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Seismic retrofit of existing frame masonry infill walls by means of sliding joints

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Abstract

The seismic strengthening of existing reinforced concrete structures is a strategic subject in many countries. In Italy, in particular, a large stock of buildings was built from '50 to '70 of the nineteen-century without specific earthquake resistance requirements. Most of them have a reinforced concrete moment resisting frame structure infilled with masonry walls.

Recent earthquakes showed that the combined in-plane high stiffness and brittleness of the traditional masonry infills, non-engineered for a structural response, represents a threat to those building safety because of the infill frame interaction. Several buildings suffered local failure or total collapse triggered by soft story or shear column mechanisms induced by such interaction, worldwide. Therefore, a retrofit strategy has to consider the actual structural role of the masonry infills and, at the same time, prevent their out of plane failure that can jeopardize the integrity of the building and safety of the occupants.

A number of construction details and techniques have been proposed to improve the seismic performance of infilled RC moment resisting frames. Such techniques typically aim at preventing the structure's collapse during an earthquake by increasing the strength and stiffness of the infill and/or the frame. The increase of the seismic capacity of infilled frames with these techniques can modify substantially their dynamic behavior and eventually lead to brittle failures after their peak resistance is reached.

The existing infill significant stiffness complicates the strengthening of the building also when additional bracings systems (steel bracings or structural walls) are attached to the construction because they typically need to be very stiff, more than the existing structure, to limit the building deformation and avoid failure of the infills.

As an alternative, in this paper the retrofit approach proposed is based on the reduction of the infills' stiffness and on the increase of their ductility, in order to limit their interaction with the structural frame. According to recent research results, the masonry infills can be given a ductile and damage free in-plane behaviour thanks to the partitioning of the infill with sliding joints, which are capable to dramatically reduce the detrimental effects of the infill frame interaction. The detailing of such engineered infills for new structures has been presented elsewhere. This paper describes the application of the technique to a prototype existing infill.

The prototype intervention was applied to a typical wall of the above recalled existing buildings. A specific detailing was necessary to ensure the desired in and out of plane performance of the infill. Cyclic quasi-static loading was applied both in and out of plane. The results of the test are discussed in terms of deformation capacity, damage levels at different drift and efficiency of the intervention technique.

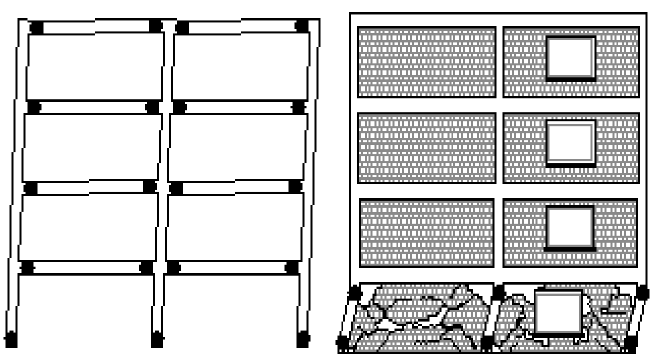
In order to reduce at the minimum the down time of a real structure, the retrofit intervention is designed to be carried out from the outer face of the wall limiting the interference with the ongoing activity inside the building.

Keywords: *seismic downgrade, damage control, existing masonry infill, vertical partitioning, out-of-plane strengthening.*

1. Introduction

In the last decades, many earthquakes around the world [1] [2] highlighted the seismic vulnerability of RC buildings, often due to an unfavorable interaction between the structure itself and the masonry infills. The most damaged were moment resisting frame buildings, built from ’50 to ’70 of the nineteen-century without specific earthquake resistance requirements. In those buildings, as still widely used nowadays, running bond masonry walls were typically built to infill the bare RC frame because of their efficiency in terms of construction ease, internal climate control and low building costs. Following this technique, the masonry infills were built as solid elements in contact to the surrounding frame, adopting stiff and brittle materials (typically fired clay or concrete blocks with cementitious mortar joints) and providing a significant increase of the structure strength and stiffness. The uncertainties connected to the masonry mechanical properties, to its construction process and contact conditions with the frame lead to a hardly predictable infill in- and out-of-plane seismic response [3] [4]. Such uncertainty in addition to possible irregular infill distribution in the structure, jeopardizes the building safety and resilience. In fact, the widespread damage observed in such infills during the earthquakes turned out, in most cases, to be also the reason of local or global structural damage and collapse (soft storey mechanism, columns shear collapses, widespread cracking, etc...). Moreover, the damage suffered by the infills during earthquakes and their often unreliable constraint to the surrounding frame jeopardizes their out of plane stability, as well, favoring their overturning collapse, which is a threat to the safety of the building inhabitants.
All these aspects highlight the influence of the poor seismic infill performance on the cost and duration of the reconstruction process and activity recover [5] [6], even after moderate intensity earthquakes [7].

Despite the possible detrimental effects of the infill-frame interaction, the post-earthquake damage survey showed also in some cases their contribution in preventing the collapse of poorly detailed buildings, not designed to withstand seismic actions; but this contribution is uncertain due to the possible activation of undesired collapse mechanism in the structure.



(a) modification of the frame collapse mechanism produced by the infill-frame interaction

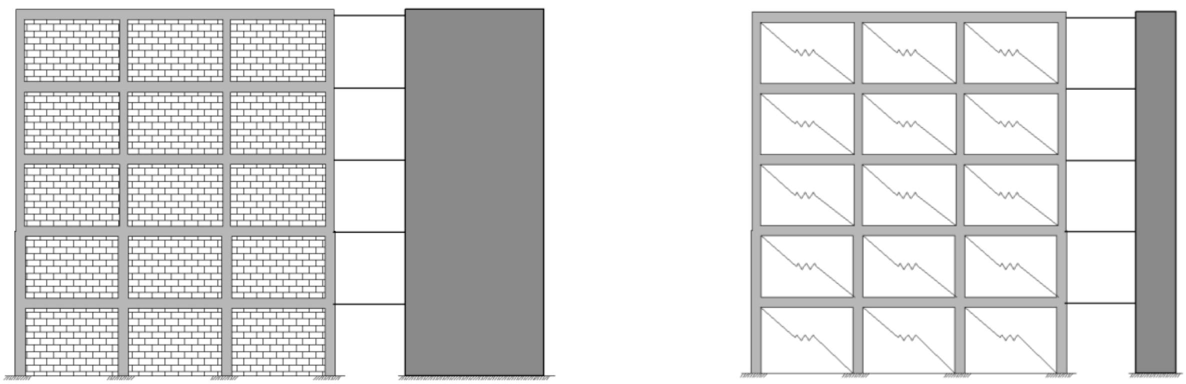
(b) damage suffered by a traditionally constructed infill wall during 2009 L’Aquila earthquake

(c) building global collapse caused by th infill-frame interaction during 2009 L’Aquila earthquake

(d) out-of-plane infill overturning during 2009 L’Aquila earthquake

Fig. 1 Collapse mechanisms connected to the infill in-plane and out-of-plane seismic behaviour.

In order to mitigate the masonry infill vulnerability many authors proposed retrofit solutions consisting in the application of reinforced mortar plaster to the infills, aiming at limiting their damage ([4] [8] [9] [10]). Although such overlays can increase the strength and ductility of the existing infills, they also increase its seismic mass and may not solve the risk of a detrimental infill frame interaction.An alternative approach presented in literature ([11] [12] [13] [14] [15] [16] [17]) consists in limiting the infill-frame interaction during the in-plane excitation by creating deformable infill walls, capable to follow the frame deformation and survive moderate to intense earthquake without damage. Following this approach the downgrade of the role of the infills in the seismic response is pursued. As a consequence, the reduced effect of infills can be ideally ignored and the sections of the bracing system can proportioned to stiffen a more flexible existing structure, and no deformation limitation is imposed by the infill damage control [18] (Fig. 2).



(a) traditional solid masonry infill (b) deformable infill

Fig. 2. Reduction of the additional bracing system size and stiffness for the retrofit of existing RC building, allowed by the downgrade of the infills.

This paper describes the set-up and testing of an innovative infill retrofit technique, which, following this second approach, aims at limiting the infill-frame interaction providing a deformable and predictable in-plane response to the infill, coupled with a stable and reliable out-of-plane performance. The proposed technique stems from the research work carried out by Preti et al. [12] [19] who obtained a deformable in-plane response for the infill, without damage, by partitioning the infill into masonry sub-panels free to relatively slide along horizontal planks embedded in some mortar layers. The infill out-of-plane stability was ensured by the sub-panel connection to the frame columns. However, a parametric study on the performance of this technique [20] [21] highlighted a significant shear demand on the frame columns, due to the concentrated frame-infill contact forces located at the masonry sub-portions corners, which could jeopardize the integrity of the frame columns or the side elements of a possible opening (window or door). In new structures, adequately detailed columns can support such shear action, on the other hand, in existing buildings a reduced shear demand is strategic in order to prevent the columns shear failure, so avoiding the need for their strengthening.

The here presented solution, maintaining the positive aspects of the previous technique, aims at reducing the shear transferred by the infill to the bounding elements by partitioning the infill in the vertical instead of the horizontal direction thanks to the introduction of planks (or equivalent beams), restrained to the frame beams, in this case designed as of out-of-plane retaining elements. The choice of the new configuration is further justified by impracticality of the introduction of horizontal partitioning elements in existing infills without their demolition and reconstruction. On the contrary the new proposed technique allows the possible insertion of the sliding elements in vertical cuts operated in the masonry, making possible their preservation and the consequent saving in terms of material disposal. The retrofit can be operated from the infill outside, limiting the building downtime. This new technique facilitates also the introduction of openings in the infill, exploiting the introduced vertical elements as posts for windows or doors (Fig. 3).

The results of in-plane and out-of-plane quasi static cyclic tests on an existing infill retrofitted with the proposed solution are reported, together with an example of proportioning and the description of the application of the technique.

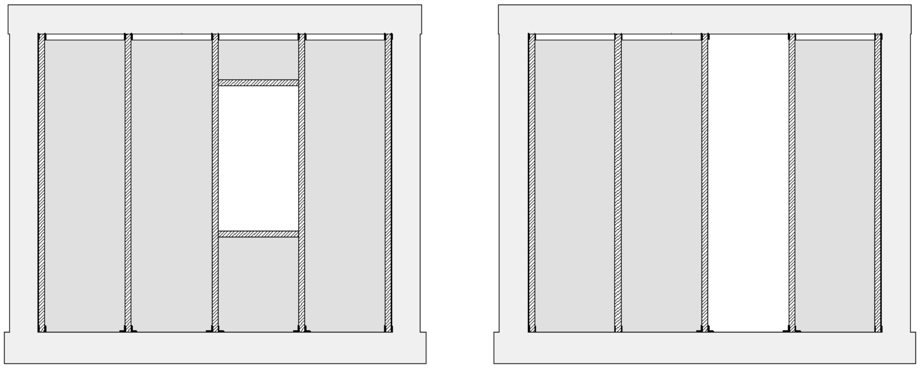


Fig. 3. Introduction of openings in the infill retrofitted with vertical elements.

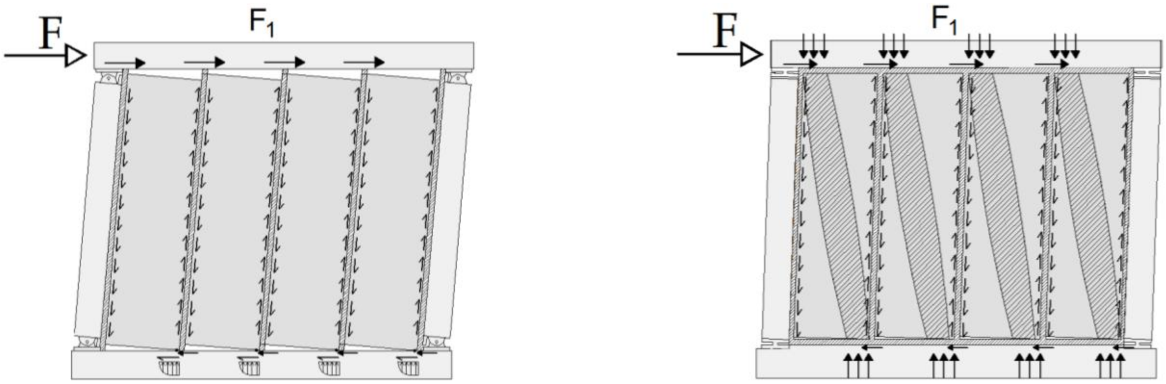
2. Retrofit technique

The proposed retrofit technique consists in partitioning the infill wall by means of the introduction of vertical elements in the masonry thickness, connected to the frame beams, working as sliding joints and retaining elements for out-of-plane actions. Such vertical elements are also located in between the infill and the columns and a gap is created between the frame top beam and the resulting infill sub-portions. Such infill configuration can be easily obtained in new infills with the aim of limiting their stiffness and damage as reported in [22]. In an existing infill the introduction of the joints is performed after the execution of vertical cuts in the masonry. In a real application, at the end of the procedure, the gaps are sealed with soft material (for thermal and acoustic performance) and the infill is covered with a facing layer.

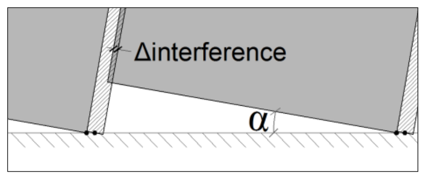
2.1. In-plane mechanism

The introduced vertical elements and the gap created between the infill and the frame beam imposes an in-plane deformation mechanism characterized by the alternate rigid rotation (rocking) of the masonry sub-panels around their toes, associated to the relative masonry sub-panels sliding along the vertical planks (Fig. 4a). The infill in-plane resisting stress is transferred from the infill to the surrounding frame through the connections of the vertical planks to frame beams. At the end of the insertion, a little gap (about 3 millimeters) remained between the lateral vertical planks and the columns; therefore no overload applies on the columns. The lateral gap is also beneficial in mitigating the interference between the linear deformation of the infill and the deformed profile of the columns under bending in a moment resisting frame. In this configuration, the presence of the top gap allows the masonry sub-panel uplift, providing a limited in-plane resistance to the infill in-plane deformation (Fig. 4a). On the contrary, lacking the gap, the uplift is impeded therefore compressed struts creates in the sub-panels, increasing the infill in-plane strength and stiffness (Fig. 4b).

The friction activated by the relative sliding of the sub-panels plays the main role in the in-plane resisting mechanism and it depends on the geometric interference between the rotations of the sub-panels and the vertical planks (Fig. 4c). This interference increases the normal action along the sliding surfaces, producing an increased friction resistance. However, the reported experimental results on the tested prototype shows that the small gaps produced by the material shrinkage (in the order of decimals of millimeters) are sufficient to limit the friction contribution to the infill overall resistance.



(a) with top gap (c) without top gap

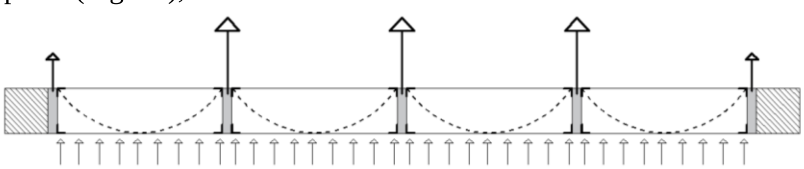


(c) ideal uplifting of the sub-panel and interference with the planks during the in-plane mechanism [22]

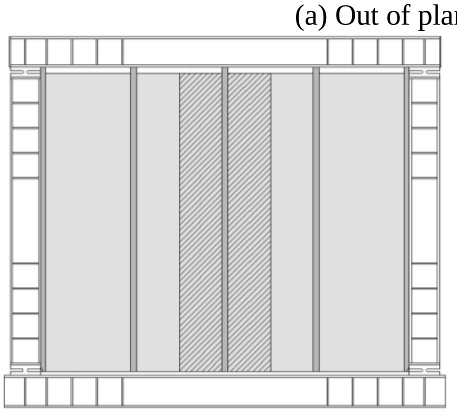
Fig. 4. In plane static scheme in the infill with vertical panels.

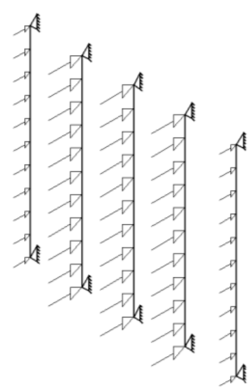
2.2. Out-of-plane mechanism

Considering the infill out-of-plane behavior, the presence of the gap between the infill and the top frame beam nullifies the possible development of a vertical arching mechanism in the masonry thickness. However, the introduction of the vertical planks ensures the infill out-of-plane stability, acting as simply supported elements on the frame beams (Fig. 5c). Thanks to an adequately shaped vertical elements section, the seismic action on each masonry sub-portions is transferred to the adjacent planks through a beam or arching mechanism in the sub-panel thickness (Fig. 5a), therefore, under this static scheme, the central planks tributary seismic mass corresponds to one subpanel (Fig. 5b), while is halved for the lateral ones.



(a) Out of plane mechanism (section)





(b) Tributary mass of the vertical planks (c) Out-of-plane actions on the vertical planks

Fig. 5. In plane (a) and out of plane (b, c) static scheme in the infill with vertical panels.

3. Specimen description

The proposed construction technique has been applied to a previously constructed infill (Fig. 6a) built with 25x25x12cm hollow fired clay blocks (voids ratio 65%) (Fig. 6b), disposed with the holes in the horizontal direction, and bed and head mortar layers. Afterwards the infill has been covered with a 1.5cm plaster on one side. The mechanical properties of the masonry prisms built with the same materials are reported in Table 1. The infill wall has been built inside the steel frame of Fig. 7 equipped with hinges at the columns ends which provide a negligible in-plane stiffness.

In order to partition the infill, several cuts have been made in the masonry (Fig. 6c) by means of a saw and, after the insertion of the vertical planks (Fig. 6d) and their connection to the frame beams, the infill continuity has been restored by means of cement grout injected into the cavity between the infill sub-panels and the introduced vertical elements (Fig. 6e).

Table 1. Average mechanical properties of the infill materials

	Compressive Strength [MPa]	Elastic Modulus [MPa]
Masonry prisms:		
-holes parallel to the load	4.57	8321.5
-holes perpend. to the load	2.15	2520
Mortar	7.68	6129
Cement grout for injection	41.82	14752
Wood perpend. to the grain	3.06	264
Wood parallel to the grain	34.63	3333

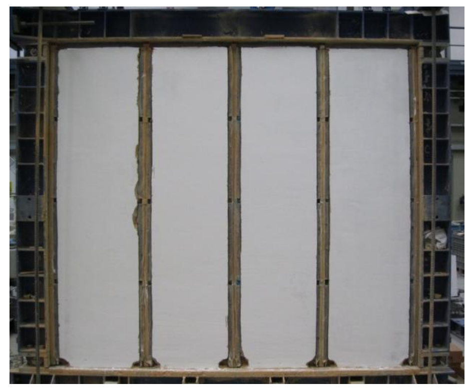
(a) solid existing infill

(b) block adopted for the infill construction

(c) phase 2: infill cut operation

(d) insertion of the vertical joints [22]

(e) mortar injection between sub-panel and vertical planks



(f) downgraded infill before testing [22]

Fig. 6. Procedure for the insertion of the vertical joints in the existing infill.

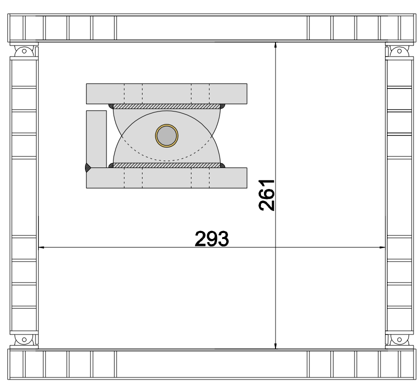
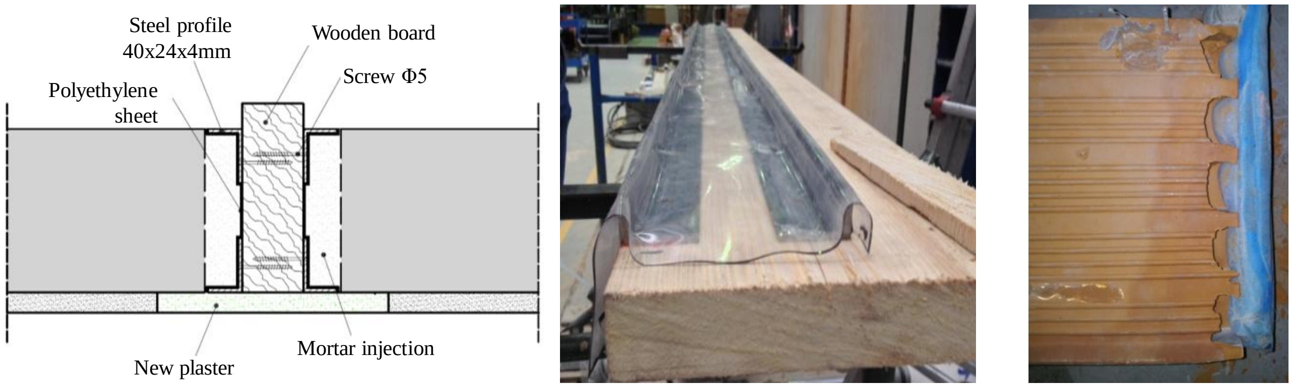


Fig. 7. Steel frame adopted in the tests with detail of the mechanical hinge at the column ends.

The vertical elements (Fig. 8a and b) consisted of wooden board with four “L” shaped steel profiles screwed to the plank in order to both act as “shear keys” for the out-of-plane actions transfer and create a formwork for the grout injection. In the hypothesis of adopting a 4cm thick wooden boards, staying in the infill thickness (12 cm), the plank section was proportioned for the bending moment generated by an ideal uniformly distributed out-of-plane action, generated by a severe design seismic acceleration equal to 4g and an infill density of 670kg/m^3. In the tested prototype, an oversized 4x20cm planks have been adopted for experimental ease, producing a stiffer response if compared to that that would be obtained with the board in the masonry thickness, as focus was made on the verification of the efficiency connections and masonry response better than the wooden board possible collapse.

In order to avoid the cohesion between the vertical element and the injected material and reduce the friction coefficient a polyethylene sheet has been placed on the planks surface. To limit the free flow of the injected grout through the blocks holes an elastic fabric has been introduced between the plank and the masonry. The deformability of the adopted fabric allowed the interlock between the masonry sub-portions and the injected grout (Fig. 8c), ensuring the out-of-plane indentation of the infill to the vertical planks.



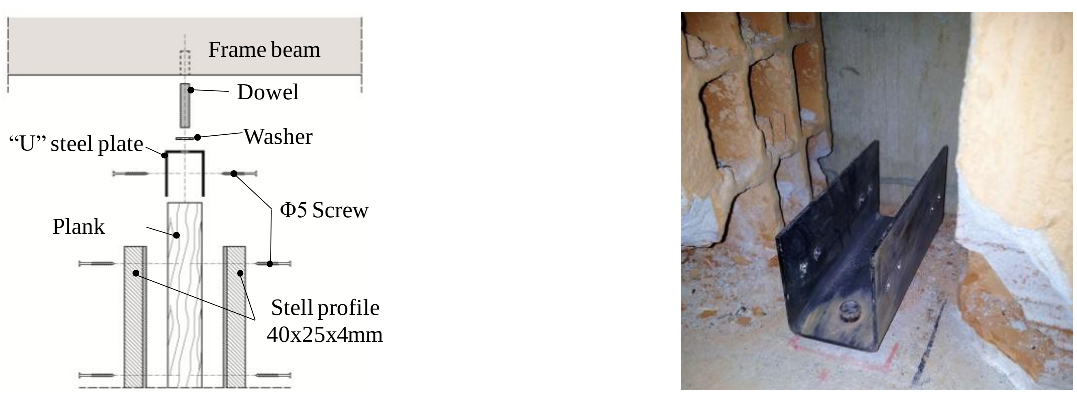
(a) scheme of the horizontal section of the vertical joints in the infill [22]

(b) picture of the vertical plank before the insertion in the infill

(c) interlock between masonry and injected grout [22]

Fig. 8. Details of the vertical planks.

The vertical planks are connected to the frame by means of "U" shaped steel plates dowelled to the upper and lower beam (Fig. 9c and d). After the insertion, the planks are screwed to the steel profile to transfer the out-of-plane stresses. To this aim, the steel elements and all the connectors are proportioned and verified to resist a shear action at each vertical plank end equal to 5.04kN, according to the static scheme of Fig. 5 and the design formulation of Eurocode 5. In order to ensure a certain degree of rotational deformability of the connection both in- and out-of-plane, a steel washer was inserted on the dowel, between the beam and the "U" steel plate.



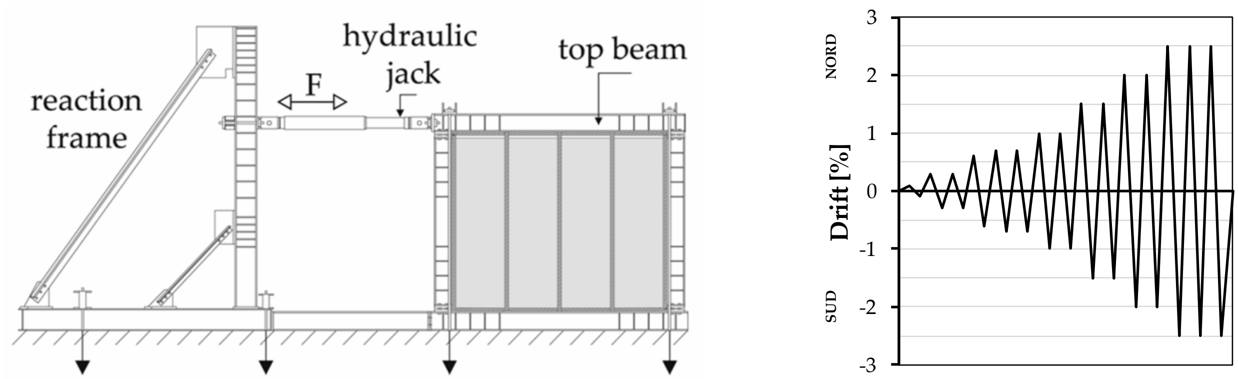
(a) exploded view of the plank-beam connection [21]

(b) U shaped plate dowelled to the upper beam

Fig. 9. Details of the vertical plank to frame beam connection.

4. Test set-up and results

The infill prototype has been tested in-plane under quasi static cyclic actions applied to the steel frame by means of an hydraulic jack hinged to the top frame beam and to a stiff reaction frame (Fig. 10a). The test has been performed imposing increasing drift values up to a 2.5% maximum (Fig. 10b) and during the test several gauges monitored the specimen inter-storey drift, the load applied by the jack, the relative sub-panels vertical sliding and their uplifting.

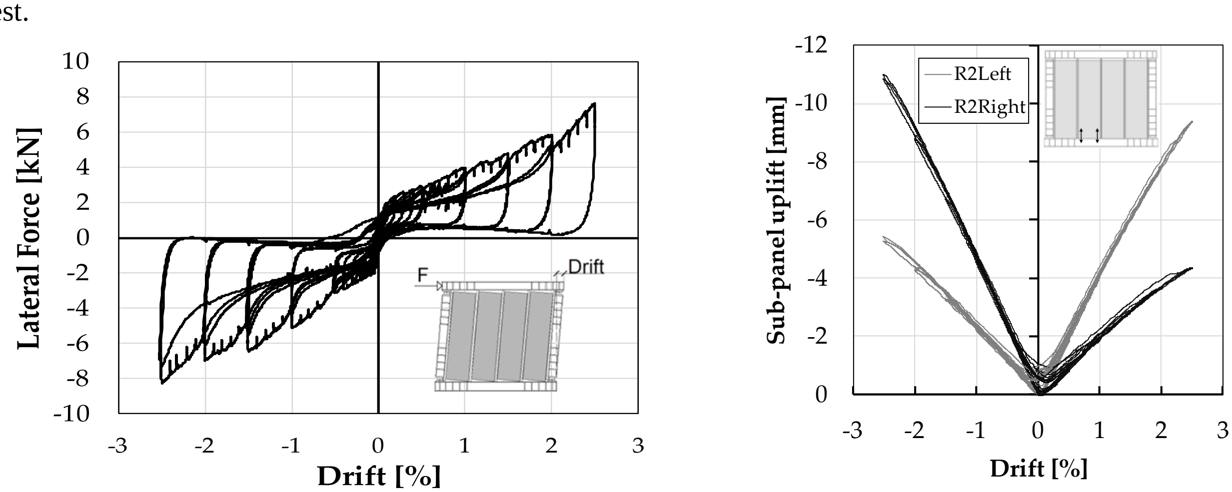


(a) (b)

Fig. 10. Set-up (a) and loading protocol (b) for the in-plane test.

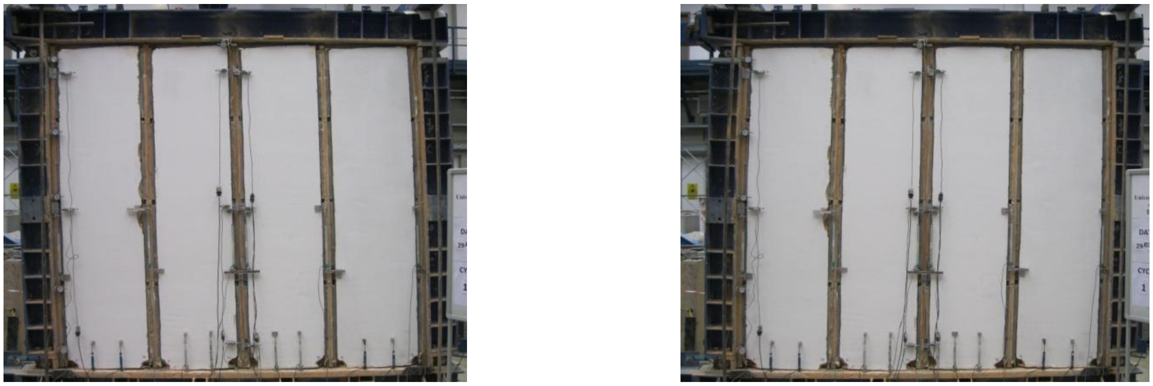
The obtained lateral force-vs.-drift curve, reported in Fig. 11a, shows a symmetric and ductile behavior for the infill, characterized by low values of stiffness and resistance. Reloading cycles showed a certain stiffness and strength degradation, probably due to degradation of the sliding resistance along the vertical boards-masonry interfaces. It is worth noting that the sliding mechanism of the infill sub-panels along the vertical planks governs the infill in-plane resistance, since the net calculated contribution of the rocking mechanism is lower than 1kN.

At the end of test, no damage was observed in the infill (Fig. 11b and c), highlighting the efficiency of the proposed technique in protecting the infill from damage and ensure a nearly negligible in-plane resistance (lower than 10kN). Regarding the masonry sub-panel toes, note that the disruption is the result of the necessary local demolition for the insertion of the vertical planks in the construction phase, which was not restored before the test.



(a) lateral force-vs.-drift curve [22]

(b) uplift measure in one of the central sub-panels



(b) deformed at -2.5% (d) deformed at 2.5% drift

Fig. 11. Results of the in-plane test.

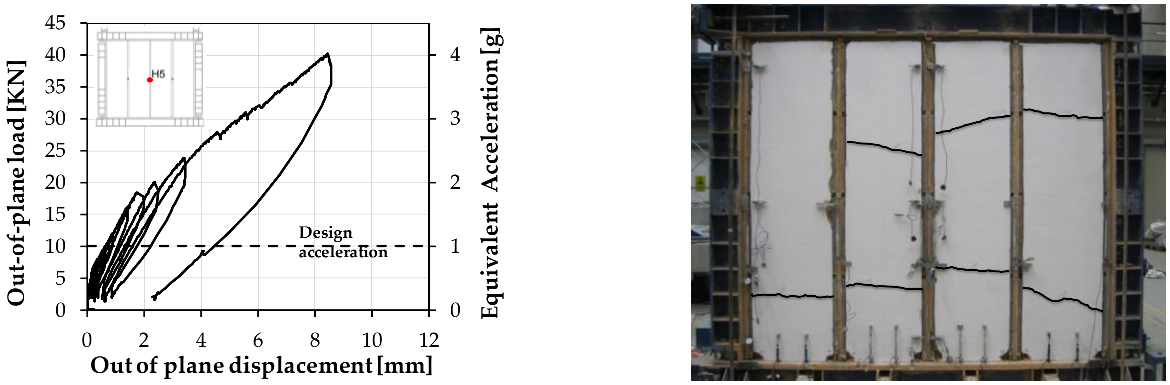
In a following experimental phase, the infill has been tested out-of-plane by applying eight equal concentrated loads (two on each infill sub-panel) in order to reproduce the maximum bending moment that the vertical planks would experience in case of an ideal uniformly distributed out-of-plane load on the infill (Fig. 12a). This loading condition has been obtained by means of the loading system showed in Fig. 12b which distributed a concentrated load, applied by means of an hydraulic jack, to the masonry sub-portions through a system of three levels of statically determined beams, each of them transferring the load from the center to the symmetric pinned-end supports. The jack acts on a reaction beam, connected to the steel frame columns to obtain a self-balanced system.

The test has been performed applying a progressively increased mono-directional load, up to a 40 kN maximum value, equivalent to a 4g horizontal acceleration (considering that the total retrofitted infill mass is estimated equal to 1027kg). During the test, the out-of-plane relative infill-frame displacement has been monitored by means of gauges lined up at the infill mid-height and along the vertical axis of planks and masonry sub-panels.

The results of the out-of-plane test (Fig. 13) highlighted a significant resistance of the infill, bearing the maximum applied load equal without losing its stability. Fig. 13a reports the load vs. out-of-plane maximum displacement in the central plank, which shows a progressive stiffness reduction increasing the load. This reduction of the stiffness was directly connected to the progressive triggering of cracks in the masonry sub-panels described in Fig. 13b, produced by the cylindrical infill deformation, governed by the vertical planks out-of-plane deflection. The development of horizontal cracks did not produce a strength degradation, as the resistance is ensured by horizontal arching in between the vertical bearing boards. At the load equivalent to 4g the test was stopped without reaching a possible failure of the loading system.

(a) experimental vs. ideal moment profile on the central vertical planks (b) load application system

Fig. 12. Out-of-plane test set-up [22].



(a) out-of-plane load-vs.-displacement

(b) crack pattern in the infill sub-panels at the end of the test

Fig. 13. Out-of-plane test results.

5. Conclusions

The efficiency of an innovative construction technique for the seismic retrofit of existing masonry infill, based on the wall partitioning into vertical sub-portions, was experimentally explored by means of in- and out-of plane tests on an infill prototype.

The operational execution for the introduction of the vertical planks in the existing infill, acting both as partition and out-of-plane retaining elements, reveled to be achievable and relatively easy, providing a good seismic response to the infill wall during the performed quasi static tests. The proposed technique, consisting in an intervention from one side of the infill only, allows the reduction of the interference of the retrofit process with the internal building activity and easily complies with the presence of openings. Moreover, the maintenance of the previously existing masonry wall reduces the material disposal, according to the sustainability requirements more and more targeted nowadays.

Considering the obtained experimental response for the retrofitted specimen, a significant downgrade of the infill in-plane reaction inside the frame was obtained, practically nullifying the interaction with the frame and the masonry damage. The intervention showed to be particularly efficient also for the infill out-of-plane resistance, allowing the specimen to sustain a transverse load equivalent to a 4g acceleration thanks to the connection of the vertical planks to the frame beams and the absence of damage experienced during the previous in-plane excitation.

Further than the beneficial effect in terms of post-earthquake damage limitation, the infill downgrade obtained with the proposed technique would also simplify the evaluation of the building seismic response, if compared to the high uncertainties connected to the presence of traditionally constructed infill walls. The reduced infill-frame interaction allows the designer to analyze, in a first step, the structure as a simplified bare frame, then providing few adjustment to take into account the limited infill contribution.

6. Acknowledgements

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