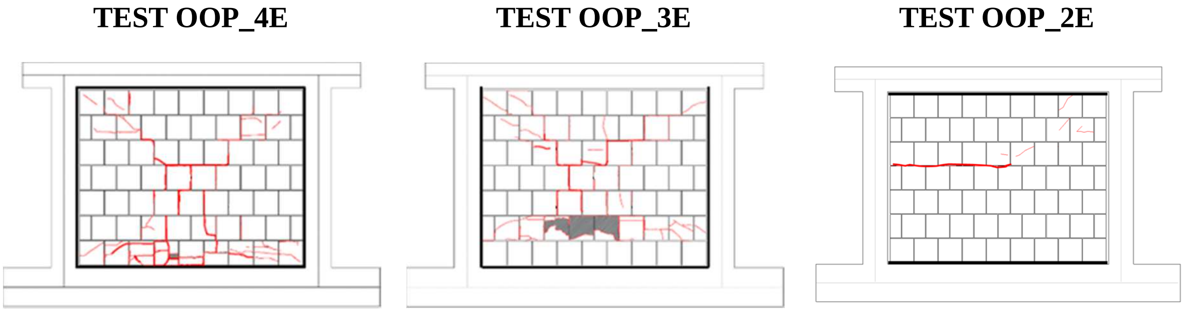


Figure 6 - Cracking pattern at the end of OOP tests for OOP_4E, OOP_3E and OOP_2E specimens.

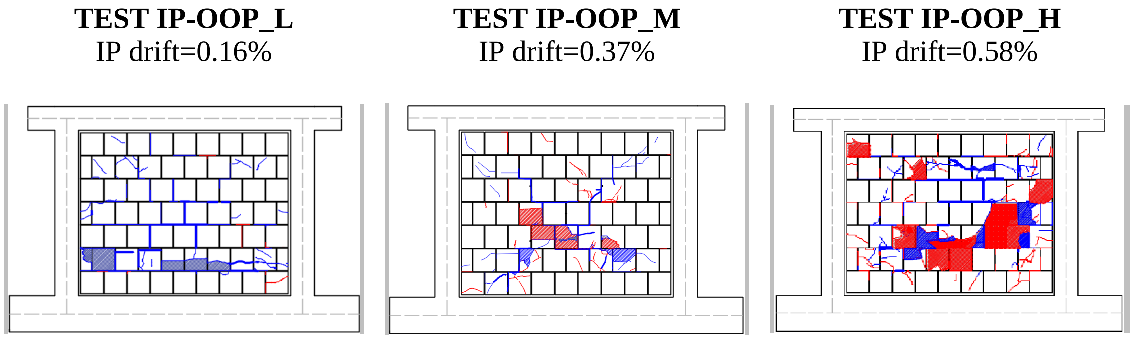


Figure 7 - Cracking pattern at the end of OOP tests for IP+OOP_L, IP+OOP_M and IP+OOP_H tests. Red lines represent IP cracks, blue lines represent OOP cracks. Shaded areas represent failed brick tiles.

3. GLOBAL OUT-OF-PLANE TEST RESULTS: CRITICAL DISCUSSION

3.1 Loading application approaches

Regarding the quasi-static tests, different loading protocols were considered all over the research works. In fact, the real seismic scenario that the panel is subjected to combined loading demands, such as IP and OOP lateral loadings combined with gravity loads. Due to the complexity of the tests setups and due to the absence of a complete characterization of the IM walls pure OOP behaviour and the respective influence of the multiple variables 42% of the tests consisted only on the application of an OOP loading. The full-scale tests were performed with airbags that pretended to mobilize the entire panel and thus simulating the expected inertial forces developed during an earthquake.

For tests carried out at the University of Naples, OOP loads were applied on four points/spherical hinges through a loading scheme two times symmetric with respect to the horizontal and vertical directions in the infill's plane. This loading scheme was also adopted by Calvi and Bolognini (2001) and by Guidi et al. (2013) for OOP tests and combined IP-OOP tests. The loading points are placed on the infill's diagonals, at a distance from both diagonal's ends equal to one-third of the diagonal length.

3.2 Gravity load effect

Throughout the literature, four different authors carried out OOP tests in as-built specimens considering the vertical dead load. In 1994 Angel et al. (1994) tested one specimen specifically to assess the influence of the gravity load in the panel response. The load was applied in the top of the frame columns. A normalized axial stress of 0.04 was applied in each column. The authors obtained almost similar force-deflection curves between the specimen 6c with and without gravity load (specimen 6t). No new cracks were observed during the test. However, the vertical stress provides an increment of the specimen stiffness until the vertical stress was overcome by the OOP loading. After this, the behaviour of both specimens were not distinguished from each other.

As presented before, the full-scale specimens Inf_01 and Inf_04 pretended to study specifically the effect of the gravity load applied in the top of the frames columns (υ=0.11) in the IM wall OOP capacity. These two specimens were tested considering the gravity load, being the first one subjected to a monotonic OOP loading and the second one to a cyclic load. Both were compared with the response of the reference specimen Inf_02 (cyclic OOP load without gravity load). Different responses between the specimens with and without gravity load were obtained.

From the study it was observed that the both panels with gravity load (Inf_01 and Inf_04) achieved lower initial stiffness, higher strength degradation. However, different impact in the maximum strength was observed, since panel Inf_01 increased about 5% and Inf_04 decreased 35%. This can be explained by the fact that Inf_01 was subjected to a monotonic OOP tests instead of the reference one that was subjected to a cyclic loading. Furtado et al. (2017) evaluated also the effect of the gravity load in the panel OOP frequency. The author found a variation of 15% with the gravity load increment applied in the top of the columns. Cracking pattern was also affected by the gravity load, namely the Specimen Inf_02 was characterized by a trilinear cracking instead of the Specimens Inf_01 and Inf_04 that obtained a vertical cracking at the middle of the panel plus the detachment from the top and bottom beam.

3.3 Previous IP damage

Similar findings were observed in both experimental campaigns, namely in terms of maximum strength and cracking pattern. From the full-scale test Inf_03 it was observed with slenderness equal to 15.3, obtained 60% lower maximum OOP strength and it was observed a very fragile behaviour. The panel behaved as a rigid body behaviour during the OOP test with no visible cracks. The energy dissipation capacity of the panel reduced 95% when compared with the reference one. As shown in Figure 6, it is observed that specimen IP-OOP_L, which was previously damaged at the lowest IP drift, exhibited an OOP strength (F_{max}) slightly greater than that exhibited by reference specimen OOP_4E. This is quite unexpected but acceptable considering the experimental variability typical of URM infills and the low IP drift imposed prior to the OOP test.

A similar circumstance is registered for secant stiffness at first macro-cracking, K_{crack}, for the same specimen. Except for these unexpected but acceptable results secant stiffness at first macro-cracking and at peak load (K_{max}), as well as force at first macro-cracking (F_{crack}) and at peak load, decrease at increasing previously applied IP displacement, as expected. Moreover, all specimens seem to exhibit a similar softening negative stiffness and a reduced displacement capacity at increasing IP damage. Empirical relationships obtained by considering the OOP tests presented in this paper and also those carried out on RC infilled frames by Angel et al. (1994) and Calvi and Bolognini (2001), for the prediction of F_{max}, F_{crack}, K_{max} and K_{crack} degradation due to IP damage are proposed in Ricci et al. (2017).

4. ANALYTICAL MODELS FOR PREDICTION OF THE INFILL MASONRY WALLS OUT-OF-PLANE CAPACITY

4.1 Literature review of existing models

In the literature, mechanical OOP strength models based on arching action were proposed for one-way spanning infill walls by Mcdowell et al. (1956) and by Abrams et al. (1996)It is worth to be noted that Abrams et al. (1996) strength model allows accounting for the effects of the confining frame deformability and of the IP damage on the OOP strength. Also Eurocode 6 (CEN 2005) proposed a strength model for masonry walls potentially extendible to infill walls. Such strength model is simply based on the equilibrium between the external lateral pressure and the internal maximum allowable arching thrust, which is calculated by assuming a triangular distribution of compressive stresses at the ends of the considered unit-width masonry stripe. Dawe and Seah (1989) proposed a stripe procedure based on yield-line theory for the prediction of the entire OOP force-displacement curve of one-way and two-way spanning masonry infills. A mechanical formulation for the OOP strength of two-way spanning infills was also provided by Bashandy et al. (1995). Both models are based on the application of the principle of virtual works and can be adapted to the four-point loading point condition, as shown by Di Dominceco et al. (2018). Empirical formulation for two-way spanning infills were proposed by Dawe and Seah (1989) modified by Flanagan and Bennett (Flanagan and Bennett 1999) and by Ricci et al. (2017).

4.2 Assessment of analytical models' effectiveness

From the comparison between the analytic models and the experimental results some differences were observed (Table 3). Large differences were observed for the prediction by all models to predict the maximum OOP capacity of the full-scale specimens. Better results were obtained by McDowell proposal, however with differences around 50% Globally, all the prediction models underestimate the OOP capacity the panels. Only McDowell and Angel *et al.* proposals overestimate the Inf_04 OOP capacity (35% and 3% respectively). The experimental strength exhibited by specimen OOP_2E was compared to that predicted by strength model accounting for one-way arching adapted to the specific loading condition. The experimental strength of specimens OOP_3E and OOP_4E is compared with the prediction of Dawe and Seah (1989) and Bashandy et al. (1995) strength models adapted for the specific loading condition.

Table 3 - Experimental OOP strength compared with literature models' predictions.

OOP strength [kN]	**OOP_2E**	**OOP_3E**	**OOP_4E**	**Inf_01**	**Inf_02**	**Inf_04**
Experimental	14.6	17.6	22.0	75.9	69.8	46
McDowell et al. (1956)	12.1	-	-	37.1	37.1	71.9
Abram set al. (1996)	5.1	-	-	22.8	22.8	47.1
Eurocode 6 (CEN,2005)	12.0	-	-	17.1	17.1	35.4
Dawe and Seah (1989)	12.9	19.5	26.3	23.6	23.6	40.7
Bashandy et al. (1995)	-	-	5.6	-	-	-

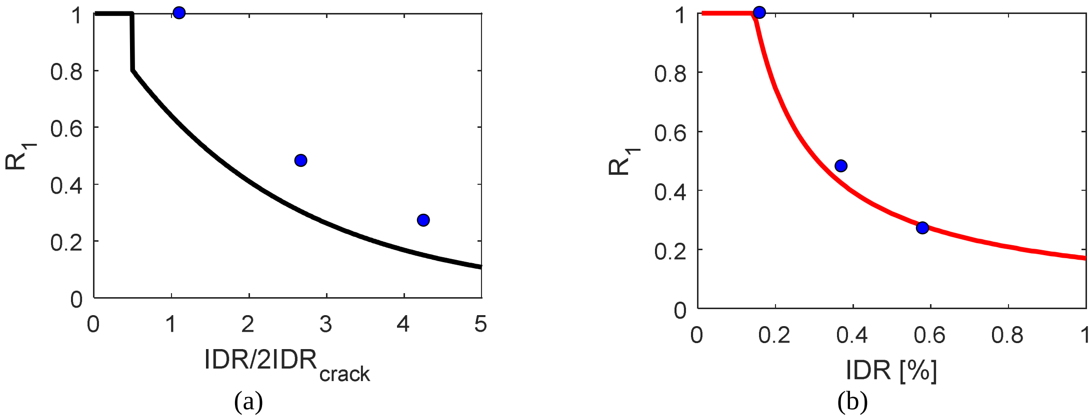
The OOP strength degradation experimentally observed on specimens IP+OOP_L, IP+OOP_M and IP+OOP_H is compared to the strength reduction factor calculated by applying Angel et al. (1994) and Ricci et al. (Di Dominceco et al. 2018) formulations. For a slenderness ratio equal to 22.9, as in the present case, Angel et al. (1994) strength reduction factor R_1 can be written as reported in Equation 1.

$$R_1= \begin{cases} 1 & \text{If } IDR<IDR_{crack} \\ 0.64^{IDR/2IDRcrack} & \text{If: } IDR\geq IDR_{crack} \end{cases} \qquad \text{Equation 1}$$

Ricci et al. (2017b)'s formulation is reported in Equation 2.

$$R_1 = \min(1; 0.17\mathrm{IDR}[\%]^{-0.92}) \qquad \text{Equation 2}$$

In Equations 2, IDR is the maximum inter-storey drift ratio attained during the IP test and IDR_{crack} is the inter-storey drift ratio at first masonry cracking, which was equal to 0.072%, 0.069% and 0.068% respectively for tests IP+OOP_L, IP+OOP_M and IP+OOP_H.
A comparison between the experimental and predicted R_1 factor for these tests is reported in Figure 8. It can be observed that Angel et al.'s relationships highly overestimates the OOP strength degradation due to IP damage for these tests.



(a) (b)

Figure 8 - Experimental OOP strength degradation for test specimens IP+OOP_L, IP+OOP_M and IP+OOP_H (blue dots) compared with the prediction by Angel et al. (1994) (a) and by Ricci *et al.* (Di Dominceco et al. 2018) (b).

5. CONCLUSIONS

This manuscript presented an experimental work focused, in the influence of different variables such as gravity load, load application and previous damage in the panel OOP capacity. Two experimental campaigns of specimens tested with uniform or four-point loading were carried out and posterior compared. From the tests with uniform loading it was observed that the application of the gravity load during the OOP tests modified the cracking pattern however different results were obtained for the maxim strength capacity. The panel subjected to monotonic OOP loading achieved 10% higher OOP strength capacity than the reference specimen and the panel subjected to cyclic OOP loading achieved a reduction about 50% of the maximum OOP strength. It was observed that the panel subjected to a previous IP drift of 0.5% resulted in a reduction of the OOP maximum strength of 60% and a fragile failure mechanism characterized by the expulsion of the panel evidencing a rigid body behaviour.
From the results of the tests with four-points loading the following conclusions can be drawn:

- The OOP strength and stiffness of URM infills depends on their boundary conditions and increase at increasing number of supported edges;
- The OOP strength of infills in which one-way arching occurs is well predicted by classical literature/code mechanical models such as Eurocode 6 (CEN 2005) and Mcdowell et al. (1956) model;
- The OOP strength of infills in which two-way arching occurs is well predicted by Dawe and Seah (1989) stripe method:
- IP+OOP interaction seems to have significant effects on the OOP strength and stiffness of infills by reducing them;
- Such reduction activates in a non-negligible way only for IP drift greater than a certain lower bound roughly equal to 0.2%;
- Angel et al. (1994) formulation is too much conservative in predicting the OOP strength degradation due to IP damage.

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