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# EXPERIMENTAL TESTS OF AN ENGINEERED SEISMIC SOLUTION OF MASONRY INFILLS WITH SLIDING JOINTS

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## *Abstract*

Within the European FP7 Project "INSYSME", the research unit of the University of Pavia has conceived a new seismic resistant clay masonry infill system with the purpose of controlling damage in the masonry and reducing detrimental effects of the panel-frame interaction, through a combined use of sliding joints inserted in the masonry and deformable joints at the wall-frame interface. The idea behind the proposed solution stems from principles already implemented in the past, in particular with reference to work by Mohammadi *et al.* [1] and Preti *et al.* [2]. The originality of this solution stays both in the adoption of different and innovative materials for the implementation of the flexible and sliding joints and in the experimental test and specimen types. An extensive experimental campaign has been performed, constituted by in-plane cyclic tests on one-storey one-bay full scale RC bare frame and on two different configurations of infilled frames (one full and one with a central opening) followed by out-of-plane shaking-table dynamic tests; a shaking-table dynamic test on a full scale two storey building has also been performed. The seismic tests on the substructures and on the building have been supplemented with tests of characterization on single materials and masonry. In this paper, besides the main characteristics of the proposed system, the most significant results of the mechanical characterization and of the in-plane cyclic tests on the RC bare, on the fully and on the partially infilled frames are reported and discussed. A comparison in terms of the experimental seismic performance between the engineered solution and a traditional infill is also performed, showing a strong reduction of the level of damage, both at moderate/low and at large deformation demand for the latter as respect to the former system, on the infill both with and without opening. The in-plane test results prove the ability of the proposed solution of limiting the level of damage at different seismic intensity, providing a prominent reduction of the cost of reparability after seismic events and a wide margin towards the life safety requirements. Although design and construction optimization of the system needs to be implemented, above all in the case of short infill panels and of walls with opening, the results of the in-plane tests appear very promising about the use of this solution as an efficient seismic resistant non-structural element in RC buildings.

*Keywords: clay masonry infill; innovative seismic resistant solution; sliding joints; experimental tests; in-plane response.*

## 1. Introduction

“Traditional” masonry infill construction solutions, where the panels are built in complete contact with the surrounding RC frame without provision of any gap or connection around the boundaries and after the hardening of the RC members, have evinced a series of critical aspects related to in-plane and out-of-plane seismic response, often observed both in the post-seismic surveys (i.e., Manzini and Morandi [3], Braga *et al.* [4]) and in the experimental outcomes (i.e., Calvi and Bolognini [5], Guidi *et al.* [6], Morandi *et al.* [7]). For example, with the support of the field experiences reported after damaging earthquakes in recent years (such as in L’Aquila 2009 and in Emilia 2012) widely spread damage to non-structural elements, in particular to masonry infills and internal partitions included in RC buildings, has been identified both with cases of in-plane failures and of out-of-plane collapses/expulsions of single leaf panels and/or external veneers in double leaf panels. This could be in part related to the intrinsic vulnerability of unreinforced masonry infills, in part to the use of bad quality material and construction details, in part even due to insufficient and unclear information in the current codes for seismic design of infilled buildings. Moreover, results from experimental tests have also shown possible large and uncontrolled levels of damage for in-plane actions already at low drift demand and limited values of resistance to out-of-plane actions, above all when slender/weak masonry infills are subjected to previous in-plane damage (i.e., Calvi and Bolognini [5]); local detrimental effects on RC members due to the thrust of diagonal strut activated during in-plane deformations could also occur and be particularly critical in the case of strong/thick masonry infills (as reported in Guidi *et al.* [6] and Morandi *et al.* [7]) which, moreover, are becoming more and more commonly used thanks to their good thermal and acoustic properties.

Although a series of researches oriented towards possible novel systems have been recently carried out in order to solve, or at least to limit the aforementioned critical issues (see Morandi *et al.* [8]), a widely recognized solution, which reduces in-plane/out-of-plane seismic vulnerability of masonry infills guarantying, at the same time, a sufficient thermic, acoustic and durability performance, has not been achieved yet.

In this regard, an European FP7 research project, called “INSYSME” [9], has been launched in October 2013 with the aim of developing innovative seismic masonry infill solutions and improving the current design criteria. Within this project the research unit of the University of Pavia, which is one of the scientific partners, has conceived and realized a clay masonry infill system with the purpose of controlling the damage in the masonry and reducing the adverse panel-frame interaction, through a combined use of proper sliding joints inserted in the clay masonry and deformable joints at the wall-frame interface. The idea behind this solution stems from principles already implemented in the recent past, with reference to systems proposed by Mohammadi *et al.* [1] and Preti *et al.* [2], adopting however different materials for the implementation of the flexible and sliding joints, and experimenting it on full scale reinforced concrete frames also resorting to dynamic shaking table tests. The developed system, for which a request of an Italian and a European patent has been submitted, lends to be used both for newly designed RC buildings and for the replacement (demolition and subsequent reconstruction) of masonry infills in existing constructions as solution capable of improving the seismic performance. In particular, the materials and the constructive details have been designed in order to ensure good thermal and acoustic insulation properties as well as durability and environmental sustainability. Moreover, a strong reduction of the repairing costs after seismic events compared to “non-engineered” masonry infills is another of the main objectives to be achieved for this system.

After the constructive implementation of the system, an extensive experimental campaign has been set through the execution of in-plane cyclic tests on full scale one bay-one story RC frames bare and infilled with the innovative solution, with and without opening; the in-plane tests on the infilled specimens have been followed by out-of-plane dynamic tests on shaking table. In addition, a shaking table dynamic test on a real scale two-story RC building infilled with the proposed solutions has been carried out. In support of the seismic tests, a complete characterization of the materials has been performed. The last phase of the research includes a numerical study on different configurations of simple RC frames infilled with the new solution, in order to optimize the elements of the system and provide guidelines for the seismic design and construction.

Besides the description of main features of the new infill, this paper deals with the available results on the tests of characterization and on the in-plane cyclic tests on the innovative infill substructures with and without opening. A comparison in terms of experimental seismic performance between the engineered and a non-engineered “traditional” infill solution concludes this work.

# 2. Features of the proposed innovative infill solution

## 2.1 Principles and construction details

The proposed engineered system aims to control the damage propagation in the masonry infill and to reduce the in-plane interaction between the RC frame and the panel, dividing the infill into four horizontal strips, able to slide one on each other through properly conformed sliding joints. Moreover, a deformable joint located at the frame/infill interfaces has the objective to reduce the local effects and the stress concentration in the proximity of the interface between the masonry panel and the RC elements. The layout of the system is reported in Fig. 1a.

The innovative infill aims to guarantee a sufficient displacement capacity without the creation of a single strut, which is instead common in traditional infill solutions. The combined use of deformable joints at the infill-frame interface and sliding horizontal joints within the infill would guarantee a suitable deformation capacity and reduce both the damage in the masonry and the infill-structure interaction. Moreover, a significant reduction of the local shear demand on the ends of the columns adjacent to the infill due to the subdivision on more strips is expected. At global level, this system would also allow limiting the concentration of deformations/internal forces in one single storey of the building, reducing the risk of formation of "soft storey" and enable to reduce the negative effects of possible irregular distributions of infills in plan and in elevation. The out-of-plane stability is governed by the horizontal flexural resistance of the masonry strips and it is guaranteed by suitable designed "shear keys" attached to the column constituted by "omega" shaped steel profiles (S235 steel grade) connected to the RC columns by means of nails shot with a nail gun (Fig. 1e); the units at the edges of the infill adjacent to the columns and to the openings are shaped with a recess (C-shaped units, Fig. 1b) in order to accommodate the shear keys. The sliding joints (Fig. 1c), having a ribbed shape, allow obtaining a mechanical interlocking that, together with a specific high-tension strength plaster placed on both sides of the masonry, should ensure the out-of-plane stability of the panel. The functioning of the proposed infill system is described in more detail in a work by Morandi *et al.* [8].

The unreinforced masonry used in the strips of the infill is realized with vertically perforated lightweight clay units and general-purpose 1 cm thick mortar bed- and head-joints. The plain clay unit (Fig. 1d) has a thickness of 25 cm and a percentage of voids of 45%. A mortar of class M5 (nominal compression strength of 5 MPa) has been used in the head- and in bed-joints. A layer of fibre-reinforced plaster of about 2.0 cm has been placed in order to increase the out-of-plane flexural resistance of the masonry strips, without jeopardizing the sliding. The single horizontal sliding joint is made up by two plastic (nylon casted with molybdenum disulphide in order to reduce friction coefficient) corrugated male-female elements, which overlap one on the other (Fig. 1c) along the entire thickness of the wall. The infill-frame interface joint, realized with cementitious material, has been adequately studied in order to obtain a mixture that allows reducing the elastic modulus E in a range of values ranging between 100 and 150 MPa, while maintaining a value of flexural and compression strength similar to that of a traditional mortar for load-bearing masonry. The thickness of the infill-column joint has been set as 2.5 cm, whereas the thickness of the infill-beam joint set as 3.0 cm.

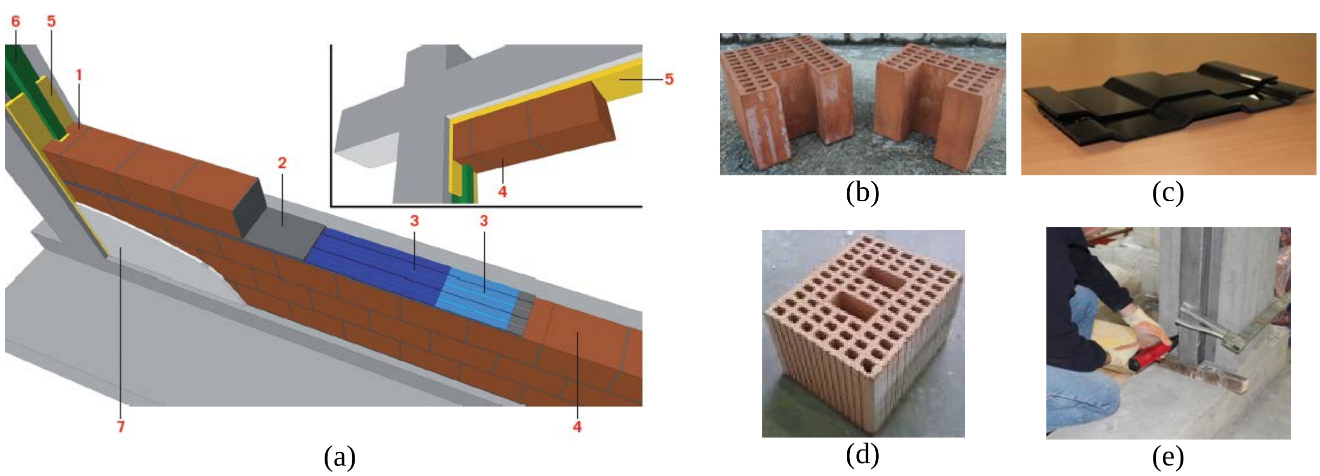



Fig. 1. – (a) Details of the innovative masonry infill with sliding joints: 1. (b) C-shape units; 2. mortar bed-joints; 3. (c) sliding joints; 4. (d) clay units; 5. interface joints; 6. (e) shear keys; 7. plaster.

## 2.2 Tests of characterization

In order to evaluate the mechanical properties of the elements of the infill system, a series of tests of characterization on single materials and on masonry specimens has been conducted, in accordance with European standards and codes. Compression strength on concrete, vertical and lateral compression strength on clay units have been carried out, along with a measure of the “local shear resistance” on the C-shaped units (shear/tensile resistance of the flange of the unit). Moreover, compression and flexural strength tests on mortars for masonry, plaster and infill/frame interface have been carried out; on the mortar for interface, the determination of the elastic modulus has also been performed. Finally, tests of vertical, lateral and diagonal compression and of flexural strength have been executed on masonry specimens with and without plaster (six samples for each test on masonry, three with and three without plaster). The references to the standards, the set-up, the loading history and the evaluation of the results of these tests have been discussed in more detail in Morandi *et al.* [10]; a summary of the main results (mean and coefficient of variation) on the single materials and on the masonry specimens has been reported in Table 1.

Table 1 – Summary of the tests of characterization on concrete, clay units, mortar and masonry specimens (mean values and coefficient of variation, C.o.v.).

| **Mechanical propetries** | **Symbol** | **Mean** | **C.o.v.** |
|---|---|---|---|
| Compr. strength on concrete cubes | $R_c$ | 31.7 MPa | 9.6% |
| Vertical norm. compr. strength on units | $f_{b,norm}$ | 21.2 MPa | 20.0% |
| Lateral norm. compr. strength on units | $f'_{b,norm}$ | 4.69 MPa | 13.7% |
| Tensile/shear stregth of “C”- shaped units | $R$ | 3.39 kN | 18.6% |
| Flexural strength of masonry mortar | $f_{fl}$ | 2.43 MPa | 17.9% |
| Compression strength of masonry mortar | $f_m$ | 7.24 MPa | 15.5% |
| Flexural strength of plaster mortar | $f_{fl,pl}$ | 6.65 MPa | 13.1% |
| Compression strength of plaster mortar | $f_{m,pl}$ | 27.3 MPa | 3.4% |
| Flexural strength of interface mortar | $f_{fl,int}$ | 2.00 MPa | 34.8% |
| Compression strength of interface mortar[1] | $f_{m,int}$ | - | - |
| Ealstic modulus of interface mortar[2] | $E_{m,int}$ | 101 MPa | 9.7% |
| Vertical compression strength of masonry[3] | $f_v$ | 6.83 - 7.02 MPa | 16.3 – 16.4% |
| Vertical elastic modulus of masonry[3] | $E_v$ | 9686 - 9920 MPa | 10.4 – 14.0% |
| Lateral compression strength of masonry[3] | $f_{lat}$ | 1.89 – 2.41 MPa | 10.6 – 17.8% |
| Lateral elastic modulus of masonry[3] | $E_{lat}$ | 2863 - 4597 MPa | 23.4 – 1.3% |
| Diagonal compression strength of masonry[3] | $f_t$ | 0.256 – 0.358 MPa | 17.4 – 16.8% |
| Shear modulus of masonry[3] | $G$ | 795 - 892 MPa | 18.4 – 22.5% |
| Flexural strength of masonry[3] | $f_{x2}$ | 0.308 – 0.397 MPa | 10.6 – 7.2% |

[1] The comrpession strength of the mortar infill/frame interface continued to increase up to very large deformation levels without the formation of a sharp failure of the specimen (values larger than 5 MPa have been found at strain levels larger than 70%), being the materil extremely flexible.
[2] The value of the modulus of elasticity of the mortar for interface has been evaluated as the secant value between a stress of 10% and of 33% of the stress calculated at 10% deformation.
[3] For these tests, the couple of values refers to masonry specimens without and with plaster, respectively.

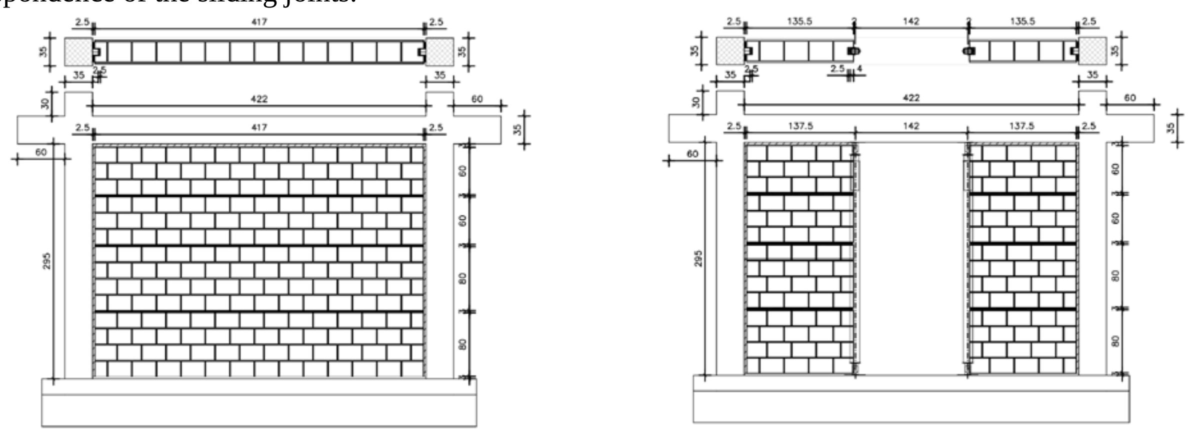
# 3. Experimental campaign on infilled frames

Within the framework of the experimental campaign, cyclic in-plane (“low-velocity” and “high-velocity”) tests have been carried out on fully and partially infilled (with a central opening) large-scale single-storey single-bay RC frames, designed according to the European and the Italian seismic code provisions. The in-plane “high velocity” test has been performed in order to investigate the response of the sliding joints subjected to dynamic actions.

## 3.1 Description of the specimens

The dimensions of the single-storey single-bay RC frame specimen to be tested have been chosen with the aim to realistically represent the part of a full-scale RC frame structure. Therefore, a clear span of 4.22 m and a clear height of 2.95 m have been adopted. The design of the RC frame specimen, described in detail by Morandi *et al.* [7], has been carried out following European code provisions (EC 8-Part 1 2004 [11]) supplemented with the Italian national code (NTC 2008 [12]).

The fully infilled specimen, called TSJ1, is shown in Fig. 2a and reports the innovative solution made up by the masonry infill subdivided in 4 horizontal strips. In Fig. 2b, the partially infilled frame, called TSJ2, is illustrated. The specimen possesses a central 1.42 m wide opening to the entire height and each of the two panels is subdivided in 4 horizontal strips and realized as for TSJ1; at the two sides of the opening two steel posts having in-plane hinges at their edges have been positioned before the realization of the masonry infill. The profile is a S355 steel rectangular tube 120x80 mm with thickness of 8 mm, whereas the upper part of the post, to be inserted in the underneath hollow profile to provide a telescopic behaviour and avoiding any flexural and axial action on the horizontal RC members, is a tube 100x60 mm with thickness of 6.3 mm. The two hinges are welded with a 4 mm thick steel plate connected to the foundation and to the beam trough nails shot with a nail gun. As for the connection with the “omega” shape profiled at the RC columns, between the steel profile of the opening and the C-shaped units a layer of 25 mm of special mortar has been placed. Both the infill walls are completed with 20 mm thick fibre-reinforced plaster on both faces of the infill, paying attention at the detail in correspondence of the sliding joints.



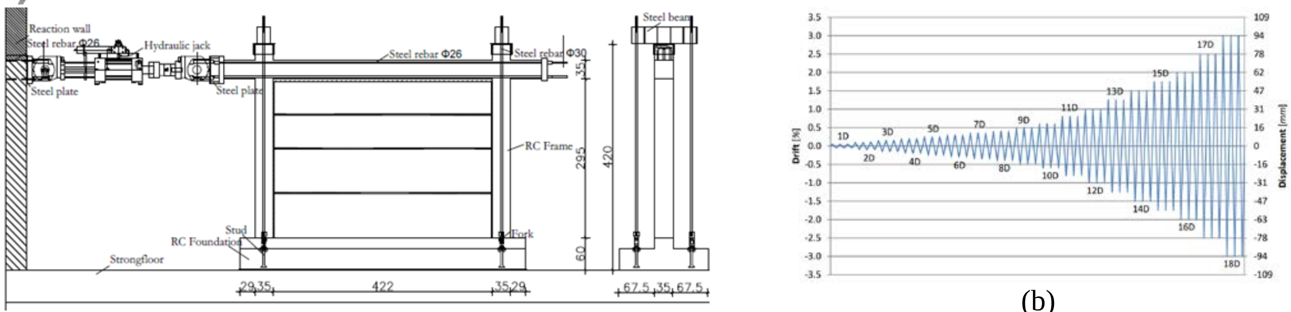

(a) (b)

Fig. 2 – Layout of the (a) fully infilled (TSJ1) and of the (b) partially infilled (TSJ2) RC frame specimens (represented without plaster).

## 3.2 Experimental set-up and testing protocols of the in-plane tests

The in-plane cyclic tests were carried out at the TREES lab of EUCENTRE and at the University of Pavia. A horizontal force has been applied on the beam of the RC frame by means of a servo-controlled hydraulic actuator with an internal load cell, transferring the reaction to a reaction wall. To transmit the horizontal force to the frame, a system of two steel plates and four prestressed rebars was applied, allowing the achievement of reverse loading cycles in both directions using a single actuator. The concentrated vertical load on the RC columns was applied by a rigid transversal steel beam tied down to the foundation with two prestressed steel bars, resulting in a self-equilibrated vertical load introduction system. The complete layout of the in-plane experimental setup is illustrated in Fig. 3a.

For the in-plane tests, after the application of a vertical load of 400 KN per column reverse cycles of horizontal in-plane loading (first pull, then push) have been imposed on the frame. In the case of pseudo-static tests displacement-controlled loading cycles at increasing levels of in-plane drift were imposed up to 3.00% drift. For each level of loading, three complete reverse loading cycles have been carried out and the duration of load application has been kept approximately constant. The test has been stopped at the end of each target level to estimate the response of the specimen and the damage propagation. Fig. 3b reports the in-plane testing protocol for test TSJ1 and TSJ2.



(a) (b)

Fig. 3 – (a) Layout of the in-plane setup for cyclic tests; (b) in-plane testing protocol for TSJ1 and TSJ2 ("low" velocity test).

The in-plane cyclic high-velocity test, carried out on specimen TSJ1 after the in-plane cyclic low-velocity test, has used the same setup and instrumentation of the pseudo-static test. The loading protocol has consisted in six parts, the first five subdivided at increasing displacement levels (from drift of 0.15% to 2.50%), whereas the last one at decreasing drifts (from 2.50% to 0.15%). The lateral displacements were applied with a sinusoidal law having frequencies depending from the target drift and repeating, for each level of loading, at least four complete reverse loading cycles. The velocity of application for each displacement has been properly selected in order to obtain frequencies similar to the ones that may occur during a seismic event, calibrated on the results of several dynamic non-linear analyses on a series of RC buildings with different infills configurations (Hak *et al.* [13]). The total duration of the last part of the test was of about 90 seconds to attain the peak drift (2.50%) and as much to get back to the minimum drift (0.15%).

In order to measure the displacements and deformations of the specimen during the in-plane test, displacement transducers (linear potentiometers) have been adopted. In total, 45 potentiometers have been used for TSJ1 and 58 for TSJ2. An optical acquisition system has also been installed to measure the in-plane displacements of optical markers on the RC frame and the masonry infill.

## 4. Experimental results on the innovative infilled frames

### 4.1 Force-displacement in-plane response and damage propagation

The results of the cyclic in-plane tests on the fully infilled frame TSJ1 ("low-" and "high-velocity") and on the partially infilled frame TSJ2 are shown in Fig. 4a, and b, in terms of force-displacement hysteretic curve and corresponding envelopes for each cycle. Fig. 4d reports a comparison between the force-displacement maximum envelopes of TSJ1, TSJ2 and of the RC bare frame (called TNT) carried out during a previous campaign (Morandi *et al.* [7]) and taken as reference for a proper evaluation of the infill contribution since it has the same characteristics of the RC frame of the infilled specimen. The test has attained a drift up to 3.50% with a testing protocol similar to the one described above; the F-D curve with the envelopes are reported in Fig. 4c.

The specimen TSJ1, previously subjected to in-plane "low-velocity" test (TSJ1_IPL), once subjected to "high-velocity" test (TSJ1_IPH), has provided a hysteretic response in accordance with the last loading cycles of the in-plane low-velocity test, with the hysteresis loops at the maximum imposed drift having nearly the same secant stiffness of the last cycle performed during the low-velocity test (see Fig. 4a).

As shown Fig. 4d, the stiffness and the maximum force of the infilled frames are obviously higher than those of the bare frame. Moreover, it can be noticed that, surprisingly, the maximum envelope of the cyclic F-D curve of the fully infilled frame is rather similar to that of the specimen with central opening, unless for slightly higher values of maximum force at imposed drifts larger than 1.00-1.50%, even if the central opening covers about 1/3 of the area of the full panel.

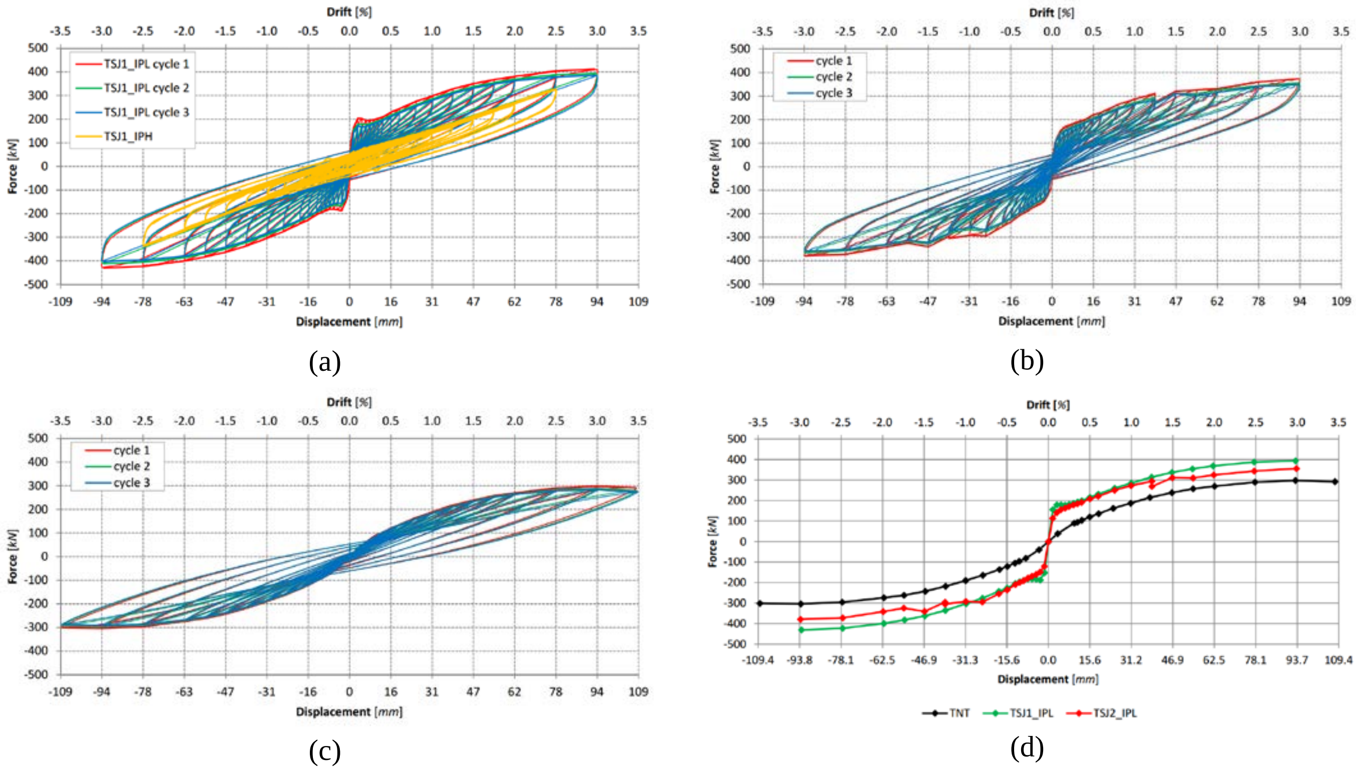



Fig. 4 – Force-displacement curves on (a) TSJ1 , (b) TSJ2, (c) TNT and (d) comparison of maximum envelopes.

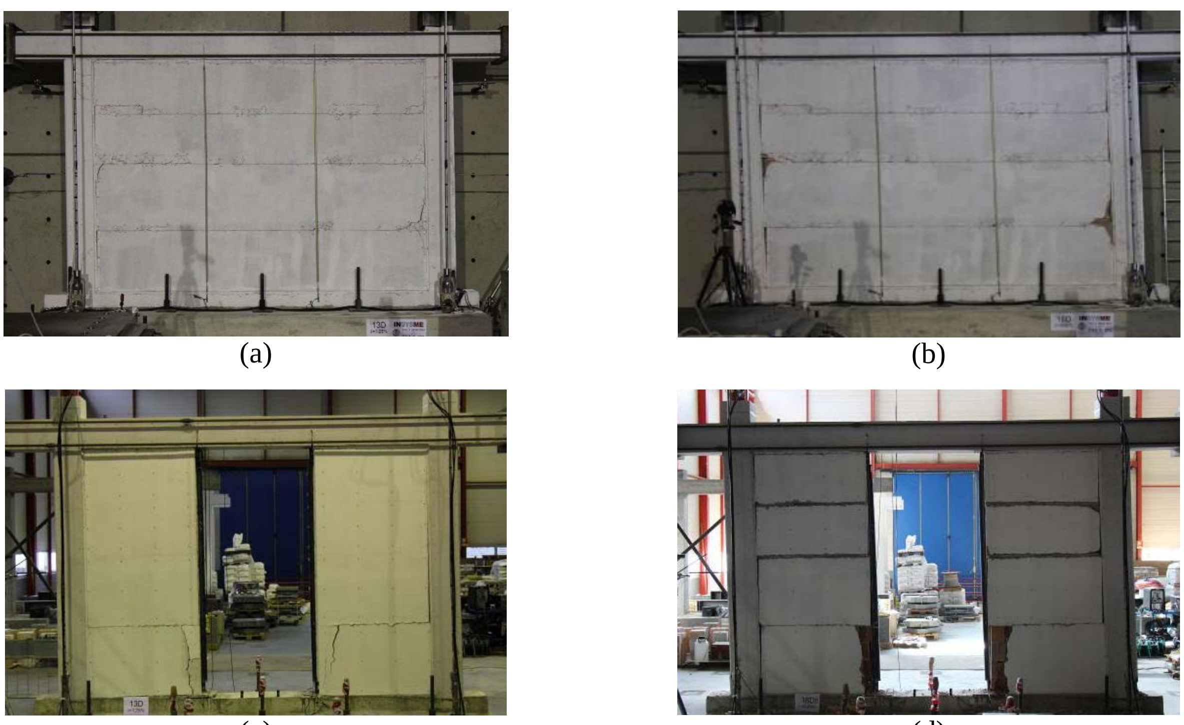
In the case of fully infilled specimen (TSJ1) subjected to the low velocity test, sliding in the three horizontal joints was observed from the first applied target drifts and subsequently, starting from the first peak in the F-D curve (0.20% drift), no further cracks have been observed in the specimen up to a drift of 0.60%, when first light cracks between the RC columns and the joints have appeared. During cycles at drift of 1.00% and 1.25% some diagonal minor cracks have been observed in the upper part of the RC columns along with an initial formation of plastic hinges at the bottom of the RC columns. At a drift of 2.00% some small areas of plaster located at the corners of the intermediate masonry strips have fallen down and, finally, spalling of the concrete cover in correspondence of the plastic hinges at the bottom of the columns has been observed at 3.00% drift. The cracking pattern of the panel has been predominantly located in the plaster in proximity of the sliding and of the interface joints, whereas any damage in the remaining part of the infill has not been observed, with the exception of some minor cracks in the units at the corners of the bottom three masonry strips, however easily repairable and occurred at very high level of in-plane displacement demand (drift larger than 2.50%). The damage pattern at final stage is shown in Fig. 5.

In the case of "high-velocity" test, no sign of damage and no alteration of the temperature of the material of the sliding joints has been observed after the test due to high-speed actions. Moreover, the damage pattern in the infill has exhibited some minor extensions of the cracks previously reported; the complete formation of the plastic hinges at the ends of the RC beam and at the base of the columns, occurred during the previous quasi-static test, has caused further spalling of the concrete cover at the bottom of the columns.

In the case of the partially infilled frame (TSJ2), sliding of the three horizontal joints was observed in both panels since the first applied target drift (0.05%), forming very light horizontal cracks in the plaster and cracks along the infill panels-frame interface. At 0.15% drift a light diagonal (sub-vertical) cracking in the bottom strip of the left panel beside and towards the base hinge of the steel stud has formed, initially only in the plaster but, after a drift of 0.80%, also involving the masonry units. At 1.00% drift, a crack symmetric to the previously described one has also occurred at the bottom strip of the right panel, initially only localized in the plaster. After the initial formation of the horizontal light cracks beside the sliding joints and the other small fissures in the plaster, no further sliding of the masonry strips has occurred. At a drift of 1.25%, the test was interrupted since it was realized that the edges of the masonry panels were rigidly adhering to the steel studs, preventing vertical sliding between the C-shape units and the studs due to high value of adherence of the interface mortar; this restraint has induced the uplift of the steel studs, disanchoring their base plate from the foundation and also limiting the horizontal sliding of the strips. At this point, the steel studs were unbonded from the edges of the masonry panels, the anchoring of the base plate restored and the test resumed. As expected, after this operation the two panels started to slide at the sliding joints, with the damage at the corners of the bottom masonry strip furtherly propagating up to spalling of parts of clay units from 2.00% of drift. With the exception of this localized damage and of the horizontal cracks in the sliding joints of both panels, no further failure has occurred in the masonry infill up to the last imposed level of displacement (3.00% drift). Regarding the damage pattern on RC members, flexural cracks have started to occur on columns at 1.00% drift and on beams at 1.25% of drift, propagating in number and length at increasing levels of in-plane deformation up to the end of the test, where, although the cracks were spread through the entire height of the columns, their width has remained small and spalling only at the base of the columns has reported at the last two levels of drifts (2.50% and 3.00%). The final damage layout of the specimen is reported in Fig. 5.

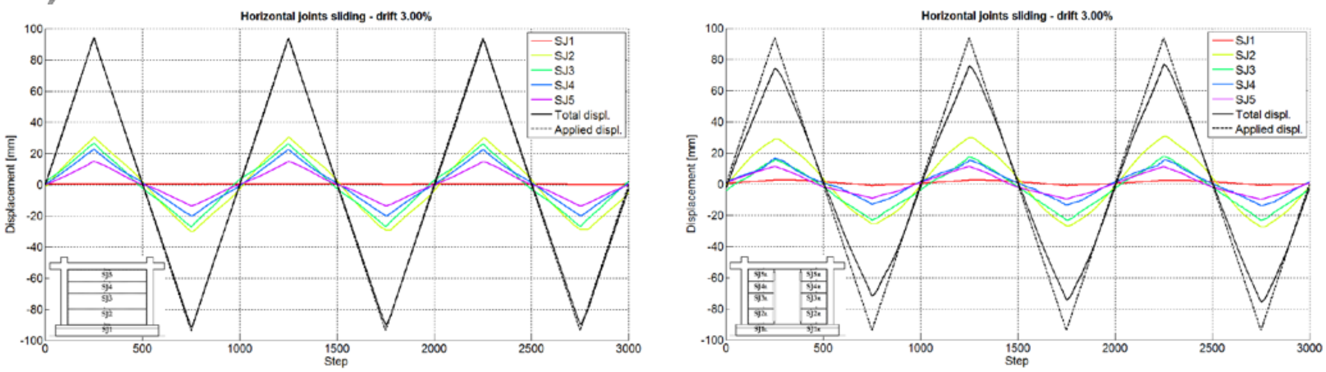
## 4.2 Interpretation of the sliding mechanism and evaluation of seismic parameters

The activation of the sliding mechanism in each of the sliding joints has been monitored through the measurement of the horizontal relative displacement between adjacent masonry strips coming from the processing of the potentiometers (see Fig. 6a for TSJ1 and Fig. 6b for TSJ2, at 3.00% of in-plane imposed drift). In the case of TSJ1 is evident that the sum of the relative displacements in the 5 joints is substantially coinciding to the total imposed displacement, meaning that there is a full activation of the sliding joints. On the contrary, the sum of the relative displacements in the 5 joints for the specimen TSJ2 is less than the total imposed displacement, meaning that only a partial activation of the sliding joints is occurred together with other deformation mechanisms, as described in the sequence of the damage pattern.



(a) (b) (c) (d)

Fig. 5 – Damage pattern of TSJ1 at (a) 1.25% and at (b) 3.00% drift ; damage pattern of TSJ2 at (c) 1.25% and at (d) 3.00% drift.




(a) (b)

Fig. 6 – Sliding of the horizontal joints at 3.00% of imposed drift: (a) TSJ1, (b) average values between the two panels of TSJ2.

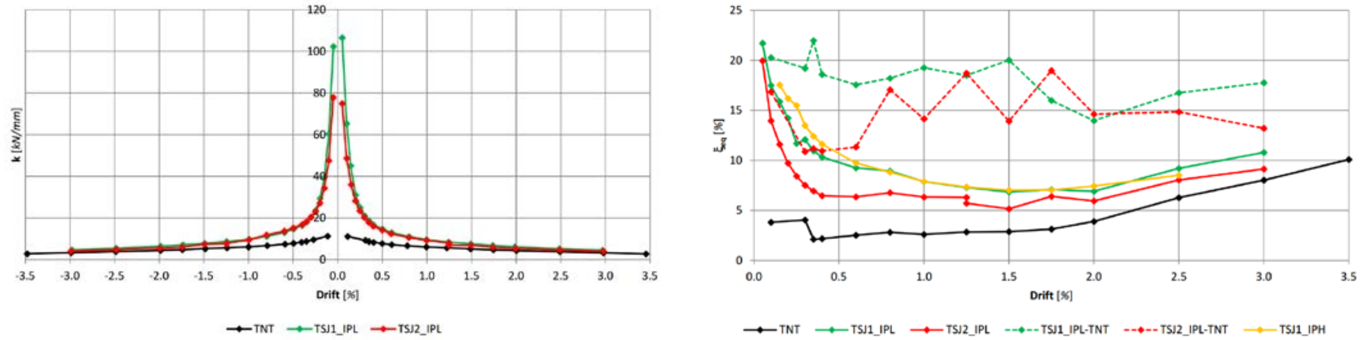
The main seismic parameters, such as the secant stiffness and the energy dissipation capacity have been evaluated for specimens TNT, TSJ1 and TSJ2.

Fig. 7a shows the degradation of the secant stiffness with the increase of the drift demand. The secant stiffness was calculated as the slope of the line joining a point on the envelope curve to the origin. As expected, the initial lateral stiffness and the stiffness degradation versus the imposed drift are much lower for the bare frame (TNT) than for the case of the infilled specimens; for example, at 0.10% in-plane drift, the stiffness of TNT is about 6 times smaller than for the fully infilled TSJ1. Moreover, it can be noticed that the values of lateral secant stiffness for the fully (TSJ1) and the partially infilled (TSJ2) frames are very similar, since the two envelopes, at least up to 1.00-1.50% drift, are almost coincident. For drifts larger than 2.00% the values of the secant stiffness of the infilled specimens tend to come closer to those of the bare frame.

A possible simplified criterion to evaluate the dissipated hysteretic energy of the tested infilled frames, often employed also in the interpretation of test on structural masonry piers, consists in the determination of the equivalent viscous damping $\xi_{eq}$. Given a single load–displacement cycle, $\xi_{eq}$ can be expressed as a function of the dissipated energy $W_d$ (area enclosed by each hysteretic loop) and the elastic energy at peak displacement $W_e$ (amount of elastic energy stored in the same loop), following the expression (in which signs + and – indicate the positive and the negative elastic branch, respectively):

$$\xi_{eq} = \frac{W_d}{2\pi\left(\left|W_e^+\right| + \left|W_e^-\right|\right)} \tag{1}$$

According to the previous equation, equivalent viscous damping ratio evolution of the tested specimens has been evaluated and drawn against the imposed drifts in the tests estimated from the load-displacement loops considering the first, the second and the third cycle at each target displacement; in Fig. 7b the curve of the equivalent viscous damping for TNT, TSJ1 (both for “low-“ and “high-velocity” test) and TSJ2 is reported for the first cycles. In the case of the RC bare frame, the damping starts to substantially increase from about 3% up to 10% starting from drifts larger than 1.50% up to a drift of 3.50%. For the infilled specimens the damping, after a first sharp decrease and a subsequent almost flat trend, starts to increase, as for the bare frame, from the 1.50% drift up to values of about 11% and 9% for TSJ1 and TSJ2, respectively. The “high velocity” test on the fully infilled specimen (TSJ1_IPH) possesses damping values similar to those of the “low velocity” test (TSJ1_IPL). Finally, an estimation of net energy dissipation capacity of the two infill walls applying Eq. (1) was also obtained, computing the area enclosed in the hysteretic cycles of the infilled frames after deduction of the area of the bare frame hysteretic curves at corresponding imposed drifts. The results, reported in Fig. 7b together with those of the infilled frames, show, after a drift of 0.60%, values of damping ranging between about 15% and 20% without a clear trend, being the contribution of the infill with opening slightly lower (average values between drift of 0.60 and 3.00%, $\xi_{eq,av.,drift\_0.60\text{-}3.50\,\%}$ = 15.2%) than the one of the full infill ($\xi_{eq,av.,drift\_0.60\text{-}3.50\,\%}$ = 17.6%) and both much larger than the bare frame.




(a) (b)

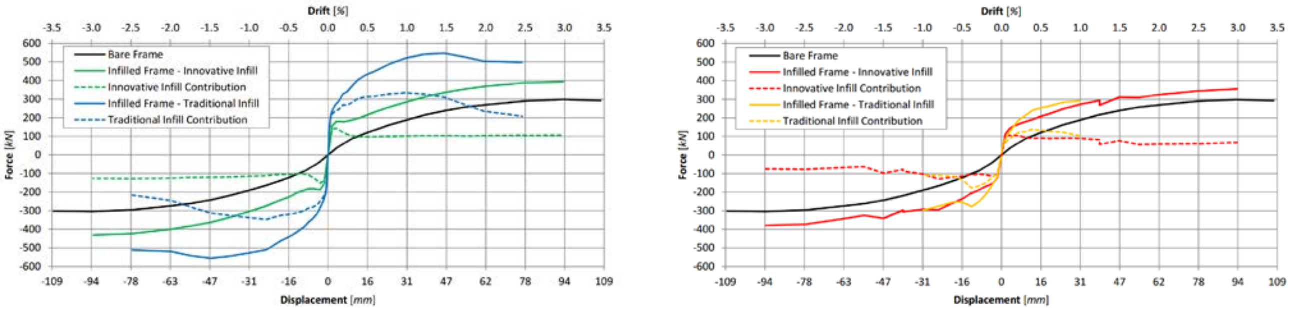
Fig. 7 – (a) Stiffness degradation vs imposed drift of TNT, TSJ1 and TSJ2 at 1st cycles; (b) equivalent viscous damping of TNT, TSJ1 (for "low" and "high" velocity tests), TSJ2, TSJ1-TNT and TSJ2-TNT at 1st cycles.

## 5. Innovative infill performance and comparison with traditional infill

Based on the experimental test results and the related infill damage observed during the test for the fully infilled frame configuration, the corresponding average resistance of the masonry infill has been evaluated as the difference between the average response of the infilled frame and of the corresponding RC bare frame. Such approach allows a consistent comparison of the experimentally obtained infill properties in terms of strength, stiffness and deformation capacity as respect to a traditional infill, which has been tested in a previous experimental campaign at the University of Pavia and EUCENTRE by Morandi *et al.* [7]. The traditional non-engineered infill is constituted by a 35 cm thick clay masonry with tongue and grove vertical joints realized in full contact with the surrounding frame and has provided values of average vertical and lateral strength and modulus of elasticity respectively of 4.64 MPa and 1.08 MPa, 5299 and 494 MPa (Morandi *et al.* [7]). Despite the larger thickness of the "traditional" infill compared to the innovative solution, the values of strength and elastic modulus multiplied by the thickness of the walls leads to less resistant and stiff masonry in the case of the "traditional" compared to the innovative masonry.

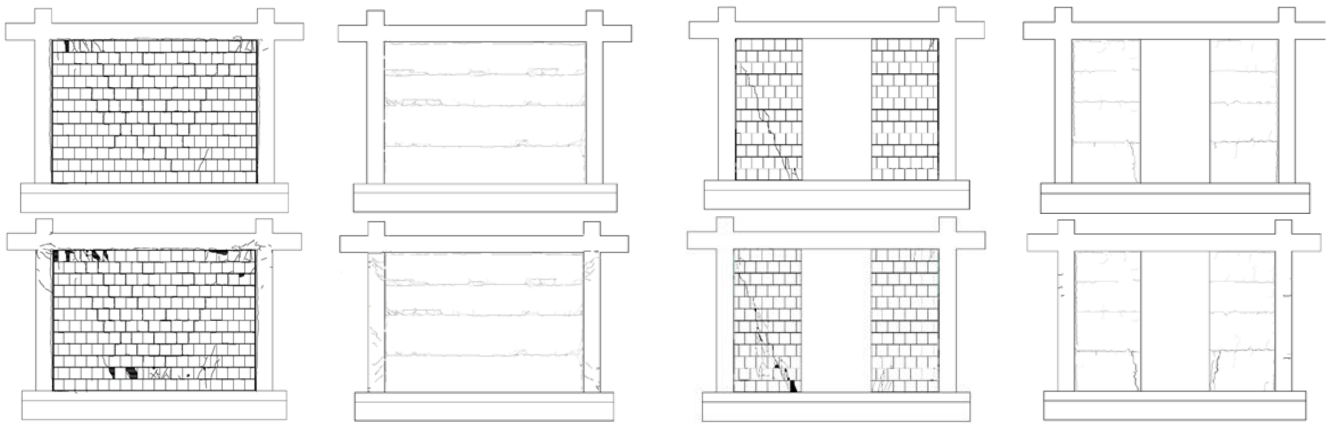
However, a significant difference in terms of infill contribution between these two infill solutions has been found, as illustrated in Fig. 8a and Fig. 8b respectively for full infill and partial infill with central opening (the opening has the same dimensions for the innovative and the traditional infill). In particular, the contribution of the traditional solution in both cases has reached a sensibly higher strength than the proposed innovative infill, which instead has provided a peak force after an initial almost linear behaviour, followed by a drop and an almost constant resistance (about 110 KN for TSJ1 and 85 KN for TSJ2) up to very large values of displacement demand, without any further strength degradation. In the new system, the first drop in the force was due to the activation of the sliding in the horizontal joints and of the exceeding of the tensile strength of the plaster at the sliding joints, without significant differences between the panels with and without opening. The larger values of strength in the traditional infills is also correlated with the formation of several diagonal cracks at the ends of the columns due to the reaction of the masonry infill on the RC members, more limited in the engineered solution.

Finally, the traditional solution has achieved values of drift corresponding to the attainment of a "damage" limit state of about 0.50% and 0.30% for full and partial infill respectively, and corresponding to an "ultimate"/"life safety" limit state of 1.75% and 1.00% for full and partial infill respectively, as discussed in Morandi *et al.* [7]. On the other side, the innovative panel without opening has reached much larger horizontal deformation capacity without significant cracks in the masonry and with the damage substantially concentrated at the level of the sliding joints and in very limited parts of the plaster. In the case of the innovative infill with opening, a damage in the units located at the corners of the bottom strip close to the base of the studs started to occur at drift of about 0.80%, without however attaining a level of damage to be classified as an "ultimate" limit state, not even at very large in-plane imposed displacement. The comparison of the cracking pattern between the two solutions is reported in Fig. 9a for full infills at 0.50 and 1.75% drift, and in Fig. 9b for infills with opening at 0.35% and 1.00% drift.




(a) (b)

Fig. 8 – Force-displacement average envelope curves: (a) comparison between bare frame, innovative and traditional full infill; (b) comparison between bare frame, innovative infill and traditional infill with opening.



(a) (b)

Fig. 9 – Comparison of the damage pattern between traditional and innovative infill: (a) fully infilled frame at 0.50% and 1.75% drift; (b) infill with opening at 0.35% and 1.00% drift.

## 6. Conclusion

The present paper has focused on the framework of an experimental study carried out with the aim to interpret the cyclic response of an innovative masonry infill with sliding joints. Within the scope of this work a fully and partially infilled RC frame with the innovative infill has been conceived and realized. The innovative solution has consisted in a clay masonry infill subdivided into four horizontal strips through sliding joints located in the horizontal bed joints and in deformable joints at the infill-frame interface.

In this work the results of the tests of characterization on the materials and of in-plane cyclic tests carried out on a bare RC frame and on two innovative infilled specimens (one with and one without opening) have been reported and discussed.

In the case of the fully infilled frame (specimen TSJ1), the response is characterized by a considerably large deformation capacity (up to 3.00% drift) without significant cracks in masonry and with a level of damage substantially concentrated at the level of the sliding joints and in very limited parts of the plaster. The application of an high velocity in-plane cyclic test after the pseudo-static one has provided a hysteretic response in complete accordance with the last loading cycles of the in-plane low-velocity test and without any distinct difference in energy dissipation capacity; moreover, no sign of damage and no alteration of the temperature in the material of the sliding joints has been observed after the test due to high rate application of the action.

In the case of the infill frame with central opening (specimen TSJ2), the in-plane behaviour has not been as performing as in the case of the fully infilled frame, since a diagonal (sub-vertical) cracking in the bottom strip beside the base hinge of the steel stud has formed in the left panel, initially only in the plaster but, after a drift of 0.80%, also involving the masonry units; at 1.00% drift the same kind of damage occurred also in the right panel. This was probably in part due to the bond provided between the edges of the infill panels and the steel studs (then removed during the test), in part due to an intrinsic limitation in the activation of the sliding in the case of short panels at the bottom of the infill. However, with the exception of the localized damage at the corner of the bottom masonry stipes and of the horizontal cracks in the plaster in proximity of the sliding joints, no further failure has occurred in the masonry infill up to the last imposed level of displacement (3.00% drift).

A comparison in terms of in-plane performance between a traditional non-engineered infill solution and the innovative system has shown a strong reduction of the level of damage, both at moderate/low and at large deformation demand for the latter as respect to the former system, on the infill both with and without opening.

The results depicted above prove the ability of the proposed solution of limiting the level of damage at different seismic intensity, providing a prominent reduction of the cost of reparability after seismic events and a wide margin towards the life safety requirements. Although design and construction optimization of the system needs to be implemented, above all in the case of short infill panels with opening, for example trying to limit the damage in the bottom part of the infill wall (i.e. increasing the number of the horizontal sliding joints and reducing the adherence at the studs/infill interface), the results of the in-plane tests appear very promising about the use of this solution as an efficient seismic resistant non-structural element in RC buildings.

## 7. Acknowledgements

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