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OUT-OF-PLANE BEHAVIOUR OF URM WALLS IN BUILDINGS WITH RC SLABS: OBSERVATIONS FROM SHAKE-TABLE TEST

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ABSTRACT

During an earthquake unreinforced masonry (URM) walls are subjected to in-plane and out-of-plane solicitation. Premature out-of-plane failure of URM walls for small accelerations can prevent the structure from developing its global capacity. The out-of-plane behaviour of URM walls depends largely on the applied boundary conditions like: the axial load applied to the wall, the moment and axial restraint applied at the top and bottom of the wall, the relative movement of top and bottom supports of the wall due to the response of walls orthogonal to the out-of-plane loaded wall. Almost the totality of newly built URM structures is constructed with rigid diaphragms in the form of reinforced concrete (RC) slabs. The boundary conditions provided by RC slabs to URM walls, especially in structures with RC and URM walls, are not well understood and can significantly influence the out-of-plane behaviour of URM walls. In the framework of a large research programme investigating the seismic behaviour of mixed RC-URM wall structures, a shake-table test was performed at the TREES laboratory of EUCENTRE in Pavia (Italy). The test specimen, built at half scale, was especially designed to collect data on the effect of the boundary conditions provided by RC slabs to the out-of-plane behaviour of URM walls. This paper discusses the observed out-of-plane response in the shake-table test and outlines future research directions that are based on these observations.

INTRODUCTION

When performing seismic assessment of URM buildings one crucial task concerns the evaluation of possible out-of-plane failure mechanisms of URM walls. On the one hand premature out-of-plane failure of URM walls can prevent the structure from developing its global capacity; and on the other hand this type of failure mechanism depends on a large number of factors and therefore it is not simple to predict.

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.

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Tests and analyses have shown that the out-of-plane behaviour of URM walls largely depends on the applied boundary conditions. These comprise: the axial load applied to the wall, the moment and axial restraint applied at the top and bottom of the wall, the input motions and their degree of synchronism at the top and bottom of the wall. Despite – or possibly because of this complexity – many building codes, as for example the Italian building code (MIT, 2009) and the Swiss building code (SIA 2003), treat this problem in a very simplistic way and provide uniquely maximum slenderness ratios and thickness limitations for the URM walls without posing any attention on the boundary conditions. The Eurocode 8 (CEN, 2004) instead considers the effect of boundary conditions on the seismic behaviour of out-of-plane loaded walls in a very general manner. The effective height of the wall is defined by reducing its clear height to account for the relative stiffness of the elements connected to the wall and to the efficiency of the connections. In none of the international building codes consideration is given to the influence of neighbouring structural elements such as RC walls or URM walls.

This article discusses the out-of-plane response of URM walls observed in the CoMa WallS shake table test. The paper commences with a short overview on the CoMa WallS project and then presents and discusses the results with regard to the out-of-plane behaviour of URM walls. The article closes with an outlook on the planned numerical investigations.

COMA WALLS PROJECT

The CoMa WallS project, Beyer et al. 2014a and Tondelli et al. 2014, is part of a larger initiative started by the group of Earthquake Engineering and Structural Dynamics of EPFL (Switzerland) on the seismic behaviour of mixed structures. The latter are composed of URM walls and RC walls coupled by RC slabs and URM spandrels. The core of the project was the performance of a shake-table test on a URM-RC walls structure built at half scale. Among the various objectives of the project one of the most important concerned the seismic behaviour of out-of-plane loaded URM walls subjected to different boundary conditions.

The test specimen, shown in Figure 1, was a four storey structure built at half-scale composed of two RC walls and 6 URM walls. Since the input motion was applied along the longitudinal direction of the building, Figure 2, two of the six URM walls were subjected to out-of-plane loading.

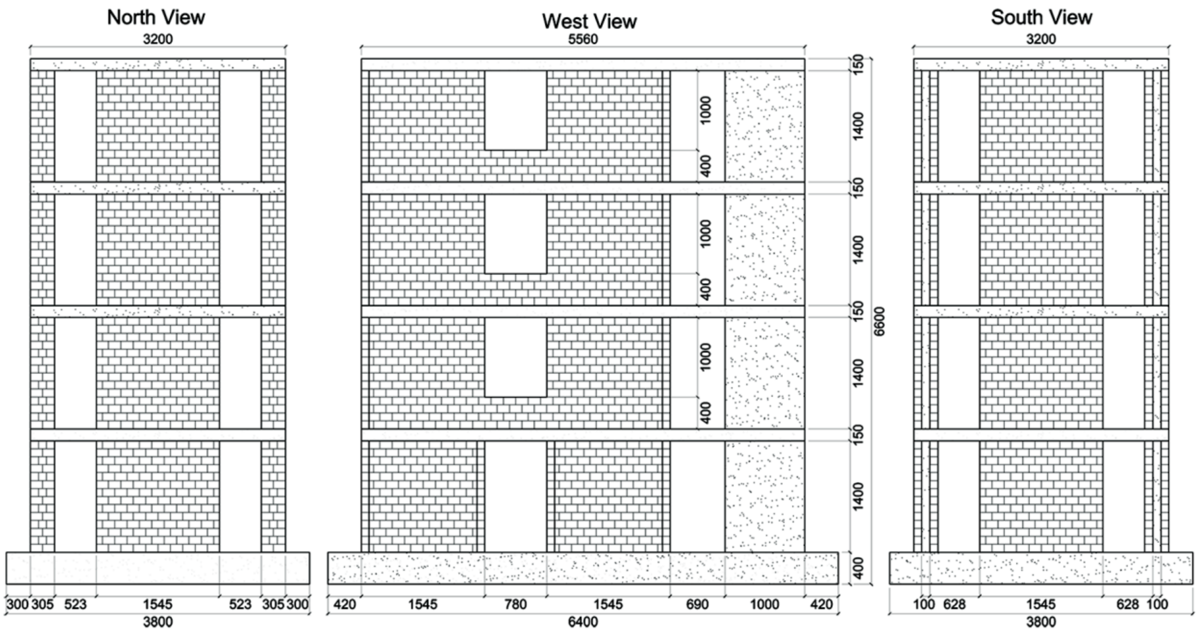

Figure 1. Test specimen: North view (left), West view (centre) and South view (right), measures in mm.

The structure was designed in such a way to provide different boundary conditions to the out-of-plane loaded URM walls of the North and South side, respectively. On the North side of the structure the out-of-plane loaded URM walls were flanked by URM walls while on the South side they were flanked by RC walls and this was expected to cause different deformations of the RC slabs and hence different constraints conditions at the top and bottom of the out-of-plane loaded URM walls.

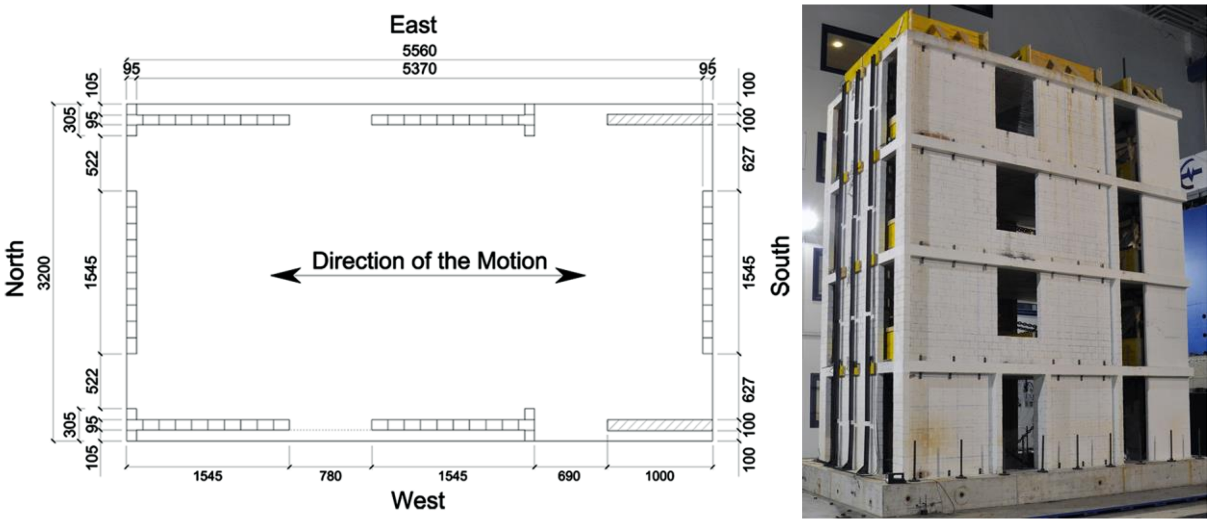

Figure 2. Test specimen: plan view (left) and view of the test specimen on the shake-table (right), measures in mm.

As outlined above the test specimen was built at half-scale and hence particular attention must be given to the scaling of the different physical properties when testing at reduced scale. In this case the “Artificial Mass Simulation” scaling law was applied with a scaling factor equal to 2. According to this model the dimensions (lengths) of the structure are halved with respect to the full scale structure while the material properties apart from the mass density remain the same. The mass density should be theoretically two times larger. Since it is not possible to alter the mass density of the concrete and masonry, additional masses were added to the structure. These additional masses should add weight to the structure but not act as structural elements. In the CoMa WallS project masses were added to the structure in the form of concrete blocks which where places on the four RC slabs. This “lumped” approach is sufficiently accurate for the global response of the structure but not for the local out-of-plane response since the additional mass corresponding to the out-of-plane loaded URM walls was also represented at the floor level.

In order to correctly scale the local out-of-plane behaviour of URM walls it would have been necessary to add the additional mass for the walls as “smeared” mass along the height of the wall. However adding smeared masses to the out-of-plane loaded walls would have been rather difficult to achieve. Moreover, the authors wanted to avoid that out-of-plane failure of URM walls would prevent testing up to in-plane failure. For these reasons the authors opted for the “lumped” solution conscious of the fact that the observed out-of-plane behaviour of the URM walls in the test was less critical than it would have been in reality and that this must be accounted for when interpreting the observed test results.

INSTRUMENTATION SETUP

The instrumentation setup necessary to monitor the motion of the structure during the shaking was composed by a large number of instruments; in total 20 accelerometers, 49 potentiometers, 24 omega gages and an optical measurement system were employed. A significant part of these instruments aimed at recording data for the interpretation of the out-of-plane behaviour of the URM walls.

Each of the out-of-plane loaded URM walls of the second, third and fourth storey was instrumented with five potentiometers. Two potentiometers (measurement range ± 25 mm) were installed on the inner and outer face of the top and bottom row of bricks recording displacements in the vertical direction to record the top and bottom edge rotations of the URM wall with respect to the RC slabs. One additional potentiometer (measurement range ± 125 mm) was employed to measure the out-of-plane horizontal displacement at the mid-height of the walls. In Figure 3 the layout of the position of the potentiometers of the 2nd storey out-of-plane loaded URM wall on the North side of the structure is shown; Figure 4 presents a complete overview of all the potentiometers employed to monitor the out-of-plane behaviour of URM walls. Photos of the two potentiometers recording the base rotation of the out-of-plane loaded URM walls at the 3rd storey of the North side of the building are presented in Figure 5.

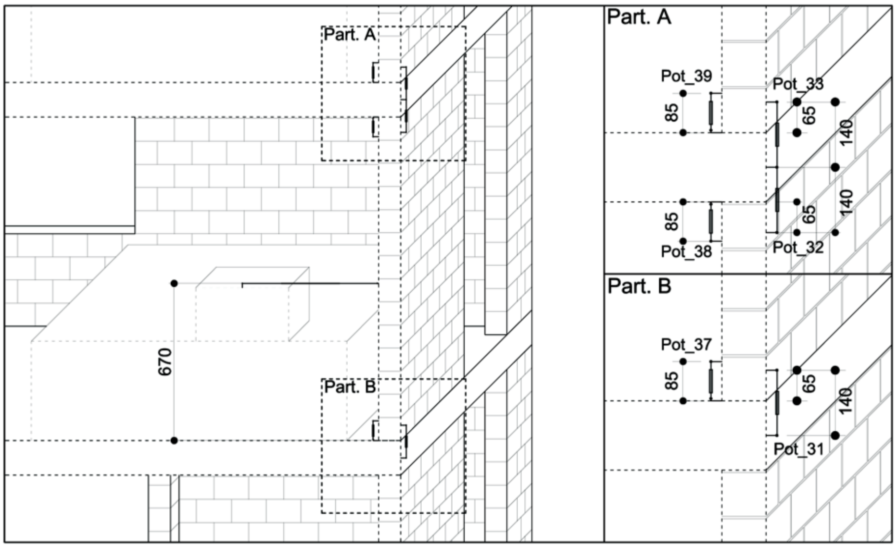

Figure 3. Potentiometers configuration for the measure of the deformations of the 2nd storey out-of-plane loaded URM walls on the North face of the building, measures in mm.

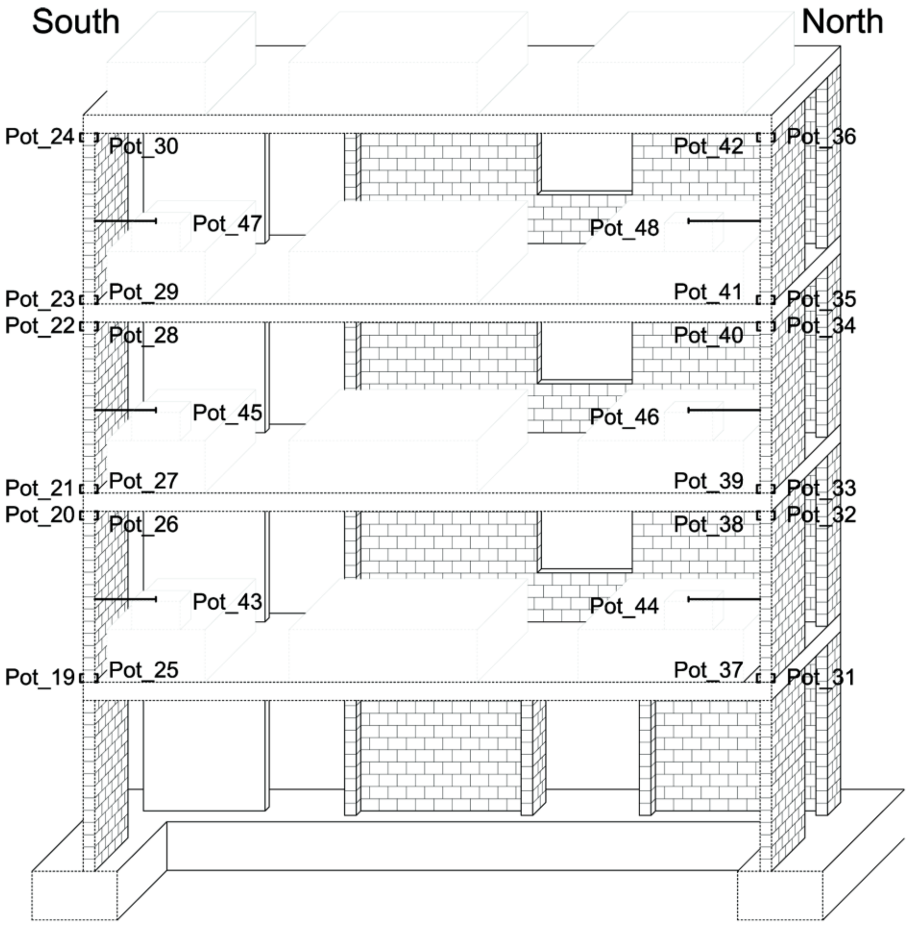

Figure 4. Potentiometers configuration for the measure of the deformations of the out-of-plane loaded URM walls of the 2nd, 3rd and 4th storeys of the structure.

Figure 5. Potentiometers: “Pot_33” (left) and “Pot_39” (right) measuring the base rotation of the out-of-plane loaded URM wall of the 3rd storey on the North side of the structure.

A useful tool employed in the monitoring of the structural behaviour of the test specimen during the shaking was the optical measurement system (Lunghi et al., 2012). The latter was able, by means of high definition cameras, to record the position of reflecting markers glued to the surface of the structure, Figure 6. This measurement system provided on the one hand a large amount of data on the in-plane behaviour of URM walls but on the other hand it also allowed to record the horizontal and vertical displacements of the RC slabs providing therefore essential informations concerning the variation of the boundary conditions that the out-of-plane loaded URM walls were subjected to during the motion.

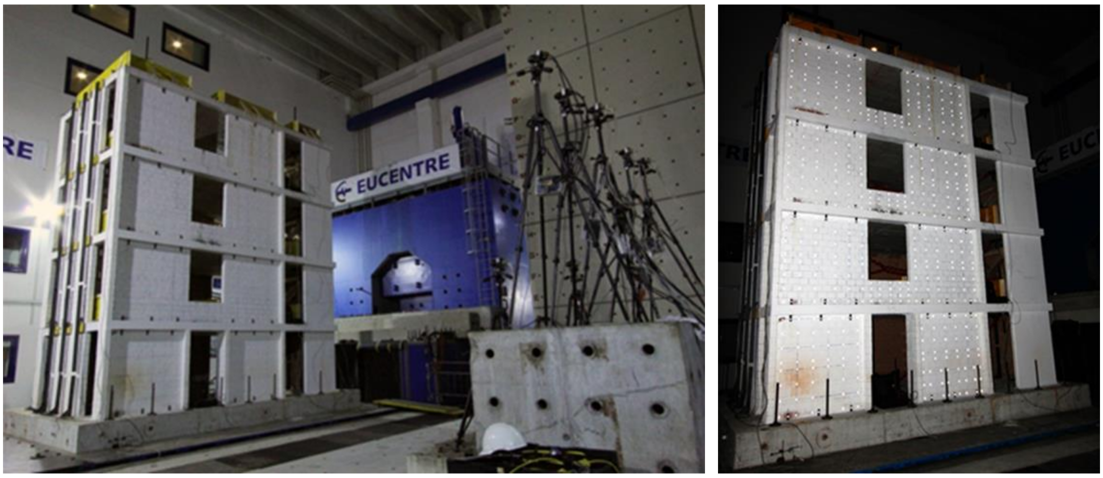

Figure 6. Optical measurement system: high definition cameras (left) and marker distribution on the West façade of the building.

SHAKE-TABLE TEST

The experimental campaign was performed at the TREES laboratory of the European Centre for Research and Training in Earthquake Engineering (EUCENTRE) of Pavia (Italy). The input motion for the shake-table test was the EW component of the ground motion recorded at the Ulciny-Hotel Albatros station during the 15th of April 1979 Montenegro earthquake. The input motion, which was applied along the longitudinal direction of the structure, was scaled in time by dividing by √2 to account for the fact that the test specimen was built at half scale. The experimental campaign comprised nine runs with different levels of intensities of excitation starting from a peak ground acceleration (PGA) of 0.05 g up to a value of 0.9 g. More detailed informations on the shake-table test campaign can be found in Beyer et al. 2014a and Beyer et al. 2014b. In the following sections the visual observations from the shake-table test campaign and the observations derived from the data recorded by the instruments installed on the structure are presented.

Visual Observations on Out-of-Plane Response of URM Walls

After each shaking a detailed survey of the structure was performed in order to identify the induced level of damage in the structure. In terms of visual identification no damage to the out-of-plane loaded URM walls was observed up to the last test. It must be recalled that the out-of-plane loaded UMR walls were characterized by half the mass they would have had in reality at full scale and therefore it was expected that they would have been less sensitive to accelerations. The last run had a nominal PGA of 0.9 g and brought the structure close to its in-plane ultimate limit state. During this run, a clear out-of-plane movement of the three top URM walls on the North side of the structure was observed. On the contrary no clear out-of-plane deformation of the walls on the South side of the structure was observed. During the survey performed after the last test cracks in the mortar joints on top and at mid-height of the top URM wall on the North side of the structure were identified, Figure 7. This was an indication that during the last shaking the URM wall was subjected to a severe out-of-plane rocking mechanism. In Figure 7 it is observable that retaining elements, in the forms of steel profiles, were installed to prevent the URM walls from falling onto the shake table, a similar retaining structure made of timber elements was installed in the internal part of the structure. This safety measure was intended to avoid that a premature out-of-plane collapse could induce a modification of the in-plane behaviour of the structure due to the redistribution of axial loads and to prevent the walls falling onto the shake table and damaging it. The retaining elements were installed at a clear distance of 56 mm from the URM walls in order to prevent the walls from overturning but at the same time not limiting the out-of-plane displacement capacity of the walls. During the last shaking it was clearly observed that the top URM wall of the North side of the structure touched the internal retaining elements and thus in normal condition the wall would have overturned.

Figure 7. Observed damages in the out-of-plane loaded URM walls at the 4th storey on the North side of the structure: whole wall (left) and crack of the top mortar layer (right).

Observations from Recorded Data on Out-of-Plane Response of URM Walls

The main objective of the sub-project on out-of-plane response was trying to understand the influence of the boundary condition on the seismic behaviour of out-of-plane loaded URM walls. To address this issue it is interesting to observe the results presented in Figure 8, Figure 9 and Figure 10. The three figures show, for the nine runs, the maximum value of the horizontal mid-height displacement for the out-of-plane loaded URM walls of the North and South side of the structure. Solid lines indicate outwards displacement while the dashed lines indicate inwards displacements. Hence, for the North wall the outward movement is towards the North and inward movement towards the South while for the South wall the outward movement is towards the South and the inward movement towards the North. The reader is reminded here that the North walls were flanked by URM walls and the South walls by RC walls (Figure 2).

While for the first three tests (Figure 8) the value of maximum displacement for North and South walls was comparable, the maximum displacements started diverging with increasing levels of shaking (**Figure 9. Out-of-plane horizontal mid-height maximum displacement for tests 4-5-7: a) North side URM walls and b) South side URM walls. (Note the different displacement scales for the two plots).**Figure 9). During the last run with a nominal PGA equal to 0.9 g (Figure 10), it can be seen that while for the 4th storey wall of the North side a maximum displacement of around 70 mm was recorded, the South URM wall of the same storey experienced a maximum out-of-plane displacement of around 9 mm, i.e., almost a magnitude smaller. This clearly indicates that the different boundary conditions of the North and South wall highly affected the out-of-plane response of the two walls. Additional findings on the maximum displacement can be drawn from Figure 10: While for the South URM walls the shape of the profile towards the internal and external part of the structure are similar and they differ only slightly in magnitude, the same does not apply to the North URM walls. For the latter it can be seen that the two displacement profiles, towards outside and inside, present a different shape and are characterized by a significant difference in their magnitude.

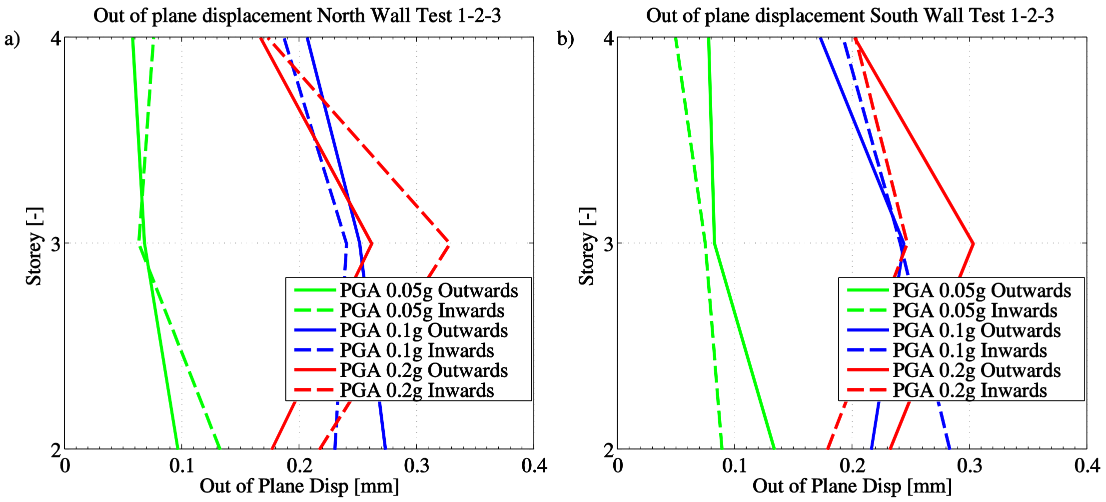

Figure 8. Out-of-plane horizontal mid-height maximum displacement for tests 1-2-3: a) North side URM walls and b) South side URM walls.

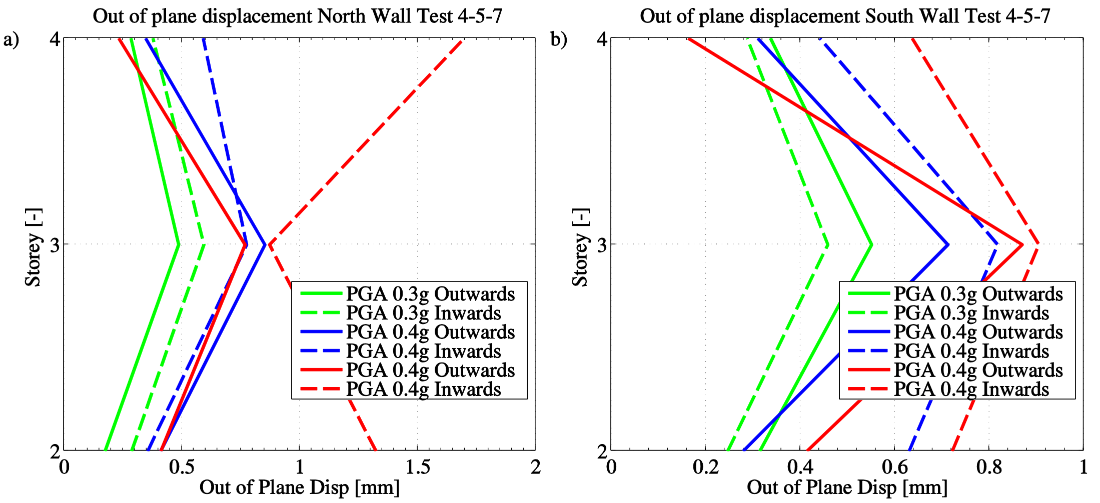

Figure 9. Out-of-plane horizontal mid-height maximum displacement for tests 4-5-7: a) North side URM walls and b) South side URM walls. (Note the different displacement scales for the two plots).

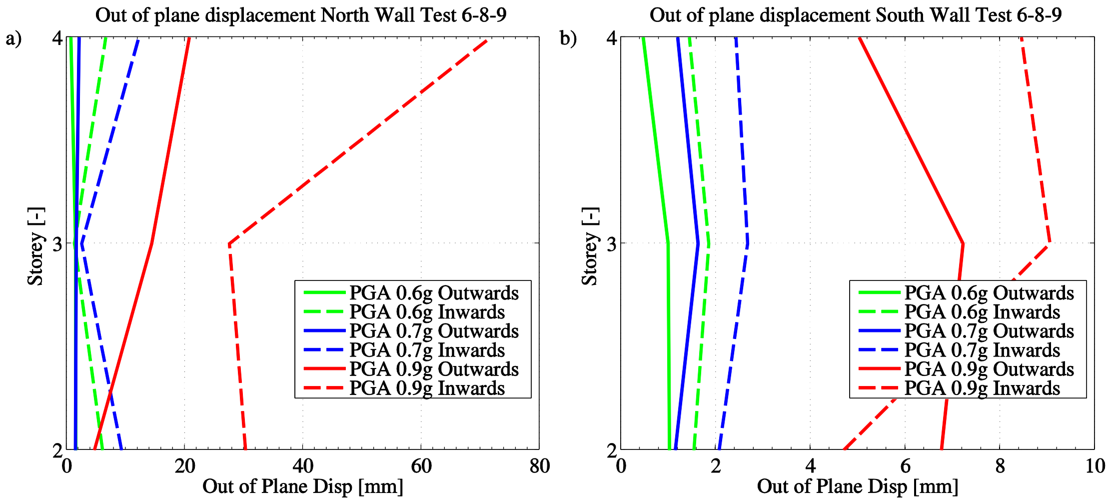

Figure 10. Out-of-plane horizontal mid-height maximum displacement for tests 6-8-9: a) North side URM walls and b) South side URM walls (Note the different displacement scales for the two plots).

At a nominal PGA of 0.9g, the displacements of the North wall of the fourth storey are larger for an inward movement. For an outward movement, the maximum displacement of the same wall is less than half. The same holds for the second storey wall of the North side while for the third storey wall the displacements in the two directions are rather similar.

The afore-mentioned observed features can be explained by analysing the global in-plane behaviour of the test specimen that, as expected, had a significant influence on the local out-of-plane behaviour. The maximum inwards displacement tends to be larger than the maximum outwards displacement due to the global overturning moment: The maximum inwards displacement occurs when – due to the global overturning moment – the axial force in the out-of-plane loaded wall decreases. As a result the out-of-plane resistance is less and therefore the out-of-plane displacement lager. This can be, for example, observed for the South wall at the runs with PGA=0.6, 0.7 and 0.9g. For the North wall, the same effect can be observed. However, for this wall the difference between maximum inwards and outwards displacement is much larger than for the South wall.

This larger difference results from the fact that for the North wall not only the static boundary conditions (i.e., the axial force) but also the kinematic boundary conditions (i.e., the restraint at the top of the wall) changed with loading direction: The North walls were flanked by URM walls while the South walls were flanked by RC walls. On the North side, the RC slab was supported by the URM walls and could therefore uplift when the axial force in the walls reduced due to the global overturning. This reduced the lateral restraint to the North wall and rendered it very susceptible to out-of-plane displacements for the inward loading direction. Hence, for the North wall not only the axial load but also the kinematic boundary conditions at the top of the wall changed with the loading direction. On the South side, the RC walls restrained the RC slab from uplifting and therefore the kinematic boundary conditions of the South walls were independent of the loading direction and only the static boundary conditions (i.e., the axial force in the wall) changed with loading direction.

To support this hypothesis we can refer to Figure 11, Figure 12 and Figure 13 which document the boundary conditions provided to the three top out-of-plane loaded North side URM walls. Each figure is composed by three parts: part a) reports the displacement time history of the shake-table, positive values of displacements are towards South; part b) shows the out-of-plane horizontal displacement time history at mid-height of the wall, in this case positive values are towards the outside of the structure. Finally part c) reports the variation of the vertical distance between the two RC slabs framing the wall, positive values correspond to an increase of distance between the two slabs.

Figure 11 shows the behaviour of the 4th storey URM wall. We can observed that the maximum out-of-plane displacement was attained when the structure had just reached the maximum base displacement in the North direction and the loading was reversing towards South (at around t=12 sec). The peak displacement is experienced simultaneously to the maximum elongation of the distance between the two supports which is around 17 mm; such a value underscores that in that instant the URM wall was subjected to no axial load and it was weakly restrained at its top edge; as a result it became highly vulnerable to out-of-plane deformations. The maximum displacement value (around 67 mm) corresponds to the distance of the internal retaining elements from the wall. This proves that during the motion the wall touched the retaining elements and that in a "not-constrained" condition it would have failed due to out-of-plane displacements.

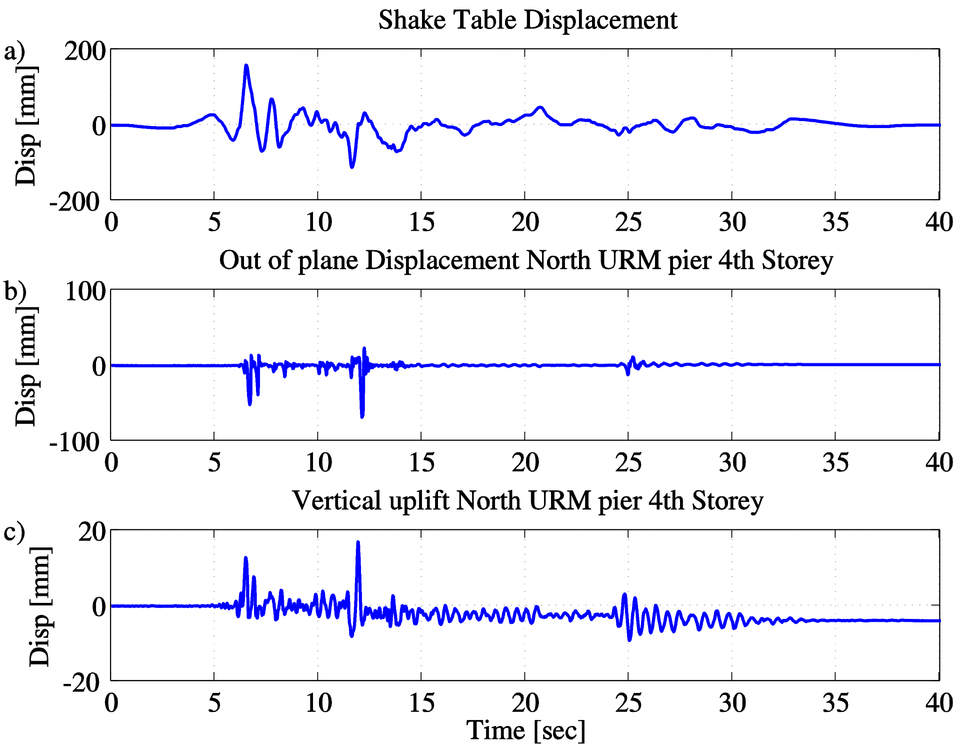

Figure 11. Time histories: a) shake-table displacement, b) mid-height out-of-plane displacement of the North URM wall of the 4th storey and c) vertical uplift of RC slabs framing the North URM wall of the 4th storey.

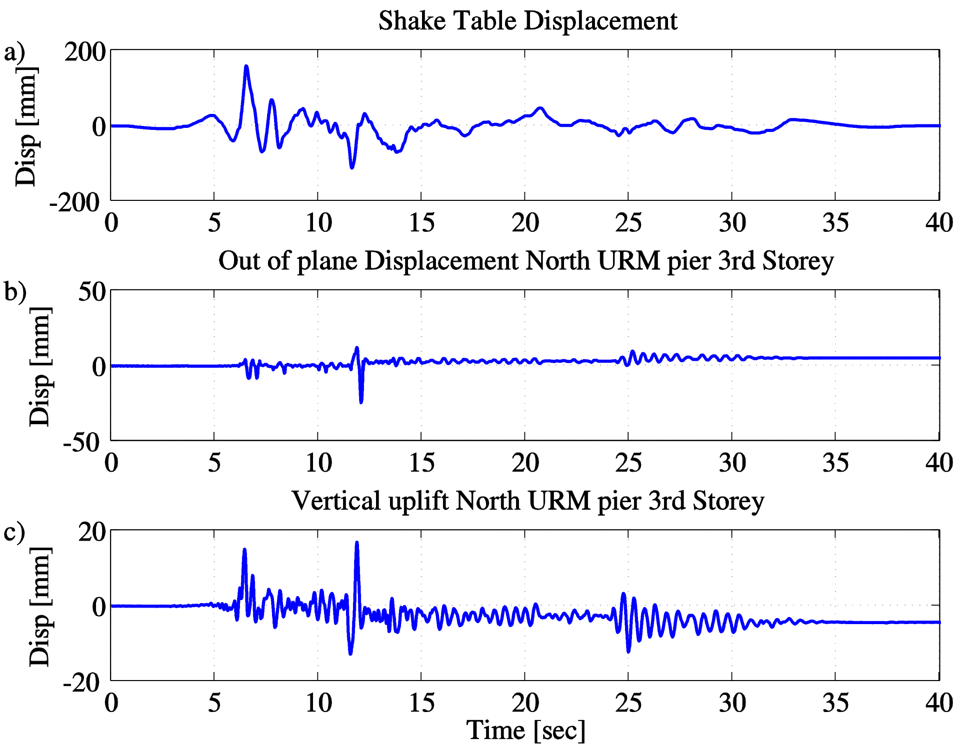

Figure 12. Time histories: a) shake-table displacement, b) mid-height out-of-plane displacement of the North URM wall of the 3rd storey and c) vertical uplift of RC slabs framing the North URM wall of the 3rd storey.

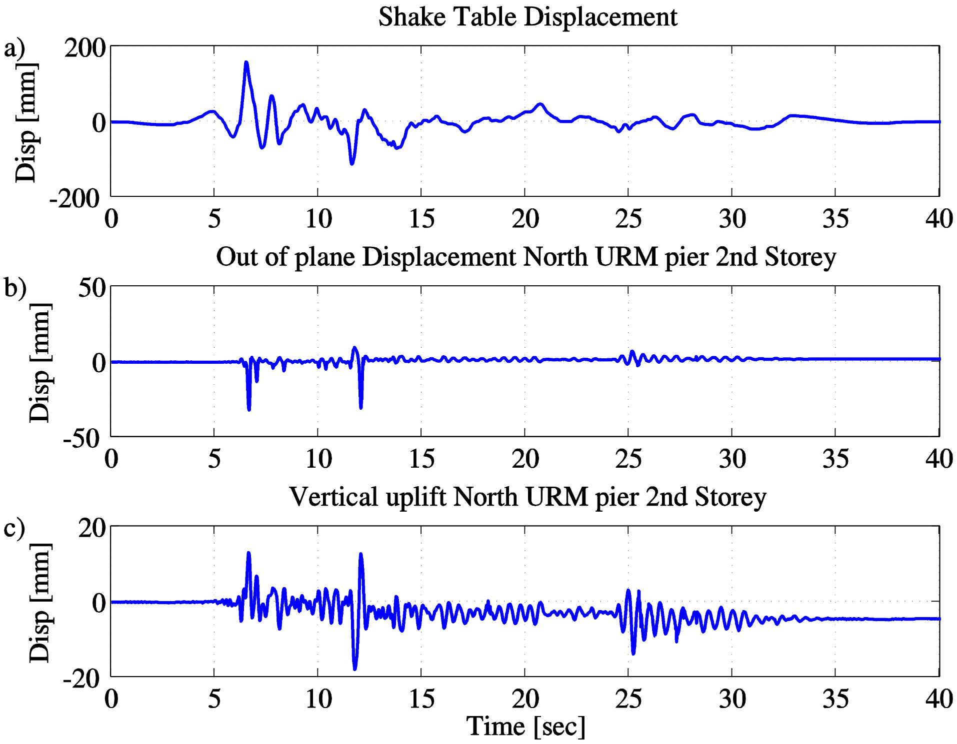

Figure 13. Time histories: a) shake-table displacement, b) mid-height out-of-plane displacement of the North URM wall of the 2nd storey and c) vertical uplift of RC slabs framing the North URM wall of the 2nd storey.

The recording from the 3rd and 2nd storey URM walls, Figure 11 and Figure 12 respectively, present similar features to those showed by the 4th storey URM wall. For all walls a significant asymmetrical behaviour in terms of out-of-plane displacements was observed and the inwards displacement exceeded always the outwards displacements. For all the three walls we observe that the peak out-of-plane displacements coincide with the peak vertical openings of the supports and again these two peaks take place when the loaded is reversed from North to South. Nevertheless a difference can be observed in the behaviour of the three walls; the top two walls experienced a main peak, both in terms out-of-plane displacement and vertical opening, the peak taking place at the same time instant, at around t=12 sec, for both of them. The 2nd storey URM wall underwent two main peaks of similar amplitude at around t=6.5 sec and t=12 sec. Moreover for this wall the first peak was the one that showed the maximum value of out-of-plane displacement.

A peculiar feature concerns the maximum out-of-plane displacement profiles shown by the North side UMR walls for the last four tests (Figure 9a and Figure 10a). When considering the profile towards the external side of the structure (solid line) we can see that at higher storeys correspond increasing values of displacements. This is the general expected behaviour of URM walls subjected to out-of-plane seismic excitations since moving to higher storeys the walls are subjected to higher values of acceleration and at the same time to lower values of axial load, which makes the UMR walls more vulnerable to out-of-plane deformations. When we consider the out-of-plane displacement profiles towards the inner part of the structure (dashed line) we can observe that in general the URM wall of the second storey experienced higher values of maximum out-of-plane displacement with respect to the third storey wall. Different factors could be the cause of this peculiar behaviour: firstly it is possible that different type of out-of-plane mechanism took place at the different storeys. For simple URM walls like the ones tested the out-of-plane collapse mechanism is linked to the formation of three hinges and a cinematic mechanism composed by two rigid bodies subjected to rocking. The hinges, which form in the mortar joints as shown in Figure 7, are not always located at the middle and at the top and bottom edges of the wall, as observed in the figure. Probably at the second and third storey a different mechanism was formed; clearly when the mechanism is different the maximum out-of-plane displacement is not attained anymore at the mid-height of the panel but where the mid-hinge formed. Hence, it is possible that the displacements recorded in the test for the different URM walls do not always correspond to the maximum displacements experienced by the wall since the displacements were only measured at mid-height of the walls. A further reason for the particular out-of-plane displacement profile could be related to the characteristics of the RC slab motion at the top and bottom of the URM walls such as asynchrony and peak drifts. These issues will be addressed in a numerical study which is the next step of the project (see the following section).

CONCLUSIONS

The presented shake-table test project allowed to collect a large amount of data, both from conventional instruments and optical measurement system, for the investigations of seismic behaviour of out-of-plane loaded URM walls in buildings with RC slabs. In particular the observations obtained from the nine runs resulted in new insights into the influence of the boundary conditions on the out-of-plane behaviour of UMR walls. The latter was shown being largely influenced by the type of elements flanking the URM walls, i.e., RC walls or URM walls, and by the loading direction.

It can be concluded that the static and kinematic boundary conditions play a key role for the out-of-plane behaviour of URM walls and that the kinematic boundary conditions which are often assumed when analysing URM walls subjected to out-of-plane accelerations (pinned-pinned with the axial load deriving from the gravity loads) are not representative of the real conditions at peak out-of-plane displacements for URM walls framed by RC slabs and flanked by URM walls.

The data collected during the test allowed to draw important conclusions on the out-of-plane behaviour of URM walls but they are still not sufficient to study the importance of the different aspects and factors in a systematic manner. For this reason the experimental campaign will be followed by a numerical study. In a first phase a numerical model will be validated against the observed out-of-plane behaviour during the shake-table test. In a second phase the validated numerical model will be employed to study a wide range of static and kinematic boundary conditions related to different structural configurations with the goal of defining indicators that control the out-of-plane response and could be implemented in code regulations.

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