Experimental analysis of Textile Reinforced Mortars strengthening strategies against the out-of-plane collapse of masonry infill walls

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ABSTRACT
Out-of-plane (OOP) collapse of masonry infill panels in existing reinforced concrete (RC) buildings due to seismic events is a key issue for life safety and seismic economic loss estimation. Few studies in the literature deal with this topic and, above all, with possible strengthening strategies against the OOP collapse. This work presents the main results of an experimental campaign about different strengthening solutions to mitigate the OOP collapse of masonry infills in RC buildings. The investigated strengthening techniques were based on the application of a thin mortar plaster and fiber-reinforced polymer nets with different connection typologies with the surrounding RC frame. The specimens were realized with traditional horizontal hollow clay bricks and were tested through the application of a semi-cyclic OOP displacement pattern by means of uniformly distributed small pneumatic jacks. Tests data and results are presented and commented in terms of OOP force-displacement responses and damage evolution. Details about the effectiveness of each retrofitting solution are provided and compared to support the selection of the best strategy for future applications.

1 INTRODUCTION

Seismic events worldwide clearly showed that a crucial issue for life-safety and loss reduction due to earthquakes for existing Reinforced Concrete (RC) buildings is related to the Out-Of-Plane (OOP) collapse of infill masonry walls. In the last thirty years, a quite limited number of experimental tests was presented in the literature on unreinforced masonry infills in RC frames under OOP loading (e.g., Angel et al., 1994; Furtado et al., 2016; Furtado et al., 2018; Di Domenico et al., 2018). Even less studies addressed the paramount topic of the strengthening strategies to prevent the infills' OOP collapse. The latter point is still a frontier issue for the most recent research works and it represents the focus of this paper.

The OOP collapse vulnerability can be reduced by using different techniques, such as fibre reinforced polymers (FRP), engineered cementitious composites (ECC), textile reinforced mortars (TRM) or bed joints reinforcement. Few experimental researches can be found in the literature that study this topic, generally by means of mechanical characterization tests on small panels or OOP tests on infill panels embedded in RC frames (e.g., Guidi et al., 2013; Koutas et al., 2014; Da Porto et al., 2015; Martins et al., 2015).

This paper presents a joint experimental work between the Civil Engineering Department of the University of Porto and the Department of Structures for Engineering and Architecture of the University of Naples Federico II, about possible strengthening solutions to mitigate or prevent the OOP collapse of masonry infills in existing RC buildings based on the TRM-technique.

Three nominally identical full-scale one-bay-one-story RC frames were built and infilled with a thin masonry wall made up of horizontal hollow clay bricks. The first specimen was representative of a typical enclosure of existing RC buildings in the Mediterranean region in its "as-built" condition. The remaining two specimens were strengthened by means of two different 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 uniformly distributed load.

The paper presents the main geometrical and mechanical properties of the specimens, and the analysis of the experimental results in terms of OOP force-displacement responses and damage evolution. Lastly, the results of the tests are compared to assess the effectiveness of the selected strengthening techniques and to provide a support towards the choice of the best strategies for future further investigations and applications.

2 DESCRIPTION OF THE EXPERIMENTAL CAMPAIGN

2.1 Description of the specimens

The first specimen was representative of the enclosure of a typical existing RC building in its "as-built" condition. The infill panels' geometric dimensions were 4.20 x 2.30 m (length and width respectively). The columns' and beams' cross sections were 0.30x0.30 m^2 and 0.30x0.50 m^2, respectively. Figure 1 shows the schematic layout of the specimen geometry. All the infill panels have equal geometry with the above-mentioned dimensions, made of (300x200x100) mm^3 hollow clay horizontal bricks (with 110 mm 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 used for the construction of the panels. Concerning to the RC frame material properties, a C20/25 concrete was assumed and steel reinforcement with a nominal mean yielding stress equal to 500 MPa were adopted.

The as-built specimen, the "reference" specimen, is herein designated as "AB-OOP".

On the other two identical specimens, two different strengthening techniques were applied to prevent the out-of-plane collapse, both based on the application of high-ductility mortar plaster and fibre-reinforced polymer nets. The two retrofitted specimens are named "R1-OOP" and "R2-OOP", respectively. In the sub-section 2.2, the strengthening solutions adopted for each strengthened specimen (panels R1-OOP and R2-OOP) will be described. Table 1 reports a summary of the three specimens tested and analysed in the following sections.

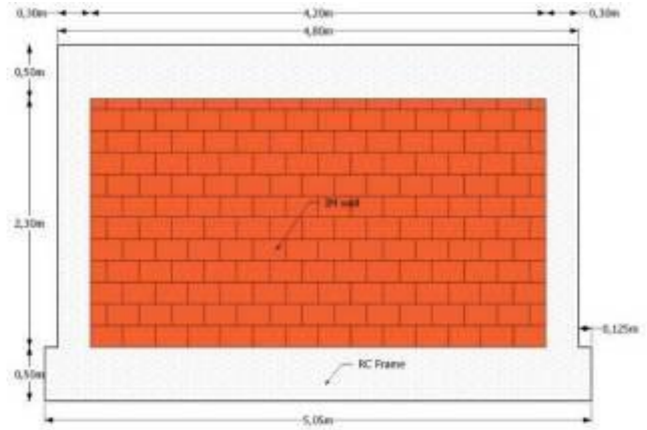


Figure 1. Infilled RC frame specimen general dimensions (in m).

Table 1. Experimental matrix.

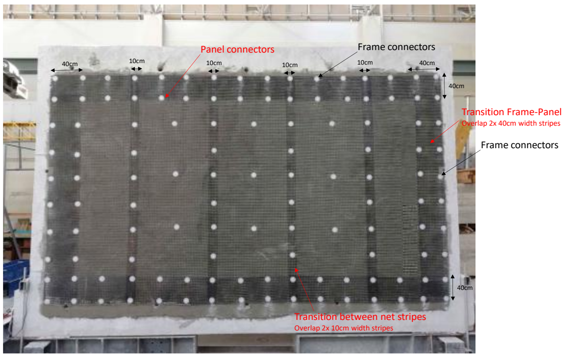
ID	Net	Connection to the frame
AB-OOP	No	-
R1-OOP	G-FRP	Poor
R2-OOP	G-FRP	Good

2.2 Retrofitting solutions

The strengthening solution adopted for the specimen R1-OOP was a textile reinforced mortar composed by a glass-fibre (G-FRP) net with a 4x4 cm matrix, a nominal tensile strength equal to 56.25 kN/m and a maximum ultimate strain equal to 3%. The mortar used for the plaster was a glass fibre-reinforced mortar, with mean compression and tensile strengths at the day of the test equal to 24.4 MPa and 6.7 MPa, respectively. The net was positioned and fixed to the RC frame and to the infill panel by means of simple plastic connectors. Thus, the application procedure of this strengthening strategy started by the application of 1 cm of plaster (see Figure 2a). Then the net was positioned and fixed with the plastic connectors (Figure 2b). The roll of net was provided with 1 meter width and 50 meters length. Five vertical strips were used to strengthen the wall, as it can be observed in Figure 2c. The overlap length used between each vertical strip were assumed to be 10 cm, and for the transition RC frame-infill panel it was assumed a duplicate net with an overlap equal to 40 cm (20 cm for the RC frame and 20 cm for the infill panel). The disposition and distribution of the connectors is shown in Figure 2c, with a general view of the specimen R1-OOP. At the end, an additional 1cm layer of plaster was applied (Figure 2d), so that the final thickness of the retrofitting plaster was equal to 2cm. A detail of the plastic connectors is reported in Figure 3a.

(a)

(b)

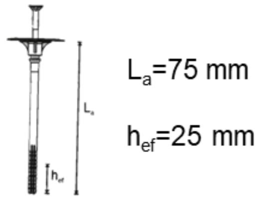


(c)

(d)

Figure 2. Phases of application of the TRM-based strengthening solutions.

The strengthening solution selected for specimen R2-OOP was similar to that adopted for specimen R1-OOP. The difference among them was related to the typology of the connection system between the net and the frame. In this case, L-shape glass bars (see Figure 3b) were used as connectors to fix the net to the surrounding beams and columns. The procedure adopted to apply this connectors was: 1) application of the first layer of plaster with thickness equal to 1 cm; 2) application of the net; 3) drilling a hole with ϕ6 mm diameter and 10 cm length for each connector; 4) full filling of the hole with epoxy resin; 5) application of the L-shape connector; and 6) application of the second layer of 1cm plaster. The net and the mortar used for plaster were the same used in the specimen R1-OOP.



(a)

(b)

Figure 3. Net-to-frame connection details for specimens R1-OOP (a) and R2-OOP (b).

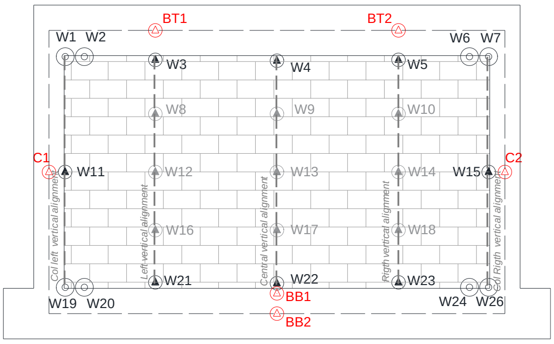
2.3 *Setup and Instrumentation*

The OOP test setup used for all the specimens consisted in the application of a distributed OOP loading through 28 pneumatic actuators that mobilized the whole infill panel surface resorting to wood plates with dimensions 0.5x0.5 m^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. (2016; 2018). The steel structure is attached to the RC frame in twelve points (5 in the bottom beam, 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. Figure 4a shows the general view of the adopted test setup.

About the instrumentation (see Figure 4b), 34 displacement transducers were used for each test to measure the OOP displacements of the panel, the OOP displacements of the frame, the relative displacements between the panel and the frame.

Lastly, the loading protocol consisted on the application of half-cyclic OOP displacements (loading-unloading-reloading) 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 mm; and so on 5 by 5 mm until a maximum OOP displacement of 120 mm. Two half-cycles were repeated for each lateral displacement level at the control node to evaluate the OOP strength degradation.

(a)



(b)

Figure 4. Test setup view (a) and instruments location on the wall (W), on the column (C) on the top beam (BT) and bottom beam (BB) (b).

3 EXPERIMENTAL FINDINGS

In this Section, the global responses in terms of OOP load (F_{OOP}) versus OOP displacement in the centre of the infill panel ($d_{OOP,center}$) are shown, together with the final damage state of the investigated specimens.

3.1 AB-OOP

The initial (secant) stiffness of this response – calculated as the ratio between F_{OOP} and $d_{OOP,center}$ 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 2.5 mm, at $F_{OOP,cr}$= 21.81 kN (see Figure 5). At this stage, a horizontal crack along a mortar bed joint occurred in the middle of the panel. The secant stiffness related to this first cracking is thus slightly lower than the initial one, and, in particular, equal to 8.72 kN/mm.

The 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 was reached. 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. The maximum OOP load corresponding to this stage was equal to $F_{OOP,max}$= 52.68 kN at $d_{OOP,center,max}$= 39.55 mm. The corresponding secant stiffness thus reduced to 1.33 kN/mm.

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

3.2 R1-OOP

For this specimen, the initial (secant) stiffness of the response – calculated as explained for the previous test – 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, mainly due 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 3.6 mm, at $F_{OOP,cr}$= 70.47 kN (see Figure 5). At this stage, hairline horizontal and vertical cracks appeared in the middle of the panel. The secant stiffness related to this first cracking thus reduced to 19.58 kN/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. The maximum OOP load corresponding to this stage was equal to $F_{OOP,max}$= 95.95 kN at $d_{OOP,center,max}$= 15.00 mm. At peak load, a significant detachment from the top beam was measured.

From the achievement of the peak load to the end of the test, there were the progressive widening of the central cracks, the detachment of the reinforcing plaster from the top part of the frame, and a pronounced slippage of the plastic connectors from the top beam and from the lateral columns. Figure 6b shows the end of this test.

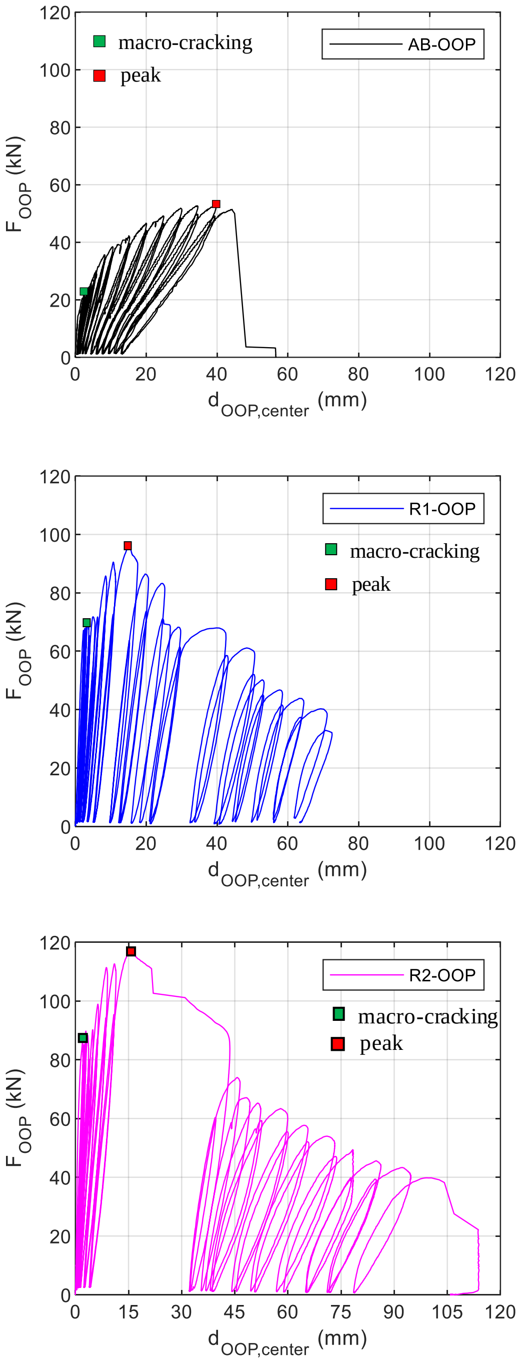
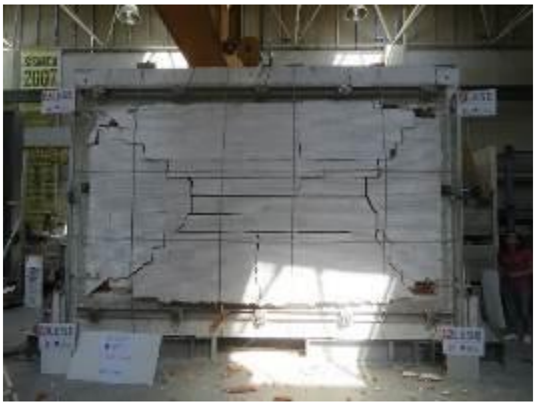


Figure 5. Out-of-plane force-central displacement responses of the tested specimens.

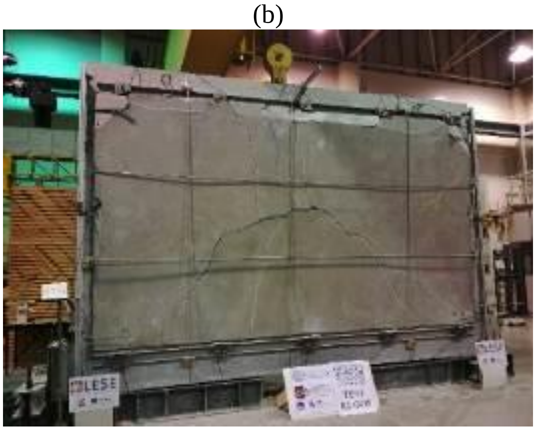
3.3 *R2-OOP*

For this test, the initial secant stiffness is equal to $k_{OOP,sec,in}$= 34.85 kN/mm, namely slightly higher than the $k_{OOP,sec,in}$ related to specimen R1-OOP, likely due to the more effective degree of connection between the retrofitting plaster on the panel and the frame.



(a)

(b)



(c)

Figure 6. Final damage states for AB-OOP (a), R1-OOP (b) and R2-OOP (c) specimens.

For increasing applied OOP displacement, a first visible (macro)-cracking was observed on the panel, at $F_{OOP,cr}$= 89.73 kN and $d_{OOP,center}$ equal to about 3 mm (see Figure 5). At this stage, a hairline horizontal crack appeared in the middle of the panel together with some smaller vertical cracks on the bottom.

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. The maximum OOP load corresponding to this stage was equal to $F_{OOP,max}$= 116.70 kN at $d_{OOP,center,max}$= 15.34 mm. 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 LVDTs), involving "monolithically" bricks and retrofitting plaster.

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 along the infill-bottom beam interface. The damage state at the end of this test, at $d_{OOP,center}$ equal to the infill wall thickness, is shown in Figure 6c. It is worth noting that, at the end of the test, the system "infill panel + retrofitting plaster" detached from the upper part, but it still remained 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, but the glass fibre net was locally cut around the connectors.

3.4 Comparisons

Figure 7 shows a comparison among the test results presented in the previous section in terms of F_{OOP}-$d_{OOP,center}$ envelopes (shown until the last first-cycle peak). Additionally, Table 2 provides a summary of the results reported in the previous sub-sections.

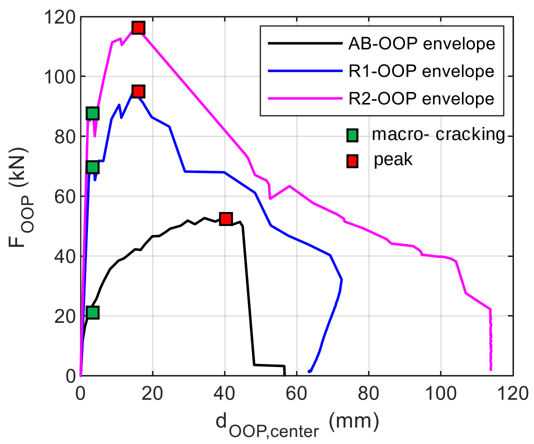


Figure 7. Comparison of the out-of-plane force-central displacement envelopes.

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 can be significantly important for typical code-based safety checks for the out-of-plane collapse of masonry infills, since they are generally carried out in terms of strength (e.g. CEN 2005; D.M. 2008).

Significant force increment are 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. 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 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 2 and they resulted 43%, on average, lower than the reference specimen. The corresponding "ductility" capacity ($\mu_{OOP,center,u,80\%}$), calculated as the ratio between $d_{OOP,center,u,80\%}$ and $d_{OOP,center,max}$, are 53% and 43% higher than the reference specimen AB-OOP, for specimens R1-OOP and R2-OOP, respectively.

Table 2. Summary of the main results.

	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 comparison among the test results can be carried out in terms of observed "failure mode". By comparing their failure mode, it can be pointed out that the most critical point of this kind of retrofitting strategy is the connection between the 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" "physically" collapse out of its plane for an OOP displacement higher than the infill thickness itself.

Nevertheless, to improve the displacement capacity of this retrofitting system, particular care should be still addressed 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 dealt with an experimental work performed in the Laboratory of Earthquake and Structural Engineering of the Civil Engineering Department of the University of Porto in co-operation 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 infills in existing RC buildings.

Three nominally identical full-scale one-bay-one-story RC frames were built and infilled with a 11 cm thickness masonry wall made up of hollow clay bricks. The first specimen was representative of the "as-built" condition. The remaining two specimens were strengthened to reduce their vulnerability to 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 strength capacity at first cracking significantly increases (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 displacement at peak load reduces in retrofitted infills by about 60%. Nevertheless, note that, for the retrofitted specimen with an effective plaster-to-frame connection, the wall physically collapsed out of its plane only for an applied OOP displacement in the centre of the panel higher than the infill thickness.

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

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