



## ENGINEERED MASONRY INFILL WALLS JOINTS FOR POST-EARTHQUAKE STRUCTURAL DAMAGE CONTROL

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### ABSTRACT

The paper presents some of the results of an experimental campaign on the behaviour of engineered masonry infill walls subjected to both in and out of plane loading. Tests on large-scale specimens and masonry subassemblies were performed in order to evaluate the infill deformation capacity, the damage associated to different drift levels and the mechanical properties of the infill components. A design solution with sliding joints for both reducing the infill-frame interaction and ensure out of plane stability, already proposed in a previous study, was developed and refined with focus on construction details. The aim of the sliding joints is to ensure a predetermined mechanism in the infill wall, governed by hierarchy of strength, capable of ensuring ductility and energy dissipation to be taken into account into the design practice, thanks to the predictability of the infill response. In the test described in this paper the infill wall specimen reached up to 3% in-plane drift with very little damage and supported an out of plane force equivalent to a horizontal acceleration 4 times the acceleration of gravity. The force-displacement hysteretic curve and crack pattern show the efficiency of the construction technique, based on affordable and tradition-like construction process and materials, in ensuring very deformable, ductile and stable response to the masonry infill.

### INTRODUCTION

The seismic vulnerability of frame reinforced concrete (RC) structures due to infill frame interaction has been repeatedly observed (EERI 1996 and 2000, Hermanns et al. 2013) and it's well acknowledged in literature (Paulay and Priestley 1992, Fardis 1999, Dolšek and Fajfar 2008). Typically, infill walls have been so far proportioned and verified as non-structural elements of the building and their role in the structural response have been often underestimated or completely neglected in design practice. Several research programs are recently addressing the need for a specific design of masonry infill wall with appropriate detailing, in order to enhance their seismic behaviour (Calvi and Bolognini 2001, Mohammadi and Akrami 2010, Preti et al. 2012, Markulak et al. 2013, Facconi et al. 2012). Two different research approach can be identified, one oriented to the strengthening of the infill, in order to make it a structural element able support the seismic loading, the second pointing to limit the infill frame interaction by reducing the infill strength and stiffness. In both cases the hysteretic energy dissipation offered by the infill is a significant resource in the overall building seismic response (Ozkaynak et al. 2013), which can be efficiently taken into account in design only if the infill wall cyclic response is stable and easily predictable. In particular, the predictability of the response is a main issue for the engineered infill walls in order to overcome the vulnerability of infilled frames. In fact, infill walls built according to traditional construction

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techniques are typically characterized by uncertain and often brittle collapse mechanisms (Mehrabi and Shing 1996), depending on several construction aspects (material and type of masonry blocks and mortar, geometry, infill-frame contact conditions, etc..) and so they are difficult to be accounted for in structural design.

The more and more important requirement for controlling post-earthquake damage (DAD-Mander and Cheng 1997, Hak et al. 2012) is an additional stimulus for defining specific construction detailing to obtain ductile infill walls, capable of absorbing the large deformation imposed by the seismic action without requiring post-earthquake expensive repair. The challenge for a successful design of such engineered infill walls is to meet the above mentioned requirements with solutions that ensure the thermo-hygrometric performance of the building peripheral walls, the affordability of the construction process and its sustainability, according to a life cycle energy analysis approach, which accounts for the entire energy in the manufacture, use and demolition of buildings (Ramesh et al. 2010).

The results of Preti et al. (2012) showed the potential of horizontal partition joints (embedded in few masonry mortar beds and acting as sliding joints), to ensure a ductile mechanism to the infill under in-plane loading, preventing the development of the typical diagonal strut mechanism (Paulay and Priestley 1992). The paper here presented briefly describes the results of that experimental program progress and it addresses also the issue related to the out of plane response of such infill walls with sliding joints, moving from the results collected in the previous experience. A more comprehensive publication with detailed description of the test results is now undergoing the peer review process (Preti et al., PeerRev). In the test presented the partition joints are made of wooden boards and their configuration is adapted to the need of the out-of-plane capacity control. For this kind of masonry infill the connection to the structural frame is very important. It must ensure support against the out-of-plane action and, at the same time, allow an adequate degree of freedom for the in-plane deformation along the sliding joints. The effectiveness of the sliding joints in limiting the in plane damage to the infill is the key point of this technique. As a matter of fact the risk of out of plane collapse of the infills may also arise in consequence of the damage associated to in-plane deformation. As shown in (Calvi and Bolognini, 2001) in-plane damage can reduce the out-of-plane strength of the wall, which under undamaged conditions is often largely in excess of the design action (Morandi et al. 2013, Guidi et al. 2013).

The construction technique, adapted from historical examples (such as *himiş*, *colombage*, *Casa Baraccata*, *GaiolaPombalina*, *half-timber*, *dhajji-dewari*, *fachwerk*) (Langenbach 2008; Pompeu Santos 1997; Paikara and Rai 2006; Bettini 2010) is meant to be fast and simple. No expensive materials are involved and no specific manpower skills are required. The effectiveness of the proposed solution for infill masonry walls was tested on large-scale walls, confined within a single bay single story frame, subjected to quasi-static in-plane horizontal cyclic loading and out of plane push-over load.

## CONSTRUCTION TECHNIQUE

The construction technique here presented is founded on the idea that horizontal joints create preferential lines of weakness along where the deformation of the masonry infill concentrates, in the form of relative sliding between the sub-portions of masonry bounded by joints and columns (Fig .1). Necessary condition for the success of this technique is that the horizontal joints have a sliding resistance lower than the shear strength of the masonry and the mortar joints, in order to protect them from cracking. In the experimental study proposed, the sliding joints were produced by laying in selected mortar bed joints of the infill wall a wooden board of 50mm thickness and width equal to the wall thickness (2). In order to reduce the friction resistance along the joint and the cohesion between the wooden board and the above mortar joint a sheet of polyethylene was interposed, simply placed on the upper surface of the table. It is worth noting that the sliding along the horizontal joints involves the partial detachment of the masonry sub-portion (1) from the columns of the boundary frame (3), as shown in Figure 1.

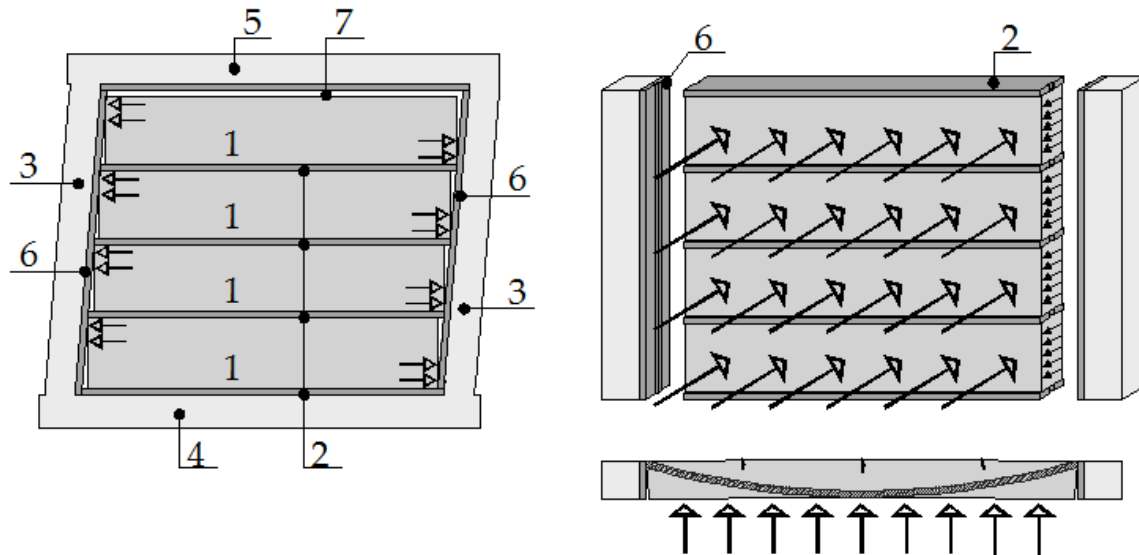


Fig.1 Masonry sub-portions sliding mechanism and static scheme of the out of plane retaining system (Preti et al., PeerRev)

This mode of deformation is possible because of the unilateral relative constraint between the column and the masonry. In order to not inhibit the sliding mechanism and, at the same time, ensure the necessary out of plane constraint between the infill and the structural frame, the realization of a specific connection is proposed, able of preventing the transverse sliding of the wall with respect to the columns without preventing its detachment in the plane of the masonry. This connection was obtained through the interposition of a wooden board (Fig.1), uprights and opportunely shaped, between the wall and the columns. The board was rigidly connected to the frame column by means of smooth steel dowels, sized to withstand with adequate over-strength the out of plane seismic action on the infill wall. A detailed description of the infill geometry and mechanical properties was included in the paper under peer review (Preti et al. PeerRev) and can be found in Migliorati et al. (2013).

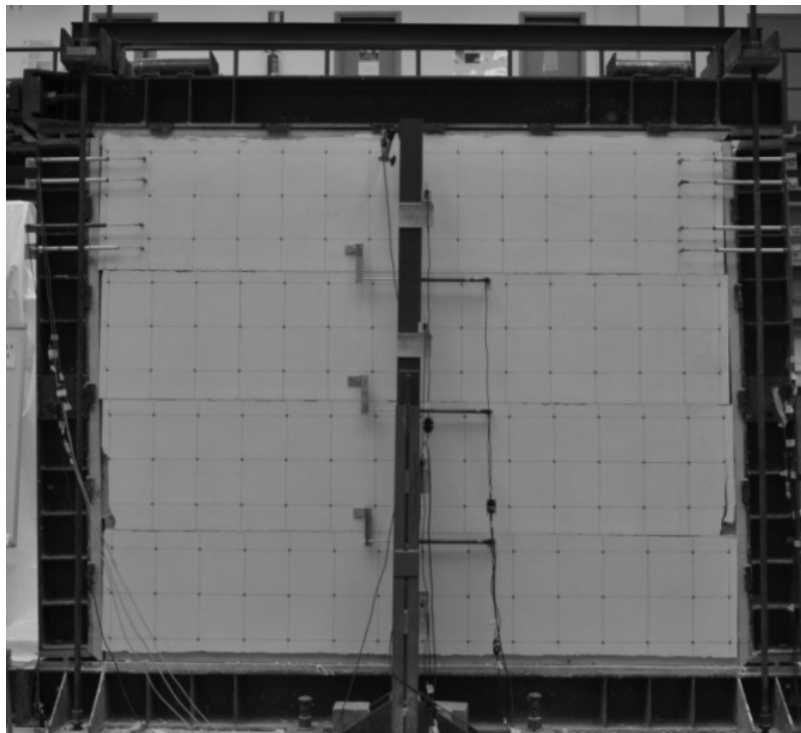


Fig. 2 Picture of the wall specimen At 2,5% drift (a) and detail of the compressive strain in the contact area between masonry-wooden board (b,c) at a sub-portion corner (Preti et al., PeerRev).

Such vertical boards, fixed on the two columns, have the additional purpose of protecting the masonry sub-portions from local crushing arising, from compatibility, due to the sliding mechanism of the wall along the horizontal joints. As a matter of fact, such sliding along the joints would not be possible without the local compressive strains in the contact area between masonry sub-partitions and the columns. As detailed in Preti et al. (PeerRev), the interposed wooden board absorbs the required local strain at the masonry sub-portion corners preventing these strains to occur in the masonry, thanks to wood ductility and low mechanical properties orthogonal to the fibers.

The experimental results in (Preti et al. 2012) have shown that the vertical confinement provided by the upper beam of the frame (Fig.1) results in a progressive increase of the friction force along the sliding joints for increasing amplitude of in plane deformation imposed on the system. This may inhibited the sliding and caused the activation of a strut mechanism. To avoid this risk, in the experimental tests presented below it was decided to completely detach the infill from the upper beam with a gap thus nullifying the effect of confinement (Fig.3).

## EXPERIMENTAL PROGRAM

The wall was subjected to cyclic loading in and out of plane. In order to assess the behaviour of the wall with the progression of the damage, the out plan load was applied following the achievement of two significant levels of deformation in-plane, 0.5% and 2.5% drift, which were arbitrarily taken as design conditions of damage and life-safety limits, respectively.

### Specimen detail

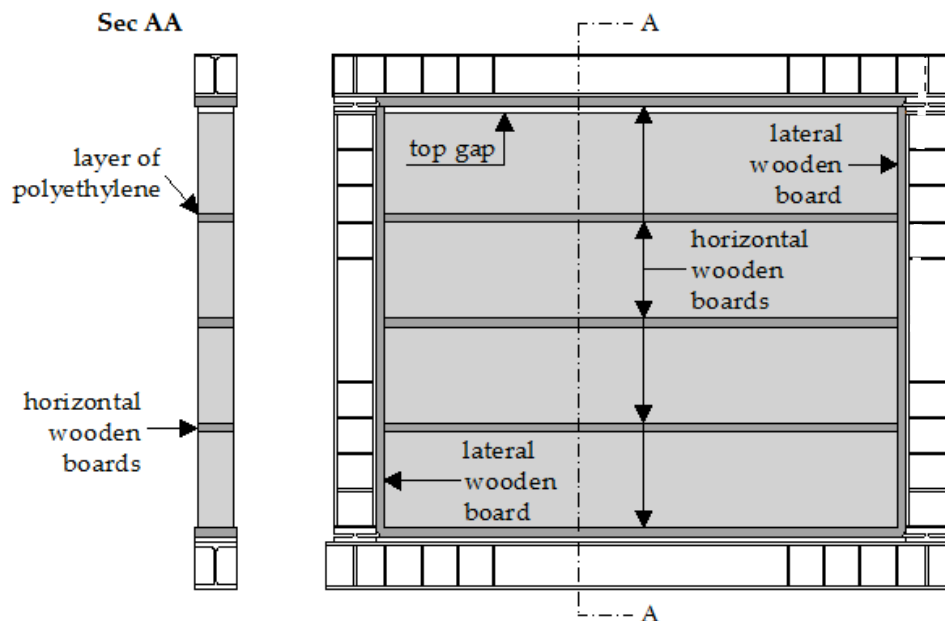


Fig.3 Components of the experimental masonry infills (Preti et al. PeerRev)

The specimen here described, with a size of 2930x2460 mm, was made with hollow brick blocks (200 × 250 × 190 mm). According to the traditional construction technique, the wall texture had mortar joints continuous in the horizontal direction and discontinuous in the vertical one, with an average thickness of 10 mm. A pre-mixed lime mortar and fired clay hollow bricks were adopted as construction materials, the latter having a percentage of the net over the gross area equal to 55% ( $A_{net}/A_{gross}$ ).

The sliding joints were obtained by laying three wooden plank of 50 mm thickness, in mortar beds at uniform distance (Fig. 4). As already said, on the upper face of each board a sheet of polyethylene was placed, in order to minimize the friction coefficient between masonry and wood. The

experimentally measured mechanical characteristics of the materials and the coefficients of friction at the sliding joints are reported in Preti et al. (PeerRev).



Fig.4 View of the specimen before gypsum plaster.

All the described planks had the same size (50x220mm) and material (C14 wood class, EC8 2004). The vertical boards have been fixed to the columns by 8 smooth steel dowels (S275) with a diameter of 12 mm, infixed into pre-formed calibrated holes of equal diameter both in the planks and the columns.

A gap of about 30 mm has been left between the top of the infill and the intrados of the upper beam in order to nullify the effect of the vertical confinement of the beam on the wall infill. The gap was then filled up with polyurethane foam to allow a uniform surface finishing on the wall.

The masonry sub-portions were reinforced for the out of plane flexure resistance with plaster of 20mm thickness reinforced with a fiber-glass mesh. A gypsum plaster was added on the specimen faces in order to highlight the crack pattern.

### Test Set-Up

The infill wall specimen was built inside a portal frame, equipped with four, preformed, plastic hinges. Such hinges were design and arranged in order to reproduce a typical structural frame deformation at the ultimate limit state, when the collapse mechanism is fully activated (Preti et al. 2012). For efficiency reasons, the four experimental hinges have been placed at the end of the columns.

The in plane system responses, described in the following, include the contribution of the bare frame shown in Figure 5. It is worth noting that neither the response of the steel frame or its interaction with the infill are subjects of this study. The focus here is on the comparison in term of stiffness, strength, deformation capacity and associated damage between infill walls made with different construction technique but having the same boundary and load conditions.

The in plane horizontal cyclic load was applied by imposing a force at the upper beam of the steel frame, Fig.6a, being the lower beam rigidly constrained to the bearing strong frame. The all set-up is fixed to the strong floor of the Lab.



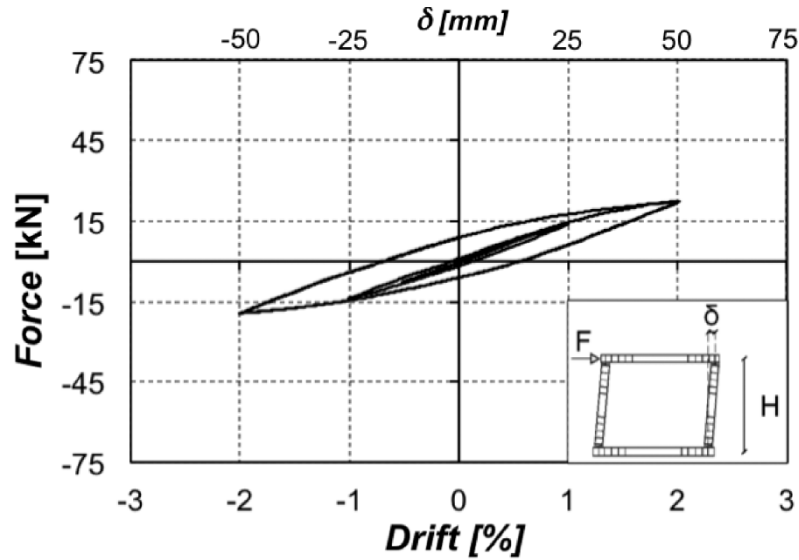


Fig. 5 Force-drift curve of the bare confining steel frame (Preti et al.2012).

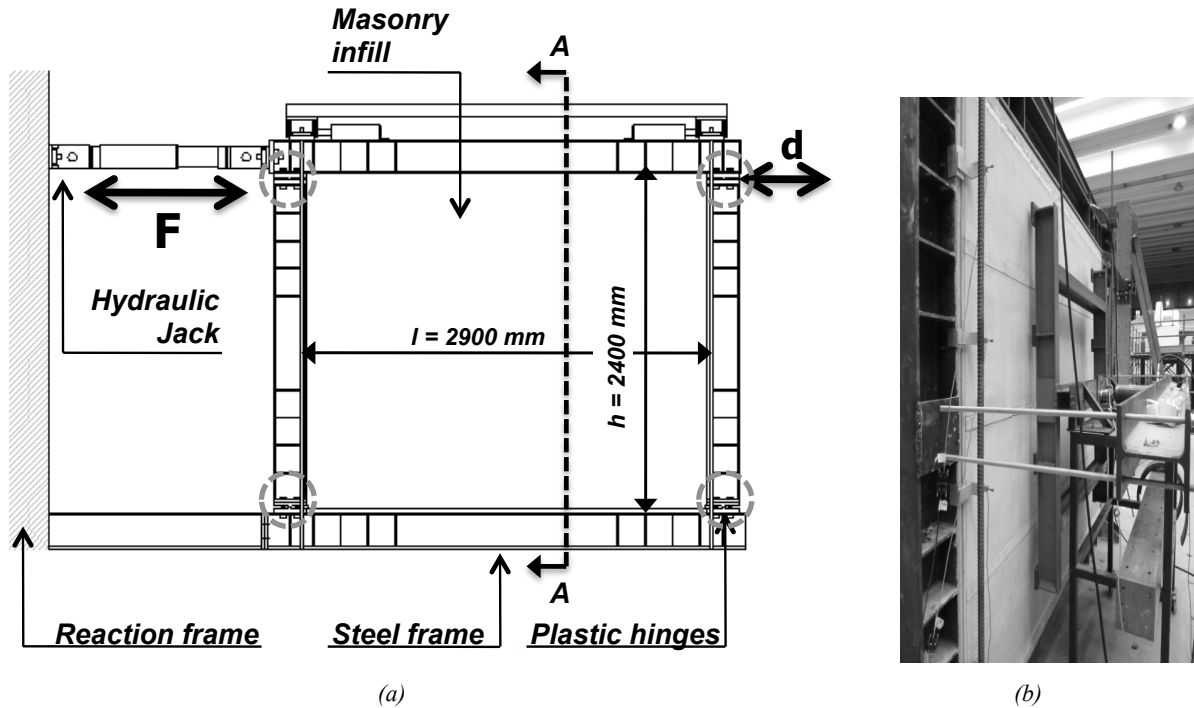


Fig. 6 Lateral view of the reaction frame and of the hydraulic jack for the application of the in plane load (a) and view (b) of the self-balanced system for the application of the out of plane 8 points load action on the infill specimen (Preti et al. PeerRev).

The steel test portal frame (grade S355) is made of HEB240 profiles for the columns and upper beam and a HEB 260 profile for the lower beam. The force was applied to the system by means of a hydraulic jack acting on the upper beam, with the interposition of a cylindrical joint. The deformation of the frame is governed by four elastic-plastic hinges obtained by reduction of the resistant cross-section of the steel columns (Preti et al. 2012). These hinges are proportioned to offer a low stiffness and resistance against rotation, providing the necessary shear strength to transfer the jack load from the upper beam to the columns.

The out of plane load on the specimen was applied imposing a one way force with loading and unloading cycles of increasing amplitude. The action was applied at 8 points, aligned two by two on the centre lines of each masonry block (Fig.6b). The detailed description of the out-of-plane load test set up can be found in (Preti et al. PeerRev).

### Loading Protocol And Instrumentation

The loading protocol is shown in Figures 7 and 8. Five in-plane loading cycles of increasing amplitude (up to 0,5% drift) were first applied, to simulate the specimen responses at a damage limit level (NTC2008, EC8). Additional ten cycles, up to 3% drift, were applied to assess the performance in terms of capacity and damage at life safety limit state.

At two intermediate steps, 0,5% and 2,5% in plane drift, out of plane loading was applied on the specimen after re-centring (0% drift), with the protocol shown in Figure 8. The aim was to assess the specimen out of plane capacity during the evolution of damage due to in plane loading. The applied load at 0,5% drift was the design load evaluated for an infill wall inside a five story building in the worst situation for the Italian context, according to the code life-safety limit state (NTC2008, EC8).

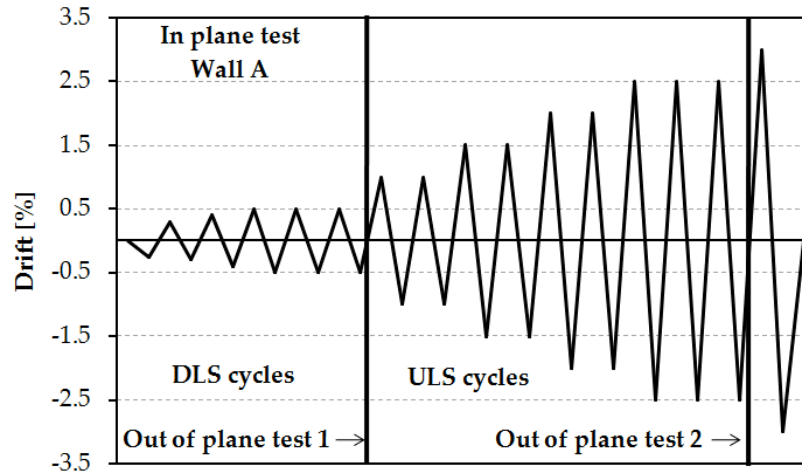


Fig. 7 In-plane loading history applied to the experimental infill wall (Preti et al., PeerRev).

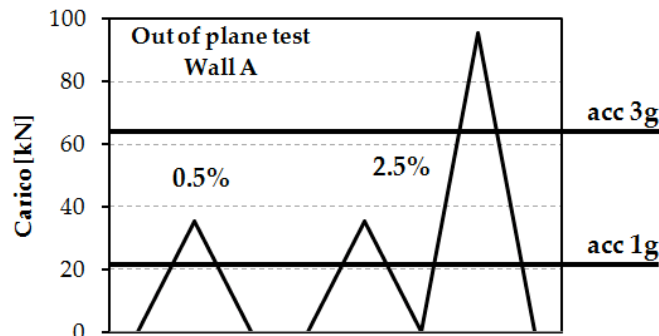


Fig. 8 Out of plane loading cycles (Preti et al., PeerRev).

The specimen drift, the relative sliding of the masonry sub-portions along the joints and the load applied by the jack were measured.

## EXPERIMENTAL RESULTS

### In Plane Cyclic Response

Figure 9 shows the response of the infill wall with sliding joints for all the in plane loading cycles applied. The system was characterized by a low stiffness compared to a traditional infill without joints previously tested under the same experimental conditions [Preti et al. 2012]. In fact, the sliding mechanism of the masonry sub-portions at the joints was triggered for very small values of drift, less than 0.1%.

The hysteretic curve shows a stable behaviour for the wall, with a hardening trend for increasing deformation. This trend was probably due to the observed increasing compressive strain in the vertical plank in the contact to the masonry sub-portions' corners (Fig.4), showing the activation of a inclined strut within each sub-portions, driven by the drift of the columns.

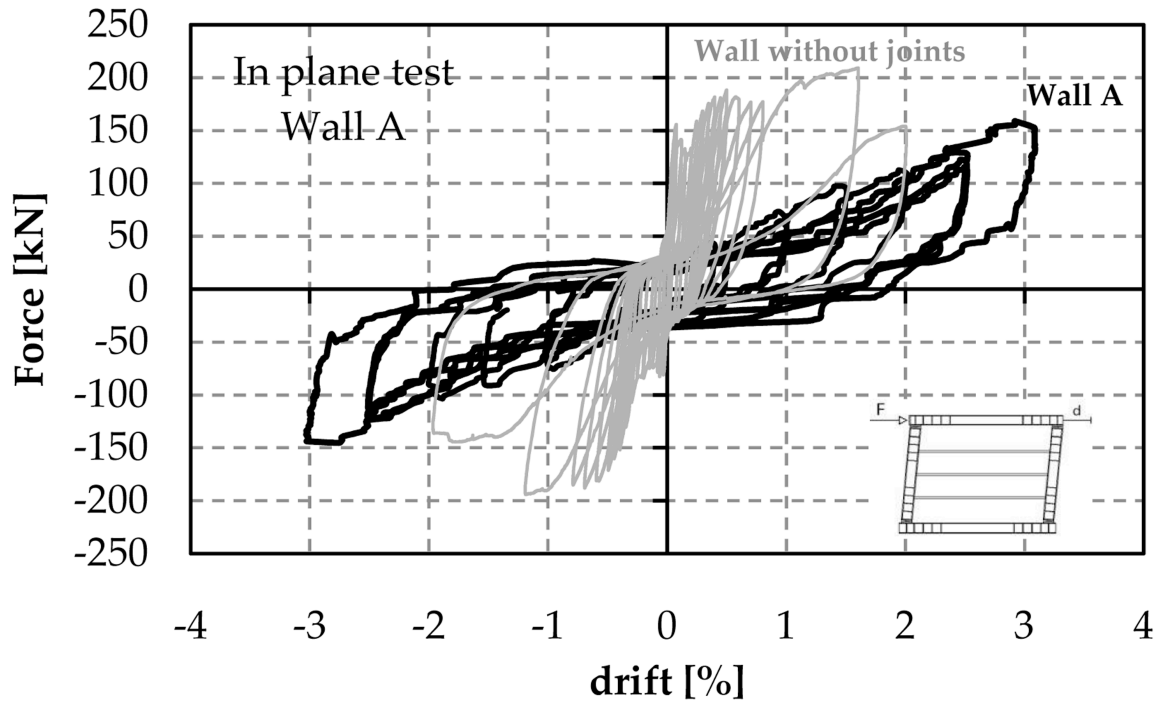


Fig. 9 Force-drift curves for all the in plane cycles applied on the full wall together with the response of a previously tested wall without joints (Preti et al., PeerRev).

It's worth noting as the non-linear strain absorbed by the vertical plank on the columns protected the masonry sub-portion corners from local crushing. Only for large drift of about 2%, some surface cracking appeared in the masonry corners, limited to the plaster (Fig.10).

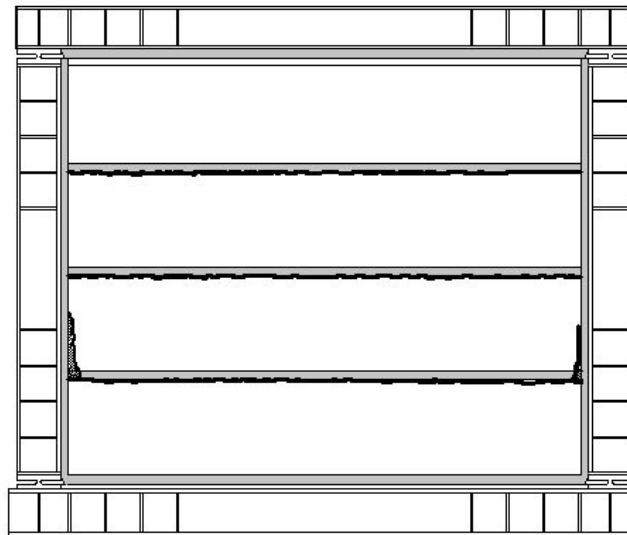


Fig. 10 Full wall - crack pattern after the 3th in plane cycle at 2.5% drift (Preti et al., PeerRev).

### Out Of Plane Response

At the first application of the out of plane loading, after having performed in plane cycles up to 0,5% drift, the response of the infill was very stiff, with a maximum deformation of 3mm measured at mid-span of the upper sub-portion. Detailed description of the results can be found in Preti et al. (PeerRev).



The specimen easily supported the design load (35kN) even after the 2,5% in plane cyclic deformation applied, without evidence of any failure mechanism out of plane.

The failure mechanism began at a load of 90kN, nearly three times higher than the design one and equivalent to an effective transverse acceleration on the infill wall higher than four times the acceleration of gravity. The mechanism caused the tensile failure of the glass reinforcing mesh of the plaster in the left vertical crack (Fig.11), that occurred first at the point load of the top masonry sub-portion and then propagated to the lower ones. It's worth noting that the glass mesh failure did not brought to an abrupt collapse. In fact, after the mesh failure the sub-portions supported an even higher load with large deformation capacity, probably thanks to the activation of an arch mechanism in the thickness of the masonry laterally supported by the confinement of the columns.

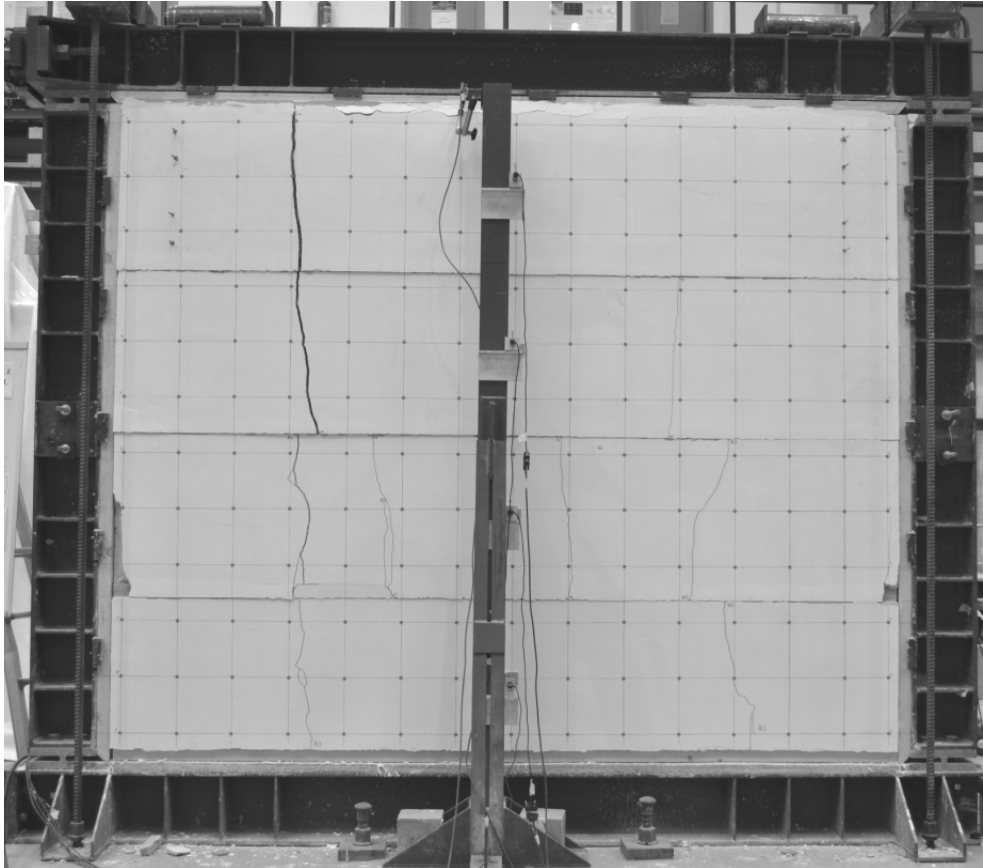


Fig. 11 Infill wall – crack pattern after the out of plane test

## CONCLUSIONS

Some results of an experimental campaign of the response of engineered masonry infill walls with sliding joints were here presented. The technique adopted for the construction consists of the insertion of horizontal sliding joints in the masonry wall, in the test presented obtained with wooden plank laid with constant spacing in mortar bed joints of the infill. The construction technique showed great efficacy in dramatically reducing the damage due to in plane horizontal loading with respect to traditional non-engineered masonry infill-wall.

The horizontal sliding joints showed to be capable of dramatically reducing the stiffness of the infill and its resistance for drift levels below 1%, and this is beneficial to avoid the detrimental interaction between the frame structure and the non-structural infill walls, that was repeatedly observed to be one of the main reasons of collapse of reinforced concrete building during earthquakes.

Moreover, the hysteretic response of the experimental specimen shows a non-negligible energy dissipation resource, stable and predictable thanks to the simplicity and certainty of the mechanism,

ensured by a design criterion based on hierarchy of strength. Such resource can be reliably accounted for in the structural design of a building. The test showed the mechanism to be governed by the sliding mechanism more than the masonry mechanical properties. This was possible thanks to the local ductile stress-strain behaviour, orthogonal to the fibres, of the vertical wooden board working as cushions in between the frame columns and masonry sub-portion corners, protecting the latter from crushing.

The infill walls with sliding joints, provided with specific construction details, supported an out of plane action more than twice the most severe design seismic action predictable for the Italian context (NTC2008, EC8). The failure out of plane occurred with a ductile mechanism, at a load equivalent to a horizontal acceleration 4 times the acceleration of gravity. Such resistance seems not to be affected by several cycles applied in plane up to 2,5% drift, also in consideration of the marginal damage suffered by the infill even at large deformation.

The development of the research project is now focusing on the numerical modelling of such engineered infills in order to quantify their possible beneficial effect in the dynamic response of infilled frames and get to design criteria after performing a parametric analysis on the infill components' mechanical properties, sliding joints configuration and infill geometry. First results of this on-going parametric analysis as been already submitted to a scientific journal for possible publication (Preti et al., PeerRev2).

The simplicity of the construction details and the use of traditional materials make the construction process fast, affordable and tradition-like, and so suitable for a wide application in the construction market.

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