Observations on out-of-plane behaviour of URM walls in buildings with RC slabs

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ABSTRACT: In Switzerland many new residential buildings are constructed as unreinforced masonry (URM) structures or as mixed structures where URM walls are coupled with reinforced concrete (RC) walls by RC slabs. At present the boundary conditions of URM walls subjected to out-of-plane accelerations are still not well quantified. In the framework of a large research activity on RC-URM wall structures a shake-table test on a four-storey mixed structure was performed. The test specimen, which was built at half-scale, was designed in such a way to allow the collection of data on the effect of boundary conditions provided by the RC slabs and adjacent RC walls on the out-of-plane seismic behaviour of URM piers. This paper presents observations on the out-of-plane behaviour of the URM walls from the shake-table test and draws conclusions for the boundary conditions to be applied in numerical studies on URM piers in mixed RC-URM wall structures.

Keywords: Unreinforced masonry, out-of-plane failure, shake-table test, seismic behaviour

1 INTRODUCTION

The out-of-plane failure of unreinforced masonry (URM) piers represents a considerable challenge in the seismic assessment of URM buildings. Premature out-of-plane failure of URM piers for small accelerations can prevent the structure from developing its global capacity. Previous studies on this topic (Dazio, 2000) indicate that Swiss URM buildings tend to present wall thicknesses and slenderness ratios which do not fulfil European provisions. Furthermore the Swiss building code itself presents limitations that are less conservative than the ones proposed by the Eurocodes and by the Italian building code (MIT, 2009), the latter is considered the most advanced and complete on this matter. Therefore Swiss URM buildings can be considered as potentially very sensitive to this typology of failure.

Out-of-plane failure of URM walls was addressed in several experimental studies: ABK 1981; Doherthy 2000; Sismir et al. 2002,2003,2004; Restrepo and Magenes 2004; Meisl et al. 2006; Dazio 2008; Penner and Elwood 2013. Moreover, several authors proposed different models for the assessment of capacity and demand of out-of-plane loaded URM walls: Paulay and Priestley 1992; Doerty et al. 2002; Griffith 2003; D'Ayala and Speranza 2003; Menon and Magenes 2008.

The out-of-plane behaviour of URM piers depends largely on the applied boundary conditions. These comprise: the axial load applied to the pier, the moment and axial restraint applied at the top and bottom of the pier, the input motions and their degree of synchronism at the top and bottom of the pier, the relative movement of top and bottom supports of the wall due to the response of walls

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orthogonal to the out-of-plane loaded wall. At the same time building codes, consider the effect of boundary conditions on the seismic behaviour of out-of-plane loaded piers in a very general manner by reducing the effective height (CEN, 2004). They do not give consideration to the influence of neighbouring structural elements such as RC walls or URM piers. Almost the totality of newly built URM structures are constructed with rigid diaphragms in the form of reinforced concrete slabs (RC). The boundary conditions provided by RC slabs to URM piers, especially in structures with RC and URM walls, are not well understood and can significantly influence the out-of-plane failure of URM piers.

The objective of this article is to discuss the observed out-of-plane response in the CoMa WallS project and to support these observations with data gained during the testing. The article closes with an outlook on the planned numerical investigation.

2 COMA WALLS PROJECT

The CoMa WallS project has, among others, the objective of gaining more insight in the seismic behaviour of out-of-plane loaded URM piers in structures with RC slabs. The test specimen, Figure 1, was specifically designed in such a way of having out-of-plane URM piers subjected to two different boundary conditions at the two ends of the structure. On the North side of the building the out-of-plane loaded URM piers were flanked by two URM piers while on the South side the out-of-plane loaded URM piers were flanked by two RC walls. It was expected, and observed during the tests, that the seismic performance of the out-of-plane loaded piers is highly influenced by the location and by the loading direction. This difference results from the distribution of the structural elements in the longitudinal direction (RC walls on one side of the structure), which induced a different in-plane global behaviour of the structure. As a consequence the RC slabs were forced to deform differently depending on the loading direction and were therefore providing different support conditions to the out-of-plane loaded URM piers.

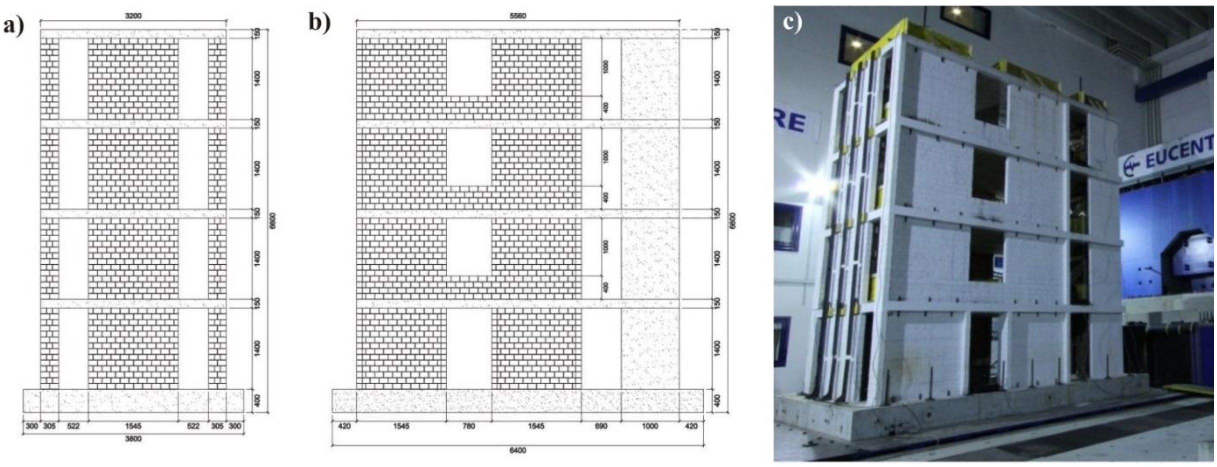

Figure 1. Test specimen: a) North view, b) West view and c) test specimen on the shake table.

The test specimen was built at half scale and it must be underscored that when testing at reduced scale special care has to be taken to the scaling of the different physical properties. In this case the "Artificial Mass Simulation" scaling law was applied. According to this model scaling the dimensions (lengths) of the structure by a factor of two requires that the mass density of each material is doubled. Since the mass density of concrete and masonry cannot be altered, additional masses were added to the structure, which increase the weight of the structure but do not act as structural members. In the CoMa Walls test the masses were added in the form of unreinforced concrete blocks placed on the four slabs. While this "lumped" mass approach is sufficiently accurate for the in-plane response of the building, the additional masses for the URM walls loaded out-of-plane were also represented at the floor levels.

To scale the local out-of-plane response of the URM walls correctly, the masses of these URM walls should have been added as “smeared” masses over the height of the piers. This was not done in the test and as a result the mass of the out-of-plane loaded URM walls was a factor of two too low. Hence, the out-of-plane behaviour of the URM piers in the test was less critical than it would have been in reality. This fact must be taken into account when considering the seismic behaviour of these walls. It was, however, a conscious choice for two reasons: First, adding smeared masses to the out-of-plane loaded walls is rather difficult to achieve. Second, we wanted to avoid premature out-of-plane failure of the URM walls which could have prevented testing the model up to in-plane failure.

3 INSTRUMENTATION SETUP

The nature of the test and the size of the test specimen led to the definition of a large instrumentation setup to monitor the motion of the structure during the shaking. A significant number of instruments aimed at recording data for the study of the seismic behaviour of the out-of-plane loaded URM piers was installed. In particular each one of the out-of-plane loaded URM piers of the second, third and fourth storeys was instrumented with five potentiometers. On the top and bottom row of bricks two potentiometers (range of measure ± 25 mm) were installed measuring vertical displacements; this allowed to obtain the base and top rotations of the pier with respect to the RC slab. In addition one potentiometer (range of measure ± 125 mm) recorded the out-of-plane (horizontal) displacement at mid-height of the piers. A complete overview of all the potentiometers employed for measuring out-of-plane deformations is presented in Figure 2.

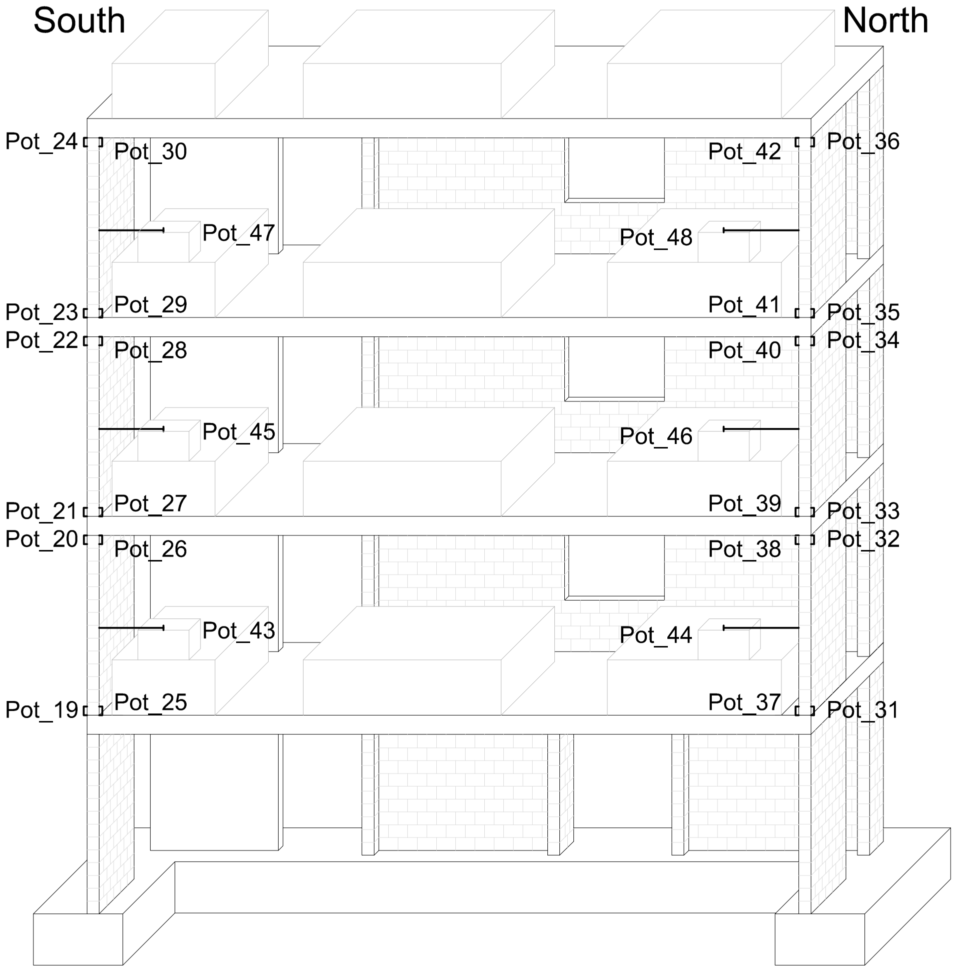

Figure 2. Potentiometers configuration for the measure of deformations of the out-of-plane loaded URM piers of the 2^{nd}, 3^{rd} and 4^{th} storey.

In Figure 3 a more detailed scheme of the position of the potentiometers is presented. The configuration of the potentiometers shown in Figure 3 is the same utilised for all the URM out-of-plane loaded piers. A photo of these potentiometers is shown in Figure 4. For all potentiometers positive values of deformations correspond to an elongation of the instruments, therefore out-of-plane displacements towards the outside of the structure.

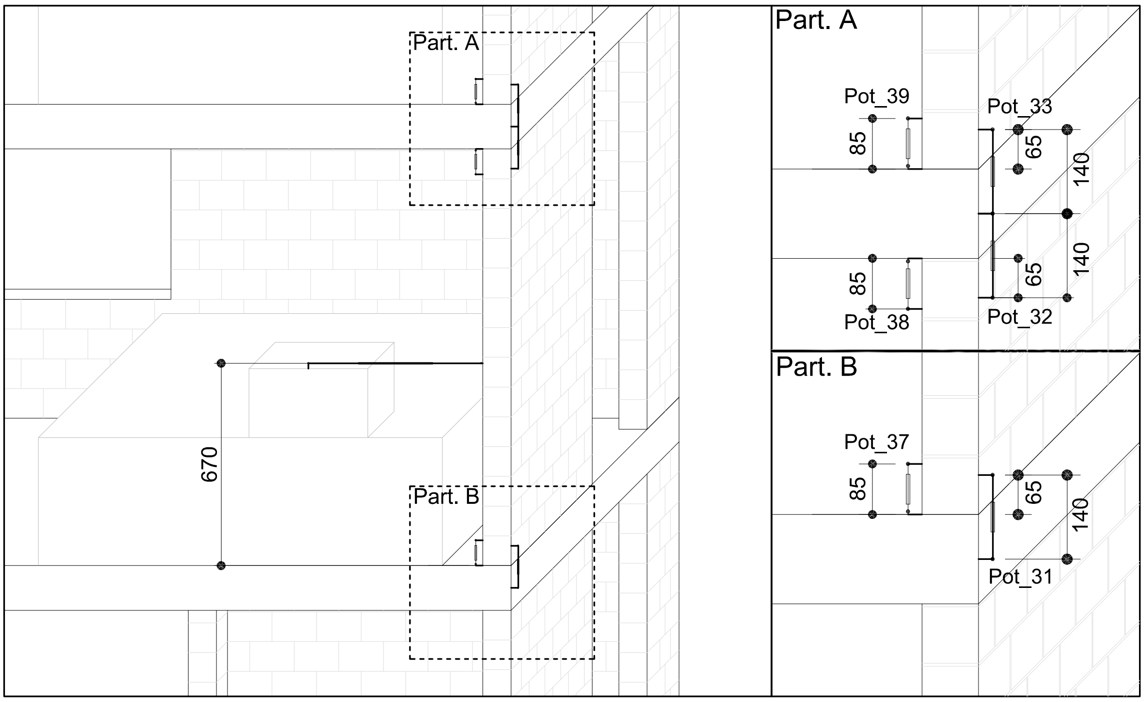

Figure 3. Potentiometers configuration for the measure of deformations of the 2nd storey out-of-plane loaded URM pier on the North face of the building, measures in mm.

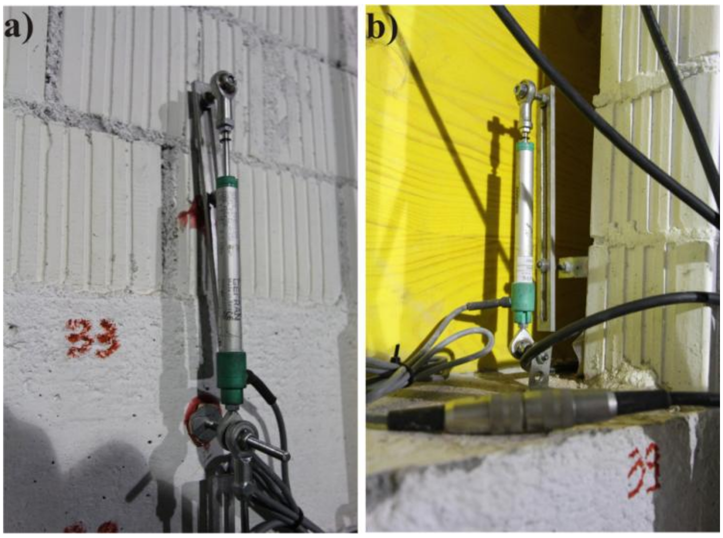

Figure 4. Potentiometers: a) "Pot_33" and b) "Pot_39" measuring the base rotation of the 3rd storey URM pier on the North face of the test specimen.

In addition to the conventional instruments, the displacement response of the structure during the shaking was recorded using an advanced optical measurement system which was able, by means of high definition cameras, to record the position of reflecting markers glued to the surface of the structure, Figure 5. This measurement system provided very useful information on the boundary conditions of the URM piers since it was capable to record not only the deformations of the in-plane loaded URM piers but also of the RC slabs.

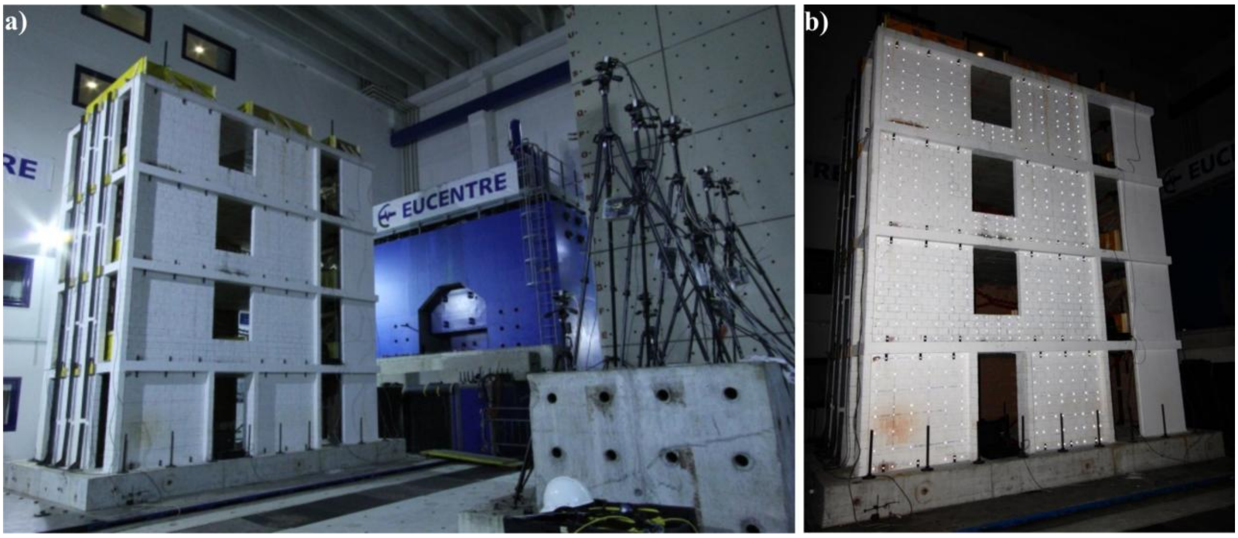

Figure 5. Optical measurement system: a) high definition camera and b) marker distribution on the West façade of the building.

4 SHAKE-TABLE TEST OBSERVATIONS

The shake-table test was performed at the TREES laboratory of the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) located in Pavia (Italy). The input motion used for the shake-table tests was the ground motion recorder at the Ulcinj station (E-W component) during the 1979 Montenegro earthquake. The record, which was applied in the longitudinal direction of the structure, was scaled in time reducing the duration by a factor $\sqrt{2}$ to account for the fact that the test specimen was built at half-scale. The experimental program of testing subjected the test specimen to nine shakings with different levels of intensities of excitation (PGA) starting from a value of 0.05 g up to a value of 0.9 g (Tondelli et al., 2013).

4.1. Visual Observations

After each shaking a survey of the building was performed. Up to the last test, damage to the out-of-plane loaded piers was not observed. As mentioned before these walls were characterized by only half the mass than what would be required to represent correctly the reality, therefore they were less sensitive to accelerations. During the last test, with a nominal PGA of 0.9 g, an evident out-of-plane deformation of the three top piers on the North side of the structure was observed while no significant deformations were observed for the out-of-plane loaded URM piers on the South side. During the survey after the shaking one could observe cracking of the mortar joints at the extremities and at mid-height for the 4th storey pier at the North side indicating that significant out-of-plane rocking had taken place, Figure 6.

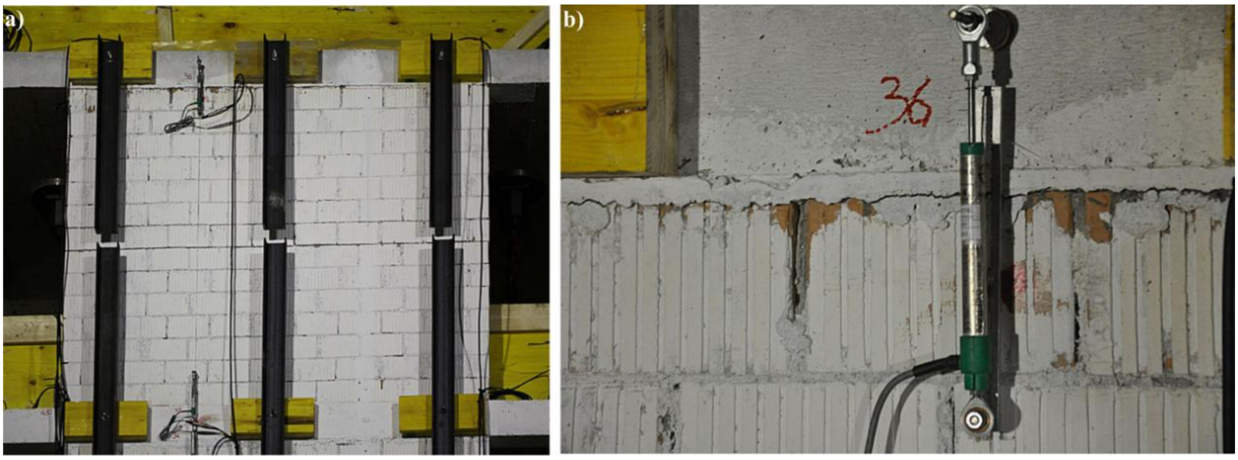

Figure 6. Damages in the out-of-plane loaded URM pier at the 4th storey on the North side of the structure: a) whole pier and b) crack at the top.

Figure 6 shows also the retaining elements (steel profiles) which were installed to avoid the possibility of an out-of-plane loaded pier collapsing onto the shake table; these elements were installed both on inwards and outwards of the out-of-plane loaded piers. These elements were installed at 5.6 cm clear distance from the UMR pier in order to not limit its displacement capacity significantly but at the same time preventing the complete collapse of the pier. During the last test it was observed that the URM pier touched the internal retaining structure thus in normal condition the pier would have collapsed.

4.2. Findings From Recorded Data

In terms of recorded data, a first indication regarding the performance of the out-of-plane loaded URM piers can be obtained from the out-of-plane displacements measured at mid-height of the piers. In Figure 7, Figure 8 and Figure 9 the profiles of the maximum out-of-plane displacements for the North and South URM walls are reported. For North and South URM walls, solid lines indicate displacements towards the outside of the structure while dashed lines correspond to displacements towards the inside of the structure.

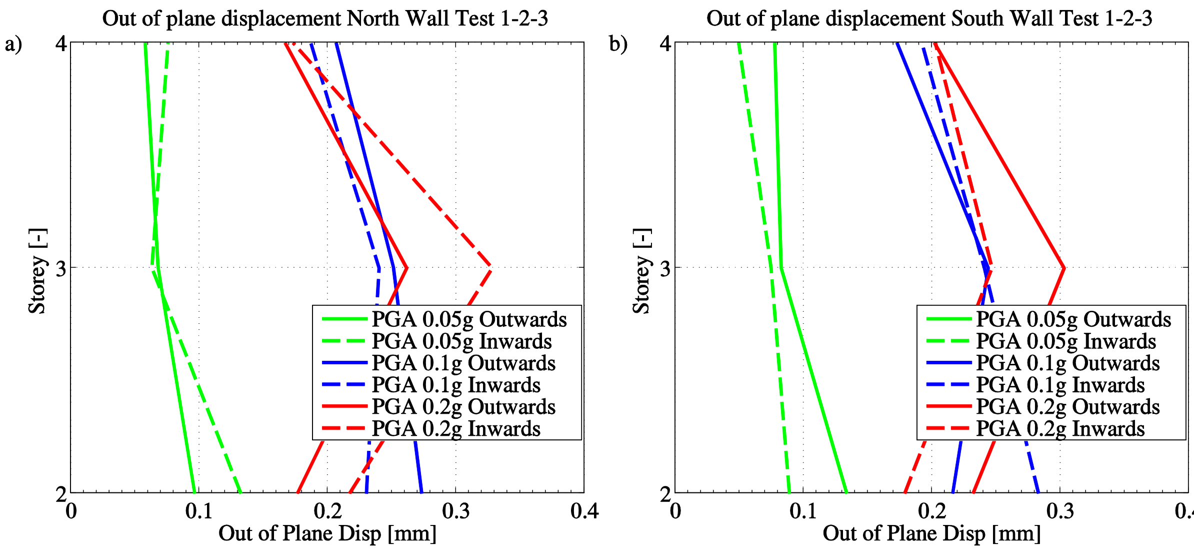

Figure 7. Out-of-plane displacement profile for the tests 1-2-3: a) North URM piers and b) South URM piers.

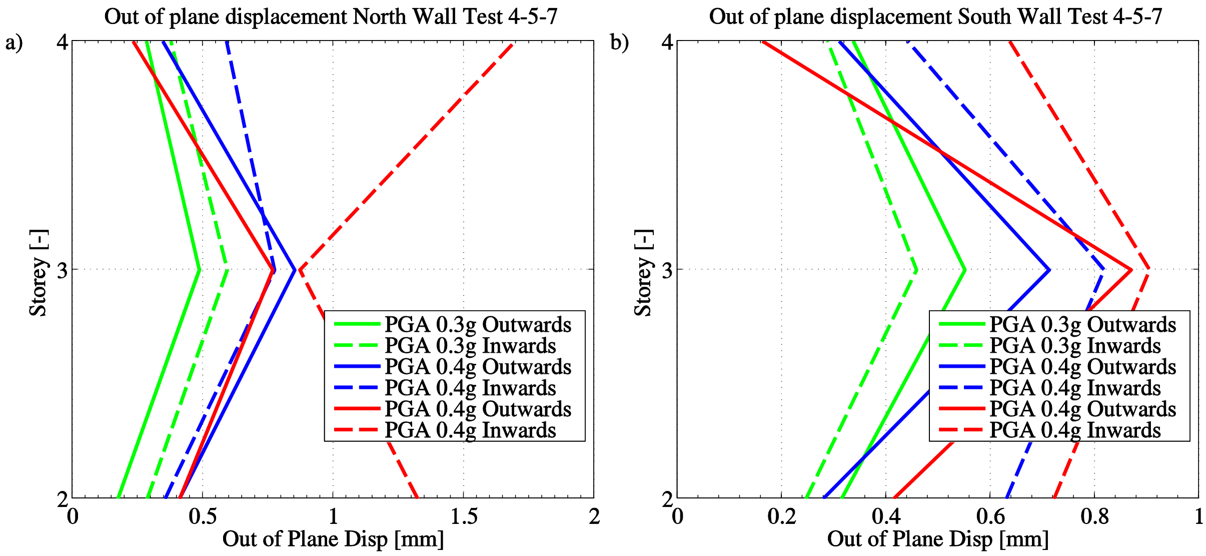

Figure 8. Out-of-plane displacement profile for the tests 4-5-7: a) North URM piers and b) South URM piers.

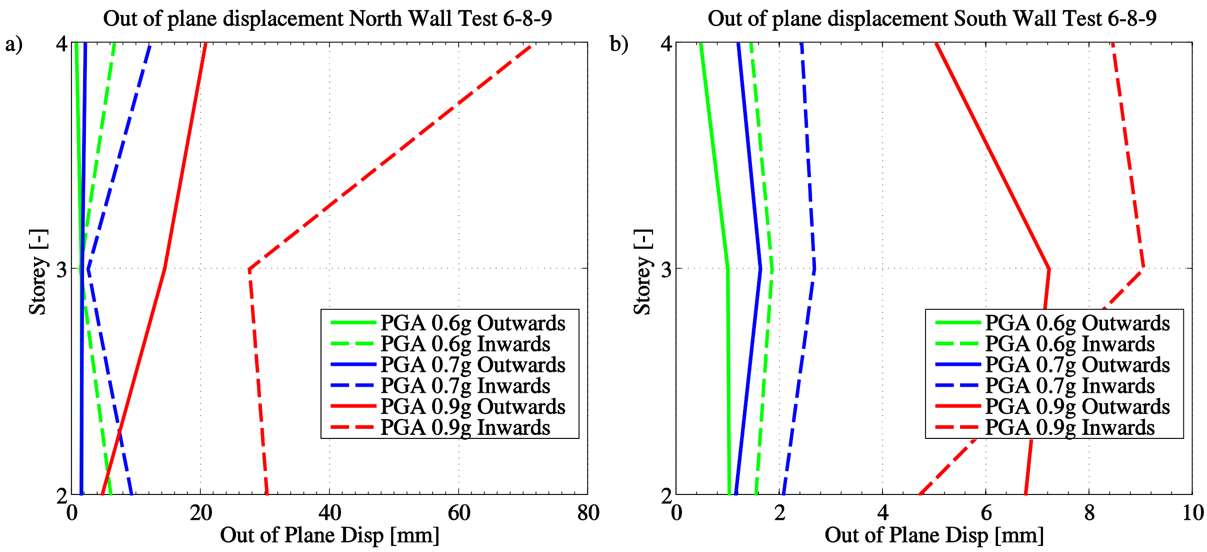

Figure 9. Out-of-plane displacement profile for the tests 6-8-9: a) North URM piers and b) South URM piers.

For levels of base acceleration up to 0.6 g very limited out-of-plane displacements of the URM piers were recorded. Nevertheless, it is evident that, for all the tests, the out-of-plane loaded piers on the South side of the structure experienced displacements which were significantly lower than those experienced by the piers on the North side. Moreover, this effect becomes more and more evident when moving to higher levels of shaking. Considering the results of the last test (nominal PGA 0.9 g) it is possible to notice that while on the North side of the structure out-of-plane displacements up to almost 70 mm were observed, the displacements on the South side were smaller than 10 mm, therefore almost one order of magnitude smaller.

As expected the different boundary conditions provided on the two sides of the structure highly influenced the out-of-plane behaviour of the URM walls. On the South side the presence of RC walls flanking the URM out-of-plane piers restrained possible deformations of the RC slabs. Depending on the loading direction the amount of axial force in the URM piers could vary but the RC slabs on top and bottom of the single URM piers undergo small deformations and therefore did not allow vertical differential movements of the top and bottom URM pier supports.

On the other hand the seismic behaviour of the North side URM piers was highly influenced by the loading direction. When the structure was pushed towards the North the URM piers were subjected to a significant increase in axial load, which reduced the out-of-plane response of the piers. Instead when pushing the structure towards the South, the RC slabs could move up vertically, since at the South end they were supported on the in-plane loaded URM piers. In particular during the last two tests, an uplifting of the slab edges and the opening of horizontal mortar joints in the in-plane loaded URM piers was observed when the structure was pushed towards the South. When loaded towards the South, the in-plane loaded URM piers tended to rock and therefore the distance between the RC slabs at the North end of the building increased. Hence, the top restraint of the North piers that were loaded out-of-plane became very weak.

To better understand this effect the reader is referred to Figure 10, Figure 11 and Figure 12, which document the boundary conditions provided to the North piers of the second, third and fourth storey during the last test. In each of these figures, plot a) shows the time history of the shake-table displacement, positive values indicate displacements towards the South. Plot b) represents the out-of-plane mid-height displacement of the URM pier where positive values indicate displacements towards the inside and negative values indicate displacements towards the outside of the structure. Finally plot c) represents the variation of the distance between the two RC slabs framing the pier. It can be observed that for the top pier, Figure 10, the maximum out-of-plane displacement was experienced when the structure moved towards the South after reaching the maximum displacement at the base in the North direction (at around 12 sec in the time series). Moreover it is easily observable how the peak out-of-plane displacement occurred simultaneously with the peak values of vertical uplift of the RC slabs. From plot c) one can observe that the distance between the RC slabs were increased by a bit more than 1.5 cm; this demonstrates that in that moment the URM pier was basically subjected to no axial load and a weak restraint at the top, which led to a high vulnerability with respect to horizontal forces and thus the out-of-plane collapse.

A similar behaviour can also be observed for the piers on the third and second storey (Figures 11 and 12). All URM piers present an asymmetric behaviour, where the out-of-plane displacements are significantly higher in the negative direction and the peaks of the out-of-plane displacements took place when the vertical uplift of the RC slabs peaked.

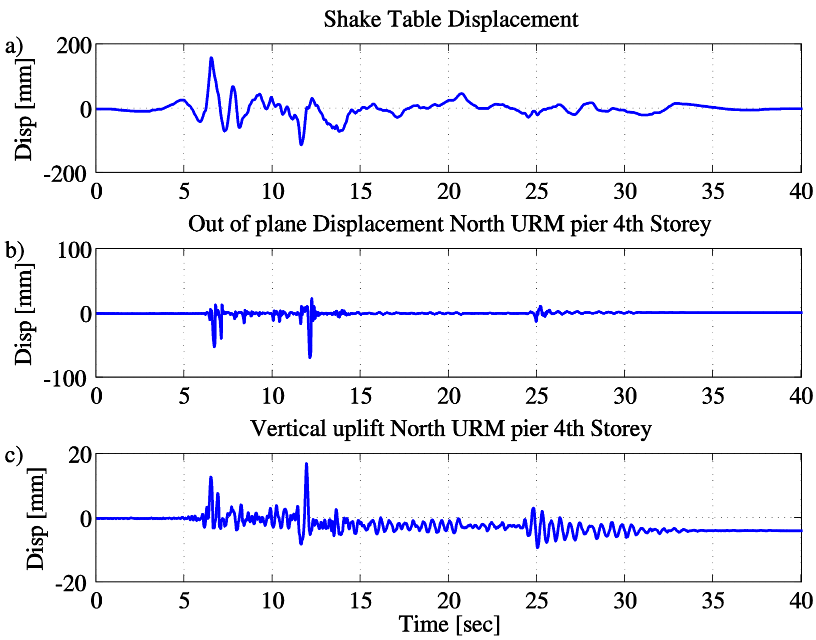

Figure 10. Time histories: a) shake-table displacement, b) mid-height out-of-plane displacement North URM pier at 4th storey and c) vertical uplift of RC slabs framing the North URM pier of the 4th storey.

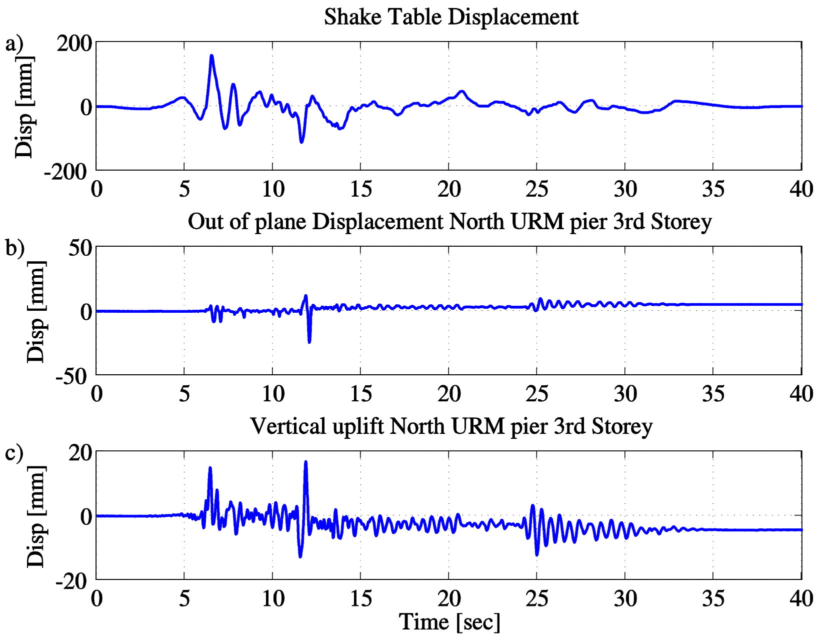

Figure 11. Time histories: a) shake-table displacement, b) mid-height out-of-plane displacement North URM pier at 4th storey and c) vertical uplift of RC slabs framing the North URM pier of the 3rd storey.

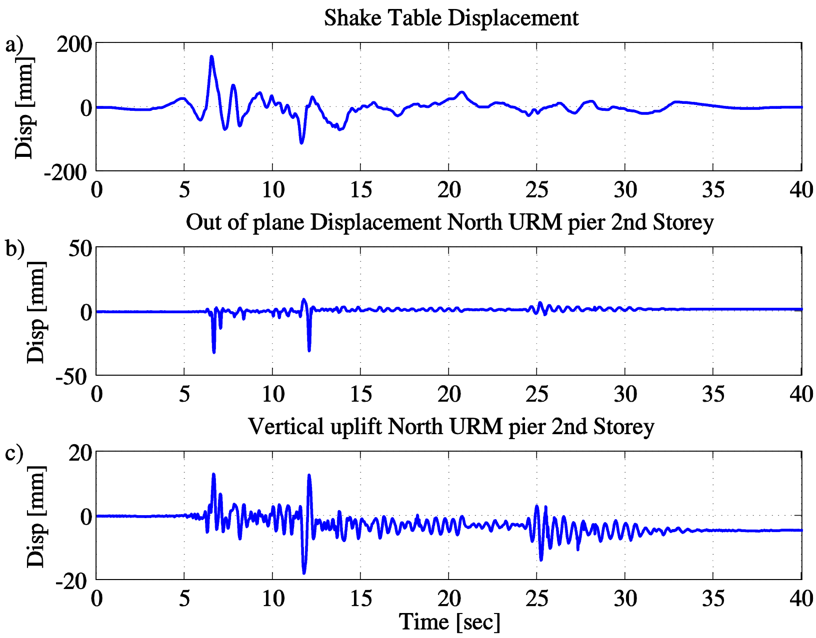

Figure 12. Time histories: a) shake-table displacement, b) mid-height out-of-plane displacement North URM pier at 4th storey and c) vertical uplift of RC slabs framing the North URM pier of the 2nd storey.

The behaviour of the three North URM piers differs nevertheless with regard to some aspects: for all three storeys there were two peaks of vertical uplift, the first at about 6.5 sec; and the second at about 12 sec; while for the two top storeys the first peak is significantly lower than the second, for the second storey the opposite holds. This effect is directly reflected in the out-of-plane displacements were for the two top piers the maximum value corresponds to the second peak while for the pier at the second storey the maximum value took place at the first peak.

Another observation concerns the profile of peak out-of-plane displacements over the height of the structure: For the North side URM piers the maximum out-of-plane displacement increases linearly from storey to storey in the positive direction but not in the negative direction. In general it is expected that piers located at higher storeys will experience higher out-of-plane displacements for two reasons: storey accelerations amplify from base to top of the structure and the axial load on the pier decreases at higher storeys. Figure 9 shows however that, in the negative direction, the pier at the second storey experienced higher out-of-plane displacement than the pier at the third storey. Several reasons could explain this observation: one possible explanation could be that different types of out-of-plane mechanisms formed at the different storeys. The out-of-plane failure is characterized in general by the formation of three hinges in the piers which identify two rigid bodies subjected to a rocking movement; the hinges, which develop in the mortar joints (Figure 6), are not always located at the extremities and at mid height of the panel. Therefore it is possible that the displacement at mid-height of the panel is not the maximum displacement experienced by the pier. Furthermore, the difference could be linked to characteristics of the RC slab motions at the top and bottom of the pier such as asynchrony and peak drifts. These points will be further investigated in a numerical study that follows (see following section).

5 CONCLUSIONS AND FUTURE DEVELOPMENT

The data recorded from the shake-table test, both from hard wired instruments and optical measurement system, allowed to observe several interesting features on the out-of-plane behaviour of URM piers in buildings with RC slabs. These points concerned in particular the influence of the boundary conditions on the peak seismic response of the URM piers. The latter depended largely on the type of walls that flanked the URM piers (RC walls or URM piers) and the loading direction. At the peak out-of-plane displacement the boundary conditions were characterised by an uplift of the top RC slab which led to a weak restraint at the top of the wall and probably zero axial load in the wall.

The main conclusion that can be drawn from this test is therefore that boundary conditions have effectively a high influence on the out-of-plane behaviour of URM piers and that often assumed boundary conditions (pinned-pinned and axial loads resulting from the gravity load case) are not representative of the boundary conditions at peak out-of-plane displacements for URM piers flanked by other URM piers. Hence, in a design code framework simply imposing slenderness and thickness limitations of URM piers to prevent out-of-plane failure may not be sufficient.

The analysis of the recorded data allows to observe key aspects in the out-of-plane behaviour of URM piers but is not sufficient to study the relative importance of different aspects in a systematic manner. Therefore, it is planned, as future development of the research program, to conduct a numerical study. This numerical campaign will focus in a first phase on the calibration of a model able to reproduce the out-of-plane behaviour observed during the shake-table test. In a second stage the numerical model will be used to study a wide range of boundary conditions of URM piers with the aim of proposing indications which can be implemented in codes or practical design procedure for the assessment of URM piers' out-of-plane capacity.

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