# Assessment of strengthening solutions for the out-of-plane collapse of masonry infills through textile reinforced mortars

**Maria Teresa de Risi**
Post-Doctoral Research Fellow
Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples, Italy, beneficiary of an AXA-RF Post-Doc grant

**André Furtado**
PhD Student
CONSTRUCT-LESE
Faculdade de Engenharia da Universidade do Porto, Portugal

**Hugo Rodrigues**
Senior Lecturer
RISCO-ESTG
Polytechnic Institute of Leiria, Portugal

**José Melo**
Post-Doctoral Research Fellow
CONSTRUCT-LESE
Faculdade de Engenharia da Universidade do Porto, Portugal

**Gerardo Verderame**
Associate Professor
Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples, Italy

**António Arêde**
Associate Professor
CONSTRUCT-LESE
Faculdade de Engenharia da Universidade do Porto, Portugal

**Humberto Varum**
Full Professor
CONSTRUCT-LESE
Faculdade de Engenharia da Universidade do Porto, Portugal

**Gaetano Manfredi**
Full Professor
Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples, Italy

## ABSTRACT

Out-of-plane (OOP) collapse of infill masonry walls in existing reinforced concrete (RC) buildings due to earthquakes represents a paramount issue for life safety and seismic economic loss estimation. Few studies from literature deal with this topic, particularly regarding possible strengthening strategies to prevent the infills' OOP collapse. This work presents the first results of a proper experimental campaign about the assessment of different strengthening solutions designed to mitigate or avoid the out-of-plane collapse of masonry infills in existing RC buildings. The investigated strengthening techniques were based on the application of a very thin high-ductility mortar plaster and glass fibre-reinforced polymer nets with different types of anchorage to the surrounding RC frame. Each specimen was built with horizontal hollow clay bricks and was tested through the application of a semi-cyclic OOP displacement pattern by means of uniformly distributed small pneumatic jacks. Mechanical properties of the adopted materials, test setup and procedure are described herein. Tests results are presented and commented in terms of OOP force-displacement responses and damage evolution during the test. Details about the effectiveness of each retrofitting solution are provided and compared to support the selection of the best strategy for further investigations and future applications.

**KEYWORDS:** hollow masonry infills, strengthening solutions, textile reinforced mortar; out-of-plane testing; experimental results.

## 1. INTRODUCTION

The presence of the infill masonry (IM) walls in reinforced concrete (RC) buildings is very common. However, even today, during the design process of new buildings and in the structural safety assessment of existing ones, infills are usually considered as non-structural elements, and their influence in the structural response is disregarded. The eventual infill walls out-of-plane (OOP) collapse can result in serious human injuries and casualties and high economic losses, as experienced in recent earthquakes.
The adequate knowledge of all the aspects related to the behaviour of infilled framed structures, of their components (structural and non-structural elements) and of the phenomena interaction is a fundamental issue to guide the practitioners in the assessment and strengthening of existing buildings. The infill walls are widely used for partition purposes and to provide thermal and acoustic insulation to the RC buildings. Their OOP vulnerability, when subjected to transversal loadings, resulted in several extensive damages or collapses that increased significantly the risk to the population and the rehabilitation' costs of the buildings. Due to their interaction with the surrounding RC frame, the infill panels can develop a higher OOP strength through arching mechanism, which mainly depends on the panel' slenderness, masonry compressive strength, boundary conditions and panel width support conditions. Other important variables such as previous damage and workmanship can play an important role in their OOP seismic performance. It is of utmost importance to validate some proposed retrofitting strategies available in the literature and develop new ones to reduce this seismic vulnerability and prevent the IM walls' collapse. Based on this motivation, an experimental testing campaign was carried out with the main aim of assess the efficiency of different strengthening solutions designed to mitigate or avoid the OOP of masonry infills in existing RC buildings. As a part of this wider campaign, three full-scale quasi-static OOP tests are presented herein, two of them on strengthened specimens. The investigated strengthening techniques were based on the application of a very thin high-ductility mortar plaster and fibre-reinforced polymer nets with different degree of connection with the surrounding RC frame. Tests results are presented and commented in terms of OOP force-displacement responses and damage evolution during the test.

## 2. EXPERIMENTAL CAMPAIGN

### 2.1. Specimens' description

The testing campaign comprised a total of three nominally identical full-scale, one-bay-one-story RC frames infilled with a thin masonry wall made up of horizontal hollow clay units. The first specimen (herein designated specimen AB-OOP) was representative of the enclosure of a typical existing RC building in the Mediterranean region in its "as-built" condition. The remaining two specimens were strengthened to prevent the collapse by means of two different strengthening techniques based on the application of innovative systems made up of high-ductility mortar plaster and fibre-reinforced polymer nets. The infill panels' geometric dimensions were defined as 4.20x2.30m (length and width respectively). The columns' and beams' cross sections were 0.30x0.30m and 0.30x0.50m, respectively. Fig. 1 shows the schematic layout of the specimen geometry. All the infill panels have equal geometry with the above-mentioned dimensions, made of hollow clay horizontal bricks with 110mm thickness. No reinforcement was used to connect the infill panel and the surrounding RC frame, and no gaps were adopted between the panel and the frame. A traditional mortar M5 class was considered a suitable choice for the construction of the panels.

Concerning to the RC frame material properties, it was assumed a concrete C20/25 and steel reinforcement A500 class. In the next sub-sections, the strengthening solutions adopted for each strengthened specimen (panels R1-OOP and R2-OOP) will be briefly described.

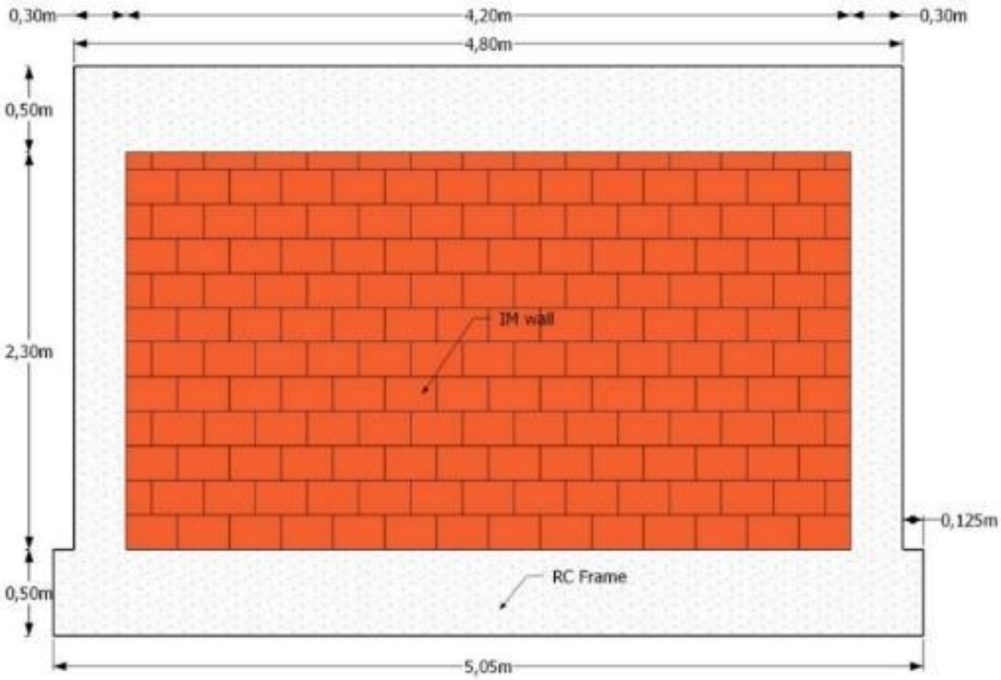
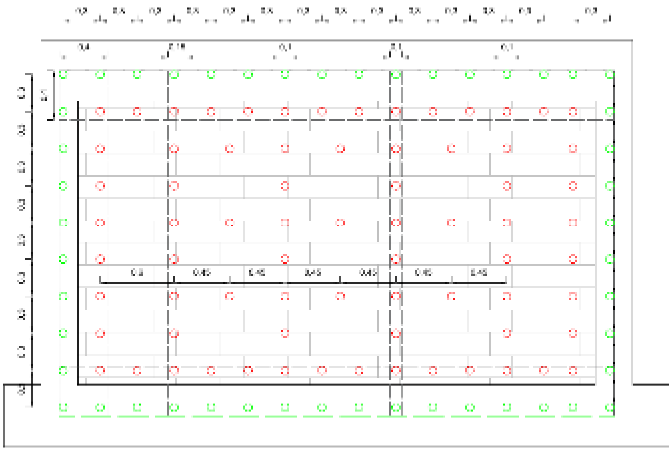


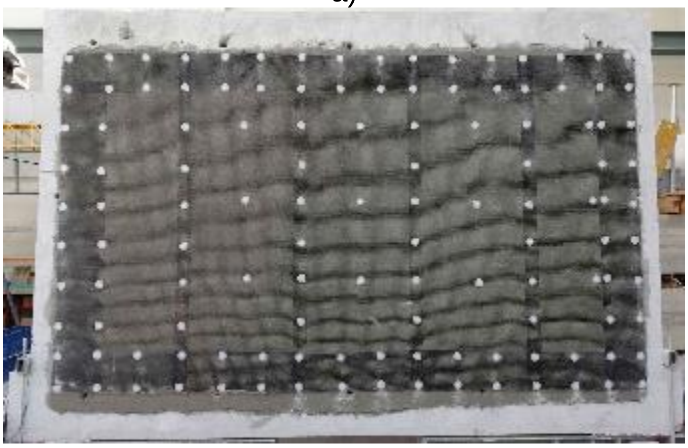

Fig. 1 - Infilled RC frame specimen general dimensions (units in meters).

### 2.1.1. *Specimen R1-OOP*

The strengthening solution adopted for the specimen R1-OOP was a textile reinforced mortar composed by a glass-fibre net designated “FASSANET ARG 40” commercialized by FASSA BARTOLO, with a matrix 4x4cm, a tensile strength equal to 56.25kN/m and a maximum ultimate strain equal to 3%. The mortar used for the plaster was a ductile one, designated “SISMA” and commercialized also by FASSA BARTOLO. The mean compression and tensile strengths of the plaster mortar at the day of the test were around 24.4MPa and 6.7MPa, respectively. The net was fixed to the RC frame and to the panel with plastic connectors. Thus, the application procedure of this strengthening strategy started by the application of 1cm plaster. Then the net was positioned and fixed with the plastic connectors. The roll of net was provided with 1 meter width and 50 meters length. Five vertical strips were used to strengthen the wall, as can be observed in Fig. 2. The overlap length used between each vertical strip were assumed to be 10cm, and for the transition RC frame-infill panel it was assumed a duplicate net with an overlap equal to 30cm (15cm for the RC frame and 15cm for the infill panel). The disposition and distribution of the connectors is shown in Fig. 2a, and the general view of the specimen R1-OOP is shown in Fig. 2b. At the end, an additional 1cm layer of ductile mortar is applied, so that the final thickness of the retrofitting plaster is equal to 2cm.



a)



b)

Fig. 2 – Specimen R1-OOP: a) strengthening schematic layout; and b) general view.

### 2.1.2. *Specimen R2-OOP*

The strengthening solution selected for specimen R2-OOP was similar to the one adopted for specimen R1-OOP. The only difference among them was related to the anchorage of the net to the frame. In this case, L-shape connectors were used to fix the net to the RC frame (Fig. 3). The application procedure adopted to apply this connectors was: 1) application of the first layer of plaster with thickness equal to 1cm; 2) application of the net; 3) drilling a hole with ϕ6mm diameter and 10cm length for each connector; 4) full filling of the hole with epoxy resin (provided by the manufacturer); 5) application of the L-shape connector; and 6) application of the second layer of 1cm plaster. The net and the plaster were the same used in the specimen R1-OOP.

Fig. 3 – Specimen R2-OOP: Detail of the L-shape connector.

## 2.2. Test Setup, instrumentation and loading protocol

The OOP test setup consists in the application of a distributed OOP loading through 28 pneumatic actuators that mobilized the entire infill panel surface resorting to wood plates with dimensions 0.5x0.5m$^2$ placed between the actuators and the panel. The pneumatic actuators were linked to four horizontal alignments performed by HEB140 steel shapes which reacted against five vertical alignments performed by HEB200 steel shapes. The horizontal alignments were coupled with hinged devices that allow lateral sliding. This steel reaction structure is a self-equilibrated structure designed with a concept similar to the previous experimental campaigns carried out by Furtado *et al.* [1, 2]. The steel structure is attached to the RC frame in twelve points (5 in the bottom and 5 in the top beam and 2 in middle-height columns) with steel bars that are coupled with load cells that allow monitoring the OOP loadings. Fig.4a and Fig.4b shows the schematic layout and the general view of the test setup.
Concerning to the instrumentation assumed for all the tests (Fig. 4c), 34 displacement transducers were used to measure the OOP displacements of the panel, OOP displacements of the frame, relative displacements between the panel and the frame and vertical displacement of the top beam.

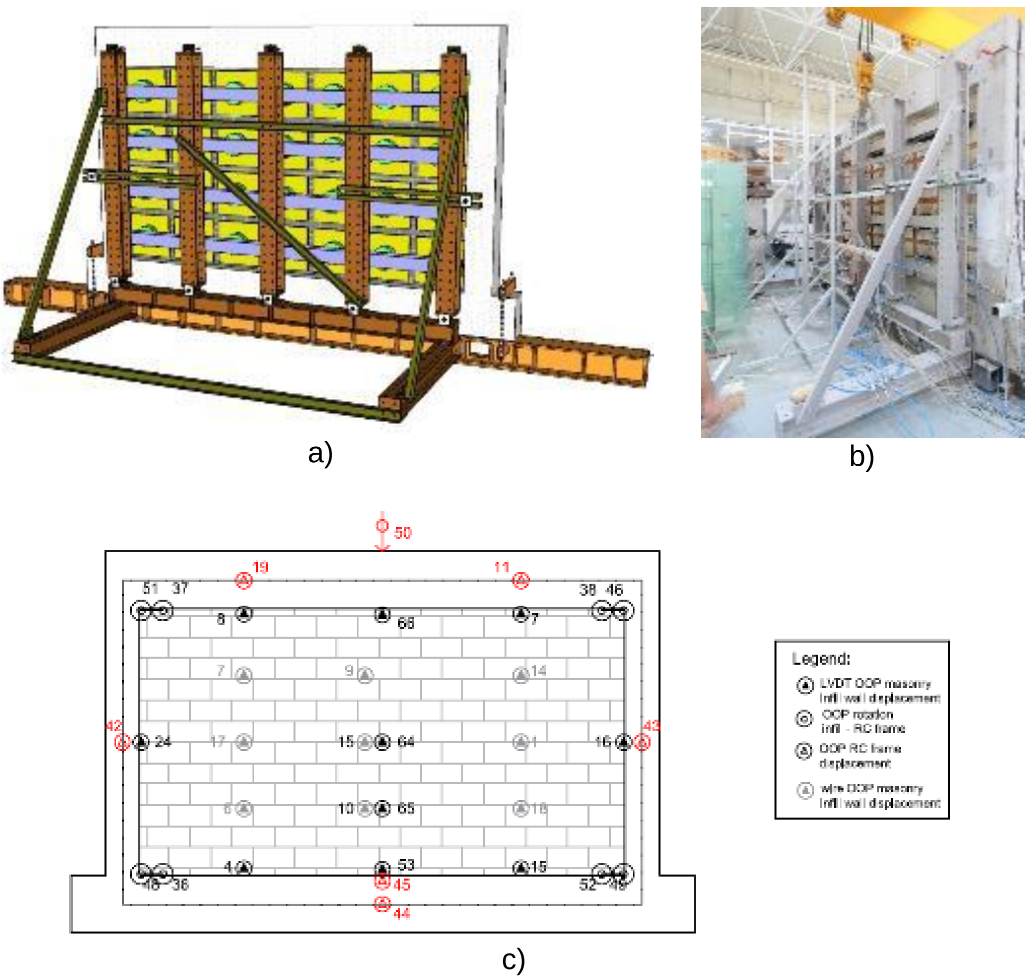



Fig. 4 – Experimental campaign: a) Test setup schematic layout; b) Test setup general view; and c) Instrumentation.

Lastly, the loading protocol consisted on the application half-cyclic OOP displacements (loading-unloading) that were imposed with steadily increasing displacement levels, targeting the following nominal peak displacements: 0.5, 1, 1.5, 2, 2.5, 3.5; 5; 7.5; 10; and so on 5 by 5 mm until a maximum OOP displacement of 120 mm. Two half-cycles were repeated for each lateral deformation demand level at the control node.

## 3. EXPERIMENTAL RESULTS

The results obtained by each specimen are analysed in this section in terms of OOP force ($F_{OOP}$) - displacement in the centre of the infill panel ($d_{OOP,center}$) hysteretic curves, cracking pattern and observed damage, and compared to each other.

### 3.1. Specimen AB-OOP results

Fig.5 shows the semi-cyclic OOP force-displacement response for the as-built specimen AB-OOP. First, note that the OOP displacement used in this plot (and in the similar ones in the following analyses) is the displacement monitored by the displacement transducer located in the geometrical centre of the panel (see LVDT 64 in Fig.4c). The initial (secant) stiffness of this response – calculated as the ratio between $F_{OOP}$ and $d_{OOP,centre}$ at the first peak related to the first applied displacement level – is equal to $k_{OOP,sec,in}$=8.89 kN/mm. By increasing the applied OOP displacement, a first visible (macro-) cracking was observed on the panel for an applied OOP displacement in the centre equal to 2.5mm, at $F_{OOP,cr}$= 21.81kN (see Fig.5). At this stage, a horizontal crack along a mortar bed joint occurred in the middle of the panel, as shown in Fig.6a. The secant stiffness related to this first cracking is thus slightly lower than the initial one, and in particular equal to 8.72kN/mm. Secant stiffness progressively reduced during the test, and progressively wider cracks appeared in the panel, drawing on it a quite clear "pavilion" shape until the peak load is reached (Fig.6b). The "pavilion" deformed shape highlights the existence of a double-arch (horizontal and vertical) resisting mechanism, as expected for an infill panel connected with the surrounding frame along four-edges [3]. The maximum OOP load corresponding to this stage was equal to $F_{OOP,max}$=52.68kN at $d_{OOP,centre,max}$=39.55mm. The corresponding secant stiffness thus reduced to 1.33kN/mm.

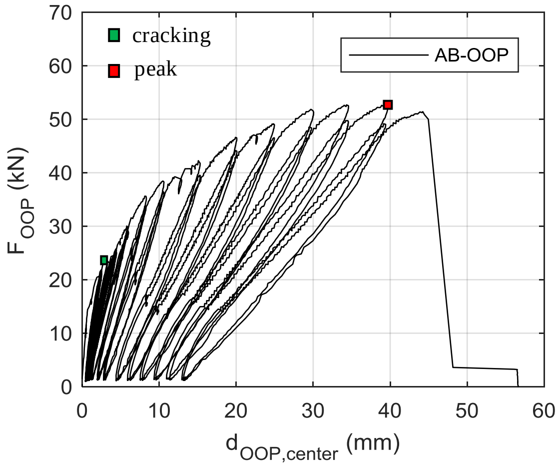
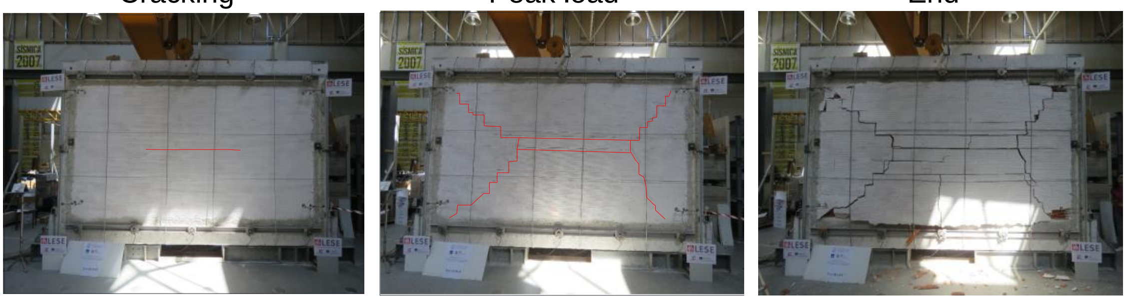



Fig. 5 - Test AB-OOP: $F_{OOP}$ - $d_{OOP}$ response.

Cracking | Peak load | End



a) b) c)

Fig. 6 - Test AB-OOP: a) First cracking; b) peak load; c) end of the test.

At about 45 mm of applied OOP displacement, the infill panel totally collapsed out of its plane, after its detachment from the top beam, and the crushing of the hollow clay bricks in the compressed portions of the panel (Fig.6c).

### 3.2. Specimen R1-OOP results

Fig. 7 shows the OOP force-displacement response for the first retrofitted specimen (R1-OOP). For this test, the initial (secant) stiffness of the response – calculated as explained before – is equal to $k_{OOP,sec,in}$=29.15 kN/mm, namely significantly higher (+228%) than the $k_{OOP,sec,in}$ related to the specimen AB-OOP. Such a difference is mainly ascribable to the presence of the plaster for the specimen R1-OOP. By increasing the applied OOP displacement, first visible (macro-) cracks were observed on the panel for an applied OOP displacement in the centre equal to 3.6mm, at $F_{OOP,cr}$= 70.47kN (see Fig. 7). At this stage, hairline horizontal and vertical cracks appeared in the middle of the panel, as shown in Fig. 8a. The secant stiffness related to this first cracking thus reduced to 19.58kN/mm. Secant stiffness progressively reduced during the test, and progressively wider cracks appeared in the panel, with additional diagonal cracks in the bottom portion of the panel, until the peak load was reached (Fig. 8b). The maximum OOP load corresponding to this stage was equal to $F_{OOP,max}$=95.95kN at $d_{OOP,centre,max}$=15.00mm. At peak load, a significant detachment from the top beam was observed.

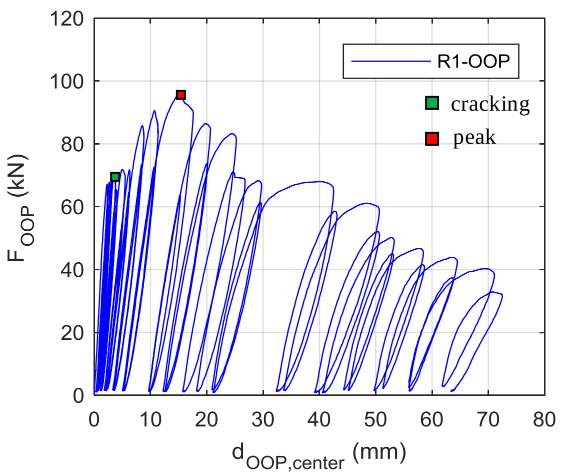
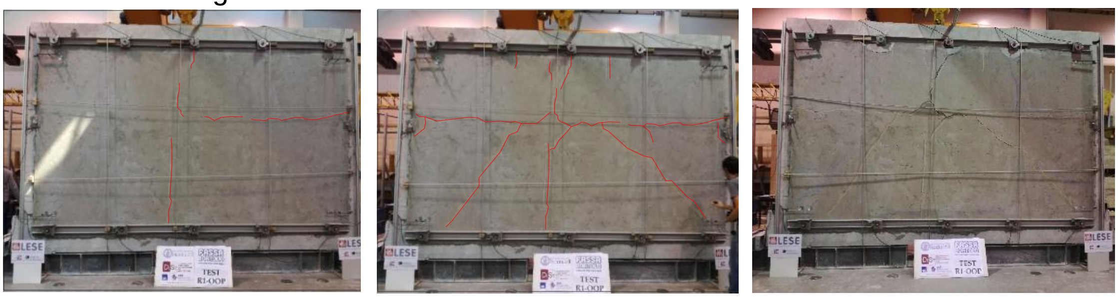



Fig. 7 - Test R1-OOP: $F_{OOP}$ - $d_{OOP}$ response.

Cracking | Peak load | End



a) b) c)

Fig. 8 - Test R1-OOP: a) First cracking; b) peak load; c) end of the test.

During the after-peak load phase, there were a progressive widening of the central cracks, the detachment of the reinforcing plaster for the top part of the frame, and a pronounced slippage of the plastic connectors from the top beam and from the lateral columns (Fig. 8c).

### 3.3. Specimen R2-OOP results

Fig. 9 shows the OOP force-displacement response for the retrofitted specimen R2-OOP and the corresponding deformed shape at the peak load, as for the previous tests. For this test, the initial secant stiffness – calculated as explained before – is equal to $k_{OOP,sec,in}$=34.85 kN/mm, namely slightly higher (about +20%) than the $k_{OOP,sec,in}$ related to specimen R1-OOP, likely due to the stronger degree of connection between the retrofitting plaster on the panel and the RC frame. For increasing applied OOP displacement, a first visible (macro)-cracking was observed on the panel, at $F_{OOP,cr}$=89.73kN and a corresponding displacement $d_{OOP,center}$ equal to about 3 mm (see Fig. 10a). At this stage, a hairline horizontal crack appeared in the middle of the panel together with some smaller vertical cracks on the bottom, as shown in Fig. 10a. Secant stiffness progressively reduced, and progressively wider cracks appeared in the panel, with additional diagonal cracks in the bottom portion of the panel, vertical central cracks, and horizontal cracks at the infill-top beam interface, until the peak load was reached (Fig. 10b). The maximum OOP load corresponding to this stage was equal to $F_{OOP,max}$=116.70kN at $d_{OOP,centre,max}$=15.34mm. The above-mentioned horizontal cracks at the infill-top beam interface highlighted the increasing OOP sliding of central bricks on the top of the panel (visible on the backside of the wall and measured by the top displacement transducers) involving "monolithically" bricks and retrofitting plaster.

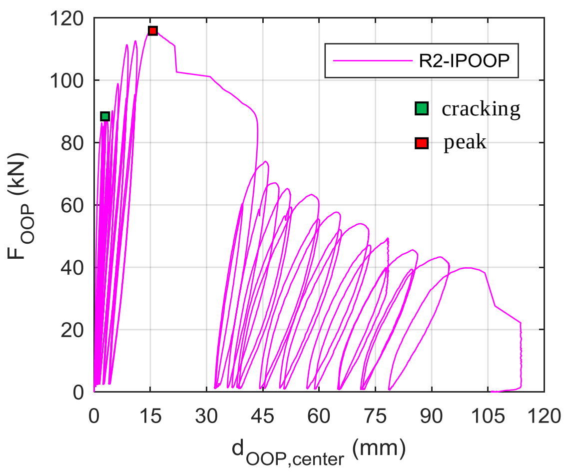



Fig. 9 - Test R2-OOP: $F_{OOP}$ - $d_{OOP}$ response.

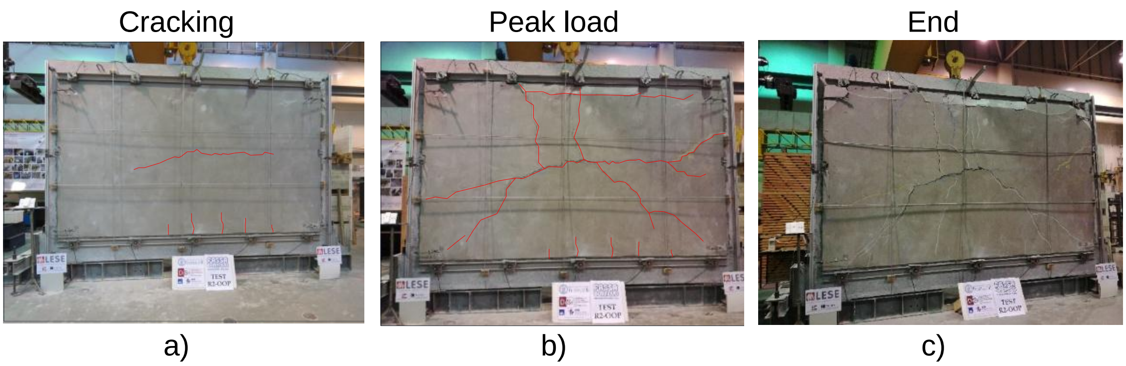



Fig. 10 - Test AB-OOP: a) First cracking; b) peak load; c) end of the test.

From the achievement of the peak load to the end of the test, there were the progressive widening of the central cracks, the crushing of some clay bricks in the bottom and a slight OOP sliding also along the infill-bottom beam interface. The damage state at the end of this test, at $d_{OOP,centre}$ practically equal to the infill wall thickness (110mm), is shown in Fig. 10c. It is worth noting that, at the end of the test, the system "infill panel + retrofitting plaster" detached from the upper part, but it remained still connected along the columns and to the bottom part of the frame. In the top of the panel, where the sliding was observed, at the end of the test, the connectors were still *in-situ*, whereas the glass fibre net was locally cut around the connectors.

### 3.4. Comparisons of the results

Fig. 11 shows a comparison among the test results presented above, in terms of $F_{OOP}$-$d_{OOP,center}$ envelope (Fig. 11a) and of secant stiffness ($k_{sec}$) evolution (Fig. 11b). Note that the envelopes in Fig. 11a are shown until the last first-cycle peak for each test. Additionally, Table 1 provides a summary of the results commented above.

It can be noted that the maximum $F_{OOP}$ for the retrofitted specimens are 1.82 and 2.22 times the $F_{OOP,max}$ related to the AB-OOP specimens, for tests R1-OOP and R2-OOP, respectively. This aspect assumes particular importance for typical code-based safety checks regarding the out-of-plane collapse of masonry infills, which are generally carried out in terms of strength (e.g. [4,5]).

Higher force increment is observed at the first (macro-) cracking condition: $F_{OOP,cr}$ is 3.23 and 4.11 times the related value for the AB-OOP specimen, for tests R1-OOP and R2-OOP, respectively, mainly due to the significant tensile strength of the adopted fiber-reinforced mortar.

Secant stiffness is also significantly affected by the presence of the retrofitting plaster, by increasing of at least of +228% with respect to AB-OOP specimen.

On the contrary, the OOP displacement at the peak OOP load ($d_{OOP,center,max}$) is about the 40% of the related displacement of AB-OOP specimen for both the retrofitted tests. The displacements corresponding to the 20% of strength reduction (namely, corresponding to the 80% of the maximum load) on the envelopes ($d_{OOP,center,u,80\%}$) are also reported in Table 1. The corresponding ductility, calculated as the ratio between $d_{OOP,center,u,80\%}$ and $d_{OOP,center,max}$, are 53% and 43% higher than the reference specimens AB-OOP, for specimens R1-OOP and R2-OOP, respectively.

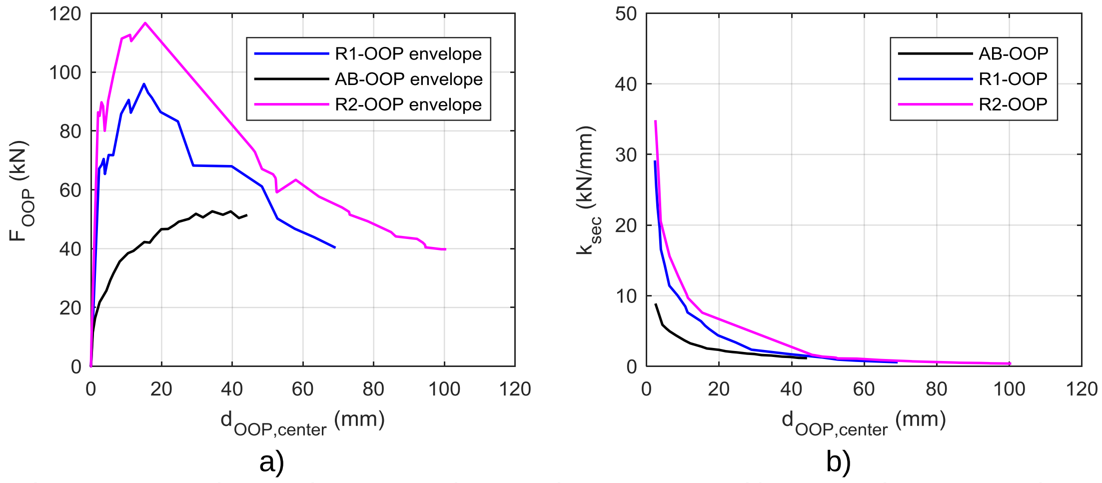



Fig. 11 - Comparison of the results: a) $F_{OOP}$ - $d_{OOP}$ envelopes; b) secant stiffness evolutions.

Table 1 - Comparisons of the results.

| Parameter | AB-OOP | R1-OOP | R2-OOP |
|---|---|---|---|
| $F_{OOP,max}$ (kN) | 52.68 | 95.95 | 116.70 |
| $F_{OOP,cr}$ (kN) | 21.81 | 70.47 | 89.73 |
| $k_{OOP,sec,in}$ (kN/mm) | 8.89 | 29.15 | 34.85 |
| $d_{OOP,center,max}$ (mm) | 39.55 | 15.00 | 15.34 |
| $d_{OOP,center,u,80\%}$ (mm) | 45.46 | 26.47 | 25.32 |
| $\mu_{OOP,center,u,80\%}$ (-) | 1.15 | 1.76 | 1.65 |

An additional interesting comparison among the presented test results can be carried out in terms of observed “failure mode”, described in the previous sub-sections.

Certainly, the most critical point of this kind of retrofitting strategy is the connection between the system “ductile mortar plaster + fibre-net” and the surrounding frame. An effective connection is necessary to prevent a premature physical collapse of the panel out of its plane. Actually, for the retrofitted specimen with an effective plaster-frame connection (R2-OOP), the system “infill panel + retrofitting plaster” did not collapse out of its plane for an OOP displacement equal to the infill thickness. Nevertheless, to improve the ductility of this retrofitting system, particular care should be still paid to the proper definition of the typology of the connectors and their spacing. To this aim, future desirable experimental tests should provide additional useful data.

## 4. CONCLUSIONS

This paper presented an experimental work performed in the Laboratory of Earthquake and Structural Engineering of the Civil Engineering Department of the University of Porto in cooperation with the Department of Structures for Engineering and Architecture of the University of Naples Federico II, about the assessment of possible strengthening solutions designed to mitigate or avoid the out-of-plane collapse of hollow clay infills in existing RC buildings.

Three nominally identical full-scale one-bay-one-story RC frames were built and infilled with a thin masonry wall. The first specimen was representative of the “as-built” condition. The remaining two specimens were strengthened to prevent the out-of-plane collapse by means of two different strengthening techniques based on the application of high-ductility mortar plaster and fibre-reinforced polymer nets. All the tests consisted in the application of a semi-cyclic (loading-unloading-reloading) history of imposed displacements in the OOP direction by means of small pneumatic jacks through a uniform distributed load.

The experimental results have been showed in terms of OOP force-displacement responses, and damage evolution, and compared to each other. It was observed that the OOP stregnth capacity at OOP load at first cracking significantly increases (of more than +200%) for the retrofitted specimens with respect to the as-built reference test, mainly due to the significant tensile strength of the adopted fibre-reinforced mortar. Similarly, the OOP secant stiffness significantly increases, as expected. On the contrary, the infill OOP displacment at peak load reduces in retrofitted infills by about 60%. Nevertheless, note that, for the retrofitted specimen with an effective plaster-frame connection, the system “infill panel + retrofitting plaster” did not collapse out of its plane for an OOP displacement equal to the infill thickness.

In conclusion, certainly the presented data can be usefull to provide a support towards the choice of the best strategies for future further investigations and applications. Addtional experimenal data will be certainly important to improve the OOP retrofitting system for masonry infills, with particular care to plaster-frame connection system.

## 5. ACKNOWLEDGMENTS

This work was developed under the support of AXA Research Fund Post-Doctoral Grant *“Advanced nonlinear modelling and performance assessment of masonry infills in RC buildings under seismic loads: the way forward to design or retrofitting strategies and reduction of losses”. This support is gratefully acknowledged.*

The authors would like also to acknowledge to the Laboratory of Earthquake and Structural Engineering (LESE) technicians, Mr. Guilherme Nogueira and Mr. Nuno Pinto for their support in the experimental activity reported in this research work. Finally, the authors would like to specially acknowledge FASSA BARTOLO for the provision strengthening materials used in these experimental tests.

This work was financially supported by: Project POCI-01-0145-FEDER-007457 - CONSTRUCT - Institute of R&D In Structures and Construction funded by FEDER funds through COMPETE2020 - Programa Operacional Competitividade e Internacionalização

(POCI) – and by national funds through FCT - Fundação para a Ciência e a Tecnologia; Project FCT PTDC/ECMEST/3790/2014.

## 6. REFERENCES


1. Furtado, A., et al., *Experimental evaluation of out-of-plane capacity of masonry infill walls.* Engineering Structures, 2016. **111**: p. 48-63.
2. Furtado, A., et al., *Effect of the Panel Width Support and Columns Axial Load on the Infill Masonry Walls Out-Of-Plane Behavior.* Journal of Earthquake Engineering, 2018: p. 1-29.
3. Di Domenico, M., et al., *Experimental Assessment of the Influence of Boundary Conditions on the Out-of-Plane Response of Unreinforced Masonry Infill Walls*. Journal of Earthquake Engineering, 2018: p. 1-39.
4. CEN (2005). Eurocode 8: Design of structures for earthquake resistance-part 1: general rules, seismic actions and rules for buildings.
5. Decreto Ministeriale del 14/1/2008. Approvazione delle nuove norme tecniche per le costruzioni. G.U. n. 29 del 4/2/2008 (in Italian).