QUASI-STATIC CYCLIC TESTS OF MIXED RC-URM WALL STRUCTURE

A. Paparo[1] and K. Beyer[2]
[1] Ph.D. student, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, alessandro.paparo@epfl.ch
[2] Professor, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, katrin.beyer@epfl.ch

ABSTRACT
In several seismic countries, residential buildings are constructed using both reinforced concrete (RC) and unreinforced masonry (URM) walls. Despite their popularity, there is a general lack of knowledge concerning the seismic behaviour of such mixed systems and they are often designed using oversimplified assumptions. For this reason, a research programme was initiated at the EPFL with the objective to contribute to the understanding of the seismic behaviour of such structures. This paper focuses on a quasi-static cyclic test of a mixed structure. The specimen is a two-third scale model and is composed of a two-storey RC wall coupled to a two-storey URM wall by means of RC beams at each floor. The horizontal forces are applied at the two floor levels. The axial load applied to the URM wall was chosen in order to cause a shear failure in the URM wall. A particular test set-up allowed the measurements of the reaction forces (axial force, shear force and bending moment) at the base of the URM wall. From the applied horizontal and vertical loads the reactions at the base of the RC wall were deducted. In such a way it was possible to back-calculate the distribution and re-distribution of the external forces between the two walls. The article describes the choice of a test unit representing a reference four-storey four-wall mixed structure, the test unit, the test set-up and selected test results like the distribution of the reaction forces at the base of the two walls.

KEYWORDS: seismic behaviour, mixed RC-URM wall structures, quasi-static cyclic tests

INTRODUCTION
Mixed RC-URM wall structures are composed of RC walls coupled to URM walls through RC slabs at each floor level. Figure 1 represents a typical mixed RC - URM wall structure. When designing such mixed structures, it is assumed that the vertical loads are distributed between the RC and URM walls according to the tributary areas of the walls. For the seismic design, however, only the lateral stiffness and strength of the RC walls is typically accounted for. Nevertheless, during an earthquake, URM walls are subjected to the same drift demands as the RC walls and will most likely be the first vertical elements to lose their axial load bearing capacity causing the collapse of the structure.

Numerical analyses of mixed RC-URM walls [1] have shown that URM walls have to be considered when the horizontal strength and stiffness of a structure are evaluated: for instance it was found that *(i)* the inter-storey drift profile of mixed RC-URM wall structures differs from the inter-storey drift profile of uncoupled walls and *(ii)* deformations in URM walls coupled to RC walls are not concentrated at the first storey, but distributed over the height of the building. At the same time, a literature review showed that experimental evidence on the seismic behaviour of mixed RC-URM wall structures is missing. For this reason, an experimental campaign has been initiated at the Swiss Federal Institute of Technology of Lausanne (EPFL) in which both dynamic and quasi-static cyclic tests on mixed RC-URM wall structures are performed.

This paper focuses on a quasi-static cyclic test of such a mixed structure. The specimen is a two-third scale model and is composed of a two-storey RC wall coupled to a two-storey URM wall by means of RC beams at each floor level. The objective of this test is to provide high quality experimental data to calibrate and evaluate numerical and analytical models. This paper presents the reference structure, the test unit, the test set-up as well as selected results like the distribution of the reaction forces at the base between the two walls and a brief summary of test observations.

Figure 1: Typical mixed RC-URM wall structure (Photo: T. Wenk).

EPFL TESTS: REFERENCE STRUCTURE AND TEST UNITS

Two two-third scale test units of mixed RC-URM wall structures were built and tested at the structural engineering laboratory of EPFL. Each test unit consisted of a two-storey URM wall coupled to a two-storey RC wall by means of two RC beams at each floor. The main difference between the two systems was the axial load applied at the top of the masonry wall: for the first system (TU1) the axial load applied was 400 kN and caused a shear mechanism; for the second test (TU2) the axial load applied to the URM wall was decreased to 200 kN in order to achieve a rocking behaviour. Also the axial load applied at the top of the RC wall was changed between the two tests from 125 kN to 0 kN. This paper presents the results of TU1. Each test unit aimed at representing the most critical elements of a four storey mixed RC-URM wall structure regarding the failure mechanism and the interaction between the members. Owing to the coupling by the RC beams, the structure featured a different behaviour for the negative and the positive loading direction.

The reference structure is a four storey building (Figure 2). One facade is composed of three URM walls with a length of 2.1 m each and one RC wall with a length of 1.2 m. The walls are coupled at the floor levels by means of RC slabs. Due to the shear forces transferred by the RC slabs, during an earthquake the axial force in the external walls changes, whereas it is almost constant in the internal walls since RC slabs frame into these walls form both sides.

Since RC walls and, in particular, URM walls are sensitive to the variation of the axial load and since failure is expected in the lower storeys, the most interesting part of the reference structure comprises the two lower storeys of the two external walls. The test unit featured therefore this part of the reference structure. The URM wall's length was 2.1 m while the RC wall's length was 0.8 m; the thickness of both walls was 0.15 m. The RC beams, connecting the two walls, had a cross section of 0.45 m (width) x 0.2 m (height) and represented the effective width of the slabs in the reference structure. According to Priestley et al. [2], the effective width of slabs coupling internal walls can be estimated as three times the wall thickness. The two RC beams were designed to provide approximately the same variation of axial load at the base of the wall as in the reference structure, where the walls are coupled by four slabs. In addition, the reference structure is composed of three URM walls, whereas the test unit comprised just one. To take into account this difference, the test unit differed from the reference structure in three points:
(i) the URM wall's aspect ratio (wall's length over wall's height) was increased in comparison to the reference structure;
(ii) the RC wall's aspect ratio was instead decreased in comparison to the reference structure;
(iii) the external vertical load applied at the top of the RC wall was decreased from 200 kN (load proportional to the tributary area) to 125 kN.

Pushover analyses on the reference structure and on the test unit showed that the behaviour of the test unit is representative of the behaviour of the reference structure regarding the failure mechanism of the URM wall and regarding the redistribution of the axial load between the two walls. In addition, the influence of the RC wall on the overall behaviour of the test unit is found to be similar to the influence of the RC wall on the reference structure.

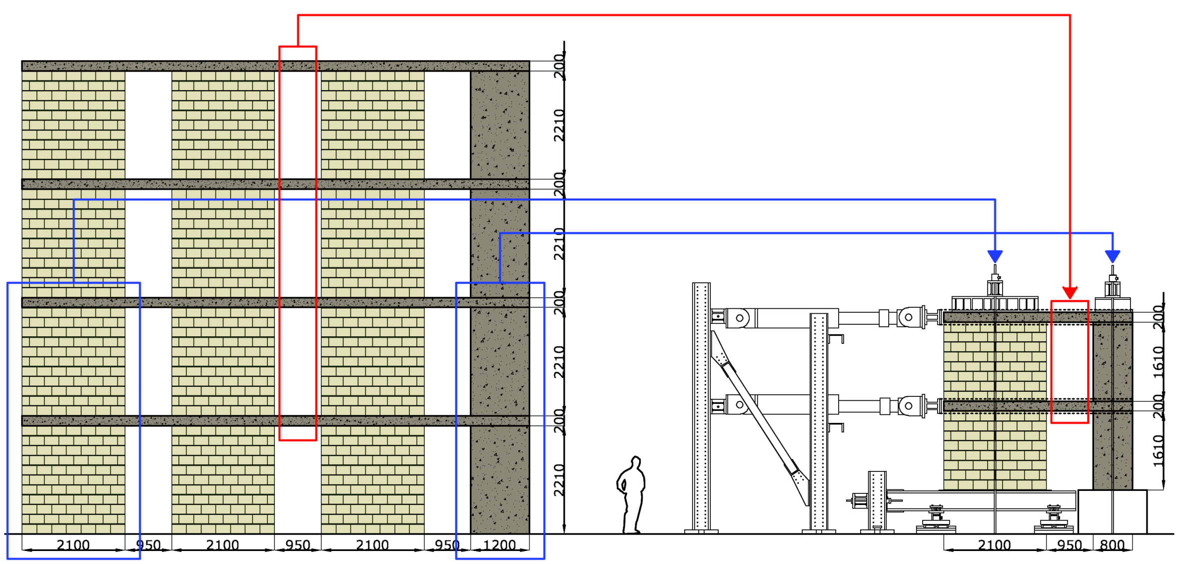

Figure 2: Reference structure and test unit; the elements of the reference structure represented in the test unit are highlighted; all dimensions in mm.

TEST SET-UP

One objective of the test was to investigate the contribution of the URM and the RC wall to the system's strength. A particular test set-up allowed the measurement of the reaction forces (axial force, bending moment, shear force) at the base of the URM wall. The layout of the test set-up is presented in Figures 3a and 3b. The URM wall was founded on one stiff steel beam supported by two systems of sliders and load cells measuring the variation of the axial load and bending moment during the test. In addition, the variation of the shear force at the base of the URM wall was measured by a system of load cells and rotational hinges at the left end of the steel beam. Figure 4a shows the close-up of the steel beam with the systems measuring the horizontal and vertical reaction forces at the base of the URM wall. The precision of the systems measuring the reaction forces was tested before the construction of the test unit by applying different configurations of horizontal and vertical forces of known magnitude to the steel beam. The RC wall was connected to the strong floor through a RC foundation. According to Figure 4b, the reaction forces (variation in axial force N_{urm} due to the applied horizontal forces, shear force SF_{urm} and bending moment M_{urm}) at the base of the URM wall can be calculated with the following equations:

$$N_{urm} = N_1 + N_2 - N_3 \tag{1}$$

$$SF_{urm} = H \tag{2}$$

$$M_{urm} = \left(-N_1 + N_2\right) \times 1.2.m + N3 \times 2.4446m + SF_{urm} \times 0.22m \tag{3}$$

where N_1 and N_2 are the variation of the vertical reaction forces and H is the variation of the horizontal force in the steel beam corresponding to the variation of base shear in the URM wall. N_3 is the variation of a parasitic force caused by the friction in the two rotational hinges which are part of the system measuring the horizontal reaction force. This force N_3 is accounted for in the evaluation of the axial force at the base of the URM wall N_{urm} and in the bending moment at the base of the URM wall M_{urm}; N_3 can account for up to 2% of the axial force N_{urm} and 4% of the moment M_{urm}. The variation of bending moment at the base of the URM wall was calculated considering the rotational equilibrium about point A (Figure 4b).

The forces acting on the system are the two horizontal forces, that are applied by the two horizontal actuators, the vertical forces applied by the system of hollow core jacks and rods, the self-weight of the test unit and the parts of the test set-up that were supported by the test unit. From these forces and the measured reaction forces at the base of the URM wall, the variation of the reaction forces at the base of the RC wall can be back-calculated (variation in axial force N_{rc} due to applied horizontal forces, shear force SF_{rc} and bending moment M_{rc}). In particular, the variation of axial load in the RC wall is the same as in the URM wall:

$$N_{rc} = N_{urm} \tag{4}$$

The axial load was applied at the top of the walls by means of vertical rods and hollow core jacks (Figures 3) and kept constant during the test. An out-of-plane frame prevented out-of-plane deformations during testing (Figure 3b). The average drift of the structure δ was calculated as the ratio between the top displacement (Δ_{top}) and its corresponding height (H_{struct}), as shown in Figure 3a:

$$\delta = \frac{\Delta_{top}}{H_{struct}} \times 100 \tag{5}$$

The top displacement (Δ_{top}) was measured at mid-height of the second storey RC beam (Figure 3a).

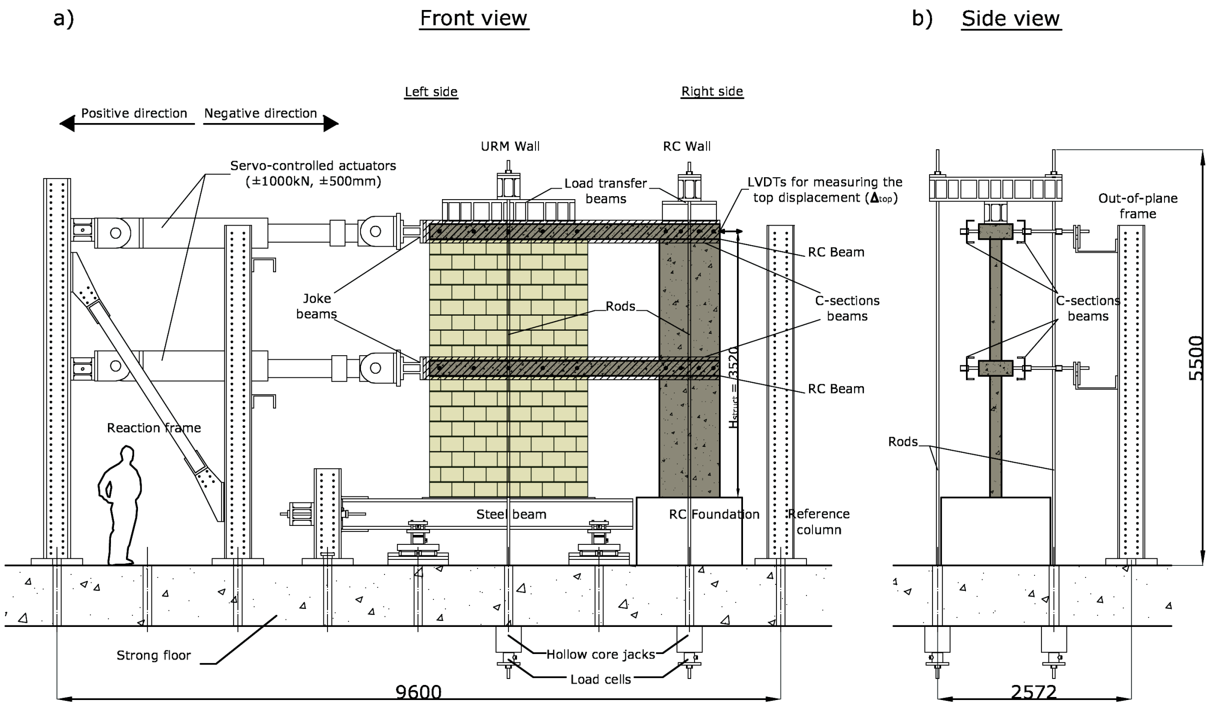

Figure 3: Drawing of the test set-up: (a) front view, (b) side view; all dimensions in mm.

During the quasi-static cyclic test, the servo-controlled actuator at the second storey applied a sequence of cyclic lateral displacements (Figure 3a). The actuator of the first storey was slaved to the actuator of the second storey and applied the same force as the actuator of the second storey. The lateral forces were transferred to the two walls through two C-section beams attached to the outer edges of the RC beam by means of nine bars per storey. The nine bars allowed distributing the horizontal force along the length of the RC beam. Applying a concentrated force at the end of the RC beam, which is often done in quasi-static cyclic tests, would have introduced an axial force in the coupling beams, which would have modified the moment capacity of the coupling beams. By changing the number of the bars, the desired distribution of the horizontal forces between the two walls was obtained. The final bar configuration used and the estimated base shear distribution is shown in Figure 5a. The bars did not all transmit the same force, since also the deformation of the C-section beams between two bars was not negligible. As a consequence, the bars applying the force to the URM wall, which are closer to the actuators, transmitted more force to the RC beams than the bars applying the force to the RC wall.

LOADING HISTORY

The loading history comprised two fully reversed cycles for each amplitude level up to a drift of δ=0.25%. The amplitudes of each half-cycles corresponded to the following average drift levels δ: 0.025%, 0.05%, 0.1%, 0.15%, 0.2% and 0.25%. At each load step the loading was stopped, photos were taken and cracks were marked. At the second load step corresponding to an average drift level of 0.3%, the strength of the URM wall deteriorated rapidly and the force in the horizontal actuators dropped by more than 20%. To avoid a premature axial load failure of the URM wall, the test was continued only in the positive direction and only half cycles were applied. The remaining average drift levels applied are: 0.4%, 0.45%, 0.5%, 0.6%, 0.8% and 1%. A schematic figure of the loading protocol is shown in Figure 6. The drift controlled load steps commences with LS2. LS0 refers to the state before any displacements or forces were applied (zero measurements). LS1 refers to the load state when the axial loads at the top of the walls were applied and the servo-hydraulic actuators applying the horizontal loads were connected.

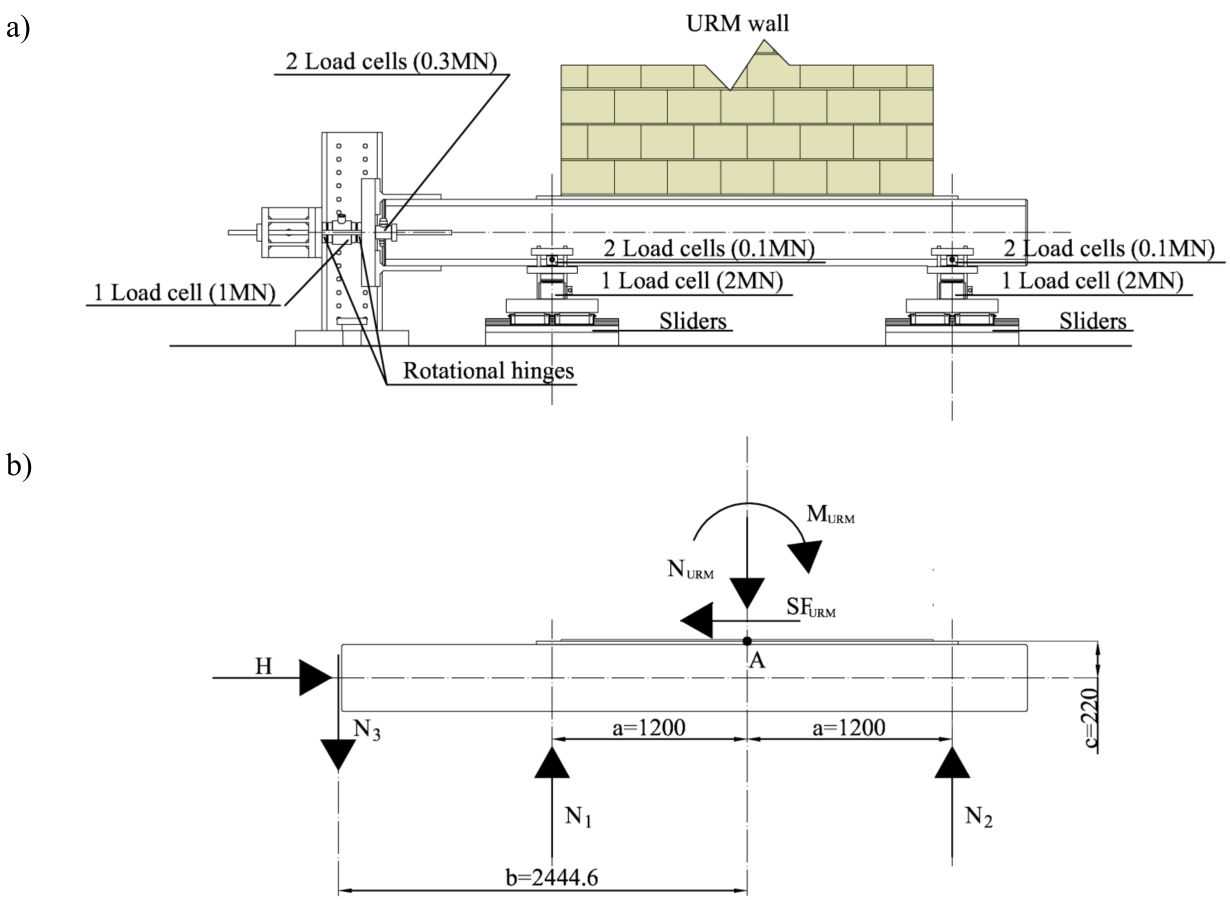

Figure 4: Close-up of the steel beam with the systems to measure the horizontal and vertical reaction forces at the base of the URM wall: (a) components, (b) free body diagram of the steel beam with the reaction forces; all dimensions are in mm.

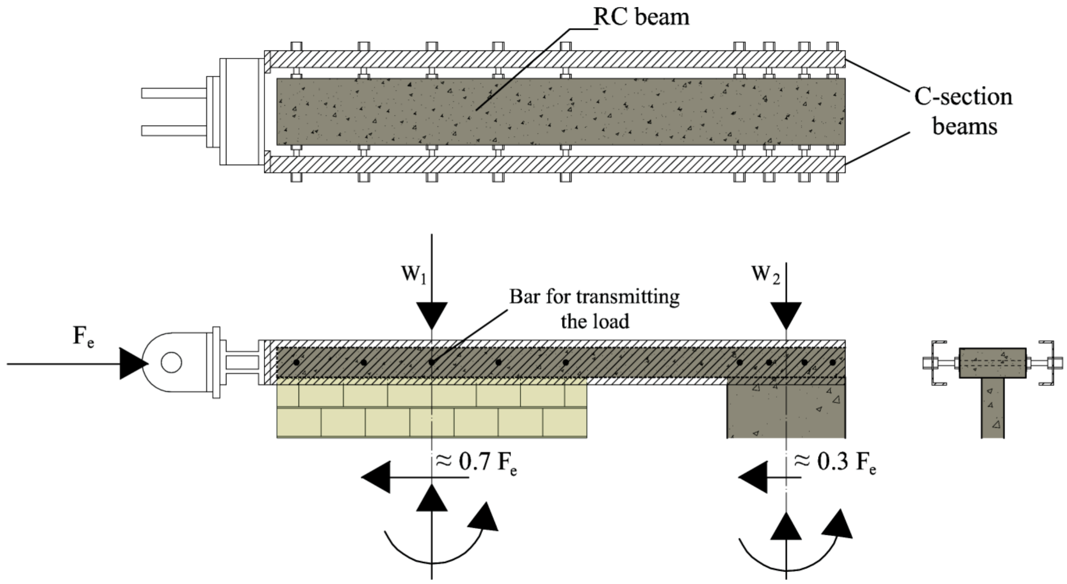

Figure 5: (a) System of C-section beams-bars to distribute the applied horizontal forces along the length of the RC beams: plan, front view and side view. (W_1 and W_2 are the vertical forces applied by the system of hollow core jacks and rods to the URM wall and to the RC wall, respectively).

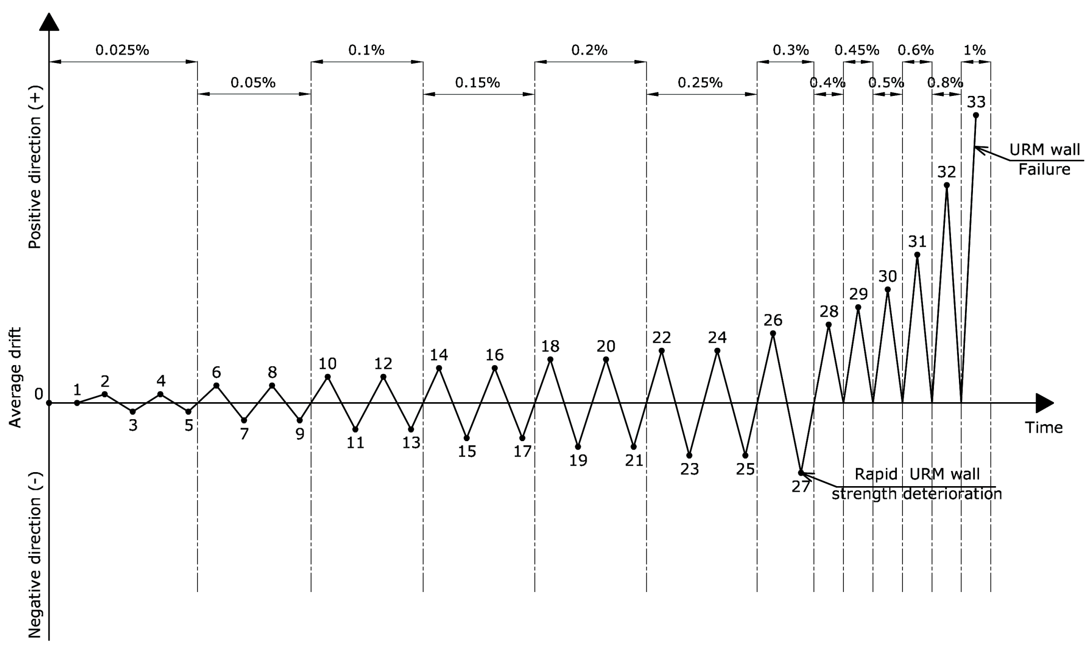

Figure 6: Loading history for TU1.

HYSTERETIC BEHAVIOUR

Figure 7 shows the total base shear and its distribution between the two walls as a function of the imposed top displacement. The variation of axial forces at the base of the two walls is shown in

Figure 8. The actual axial forces at the base of the two walls $\overline{N}_{urm}$ and $\overline{N}_{rc}$ were computed as in Equations 6 and 7:

$$\overline{N}_{urm} = W_1 + N_{urm} + 60kN \tag{6}$$

$$\overline{N}_{urm} = W_2 - N_{rc} + 25kN \tag{7}$$

where W_1 and W_2 are the vertical forces applied by the system of hollow core jacks and rods to the URM wall and to the RC wall, respectively. The values of 60 kN and 25kN correspond to the self-weight of the test unit and the parts of the test set-up that were supported by the URM wall and the RC wall, respectively.

Due to the coupling by the RC beams, the structure behaved differently when loaded in the positive and the negative direction (Figure 3): in the positive direction, the axial force in the URM wall decreased while in the negative direction the axial force in the URM wall increased. As a consequence, the URM wall was stronger when the load was applied in the negative direction. For the RC wall the axial load increased for loading in the negative direction and decreased when the system was pushed in the positive direction.

At a drift of -0.3%, the axial force in the URM wall was 590 kN. During the marking of the cracks, the strength of the URM wall deteriorated rapidly and the force in the horizontal actuators dropped by more than 20% (extensive toe-crushing damage in the bottom left corner of the bottom storey of the masonry wall). To avoid a premature axial load failure of the URM wall, the test was continued only in the positive direction until the complete failure of the URM wall. The complete failure was attained at an average drift of around +1.0% and associated with the axial load failure of the masonry wall. At an average drift of around +0.75% the RC wall yielded. Between δ=+0.5% and δ=+0.6% the URM wall lost about 20% of its strength, which – according to Eurocode 8, Part 3[3] – corresponds to horizontal load failure. Nevertheless, the total base shear did not decrease since the strength of the concrete wall was still increasing. The maximum variation of the axial load at the base of the two walls was about 190 kN.

TEST OBSERVATIONS

In the following section, a brief description of the development of the cracks in TU1 as a function of the average drift is given. At δ=±0.025% horizontal flexural cracks in the first storey of the RC wall appeared; they increased in number until an average drift of ±0.2%. At δ=±0.05% the RC beams started cracking in the vicinity of the connection with the walls. In the RC beams the number of cracks continued to increase constantly during the test.

At δ=±0.15% the first diagonal cracks in the URM wall were found; these cracks developed mainly at the second storey. In addition, the onset of toe-crushing at the left corner of the first storey of the URM wall was observed. At δ=±0.2% for the positive loading direction the onset of toe-crushing at the second storey of the URM wall was found; for the negative loading direction a diagonal crack in the first storey of the URM wall was observed.

At δ=±0.3%, for the positive direction of loading, toe-crushing at the right corner of the second storey of the URM wall was observed. For the negative loading direction, severe damages (diagonal shear crack) which decreased the shear capacity of the URM wall were detected at the first storey. At δ=+0.5% there was a concentration of diagonal cracks at the first storey of the URM wall. At this point of the loading history, the crack pattern of the URM wall was basically complete.

At a drift of +0.8%, the same cracks in the URM wall widened and the shear force measured at the base of the URM wall decreased (around 50% of the maximum measured shear strength). At δ=+0.8%, a diagonal shear crack was found in the first storey of the RC wall. The failure occurred at an average drift of around +1.0%: initially, the first URM wall storey lost the axial load capacity; then the second storey failed developing a diagonal shear crack.

In coupled RC-URM wall structures the crack pattern differs from the crack pattern of uncoupled structures. This was observed in particular for the URM wall. In uncoupled URM walls cracks are mainly developed at the bottom storey; in this case deformations are distributed along the height of the structure. Figure 9 shows the crack pattern for average drifts of +0.5%, +1%. At δ=+0.5% (Figure 9a) the crack pattern was basically complete and the deformations in the URM wall started concentrating at the first storey. Figure 9b shows the crack pattern after the failure of the URM wall at δ=+1%.

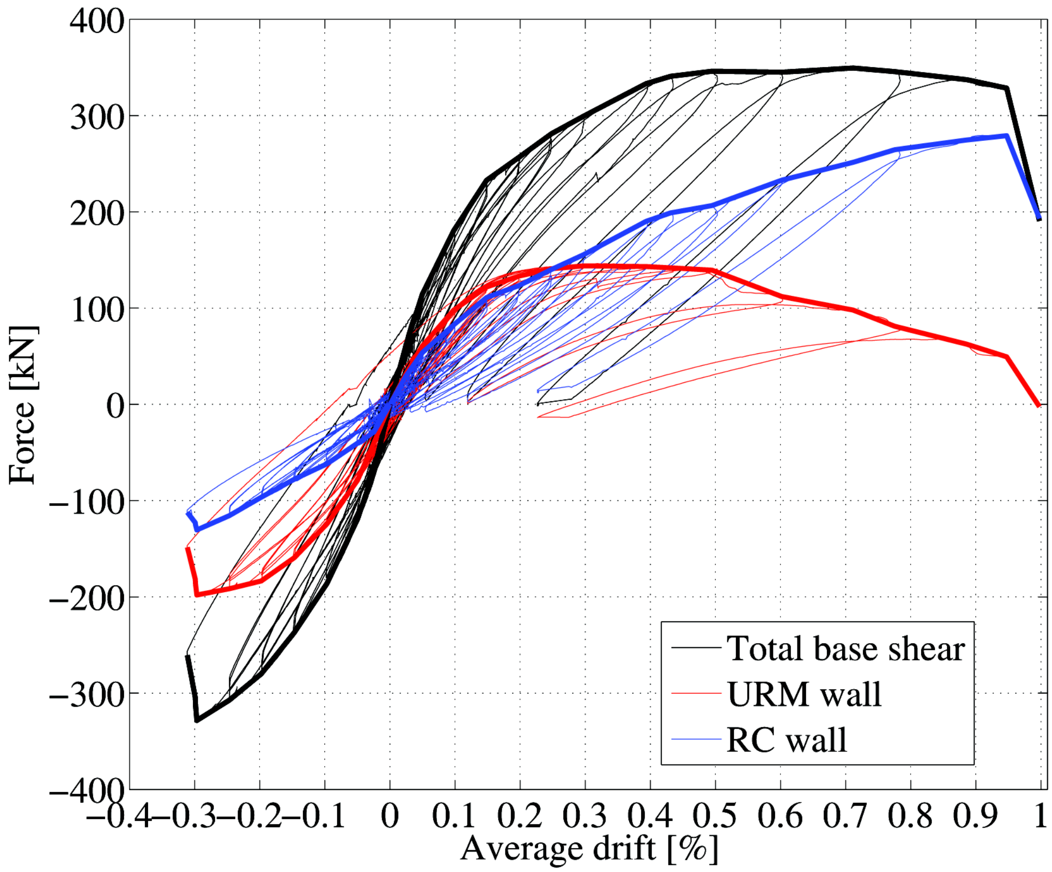

Figure 7: Hysteretics curves of the base shear forces in the walls.

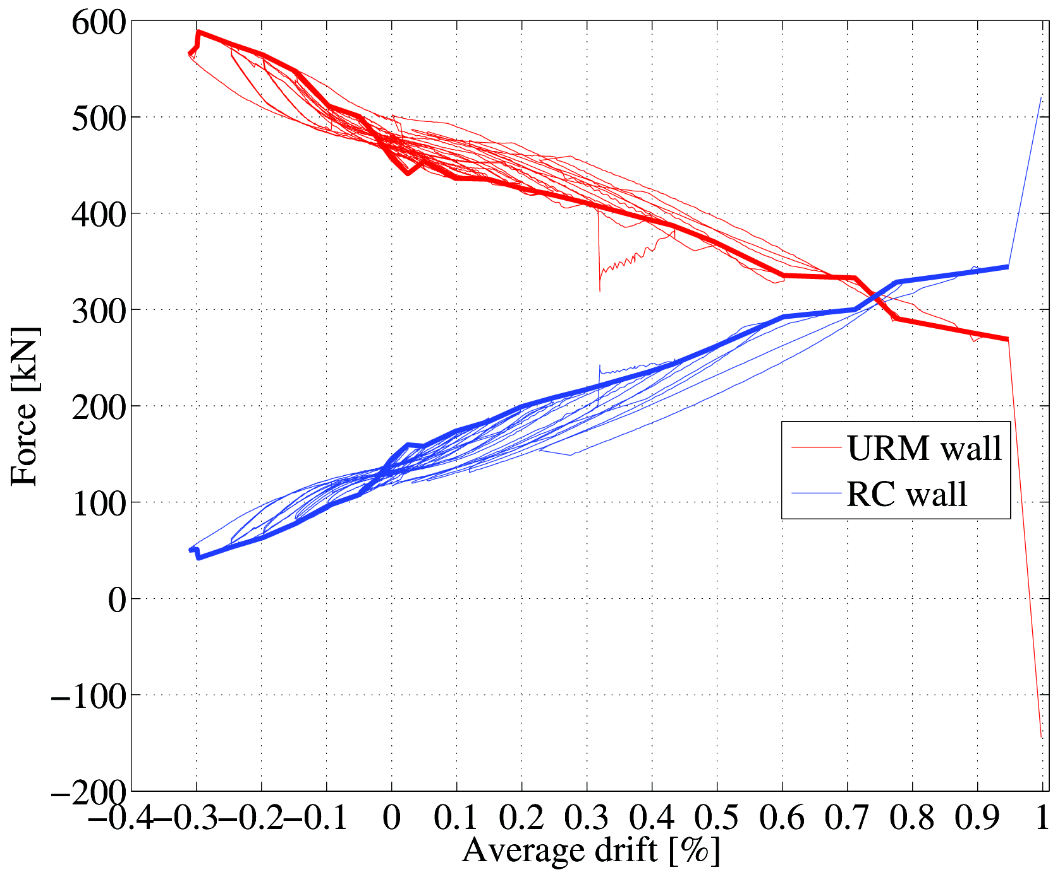

Figure 8: Variation of of the axial loads at the base of the URM wall and the RC wall.

a) b)

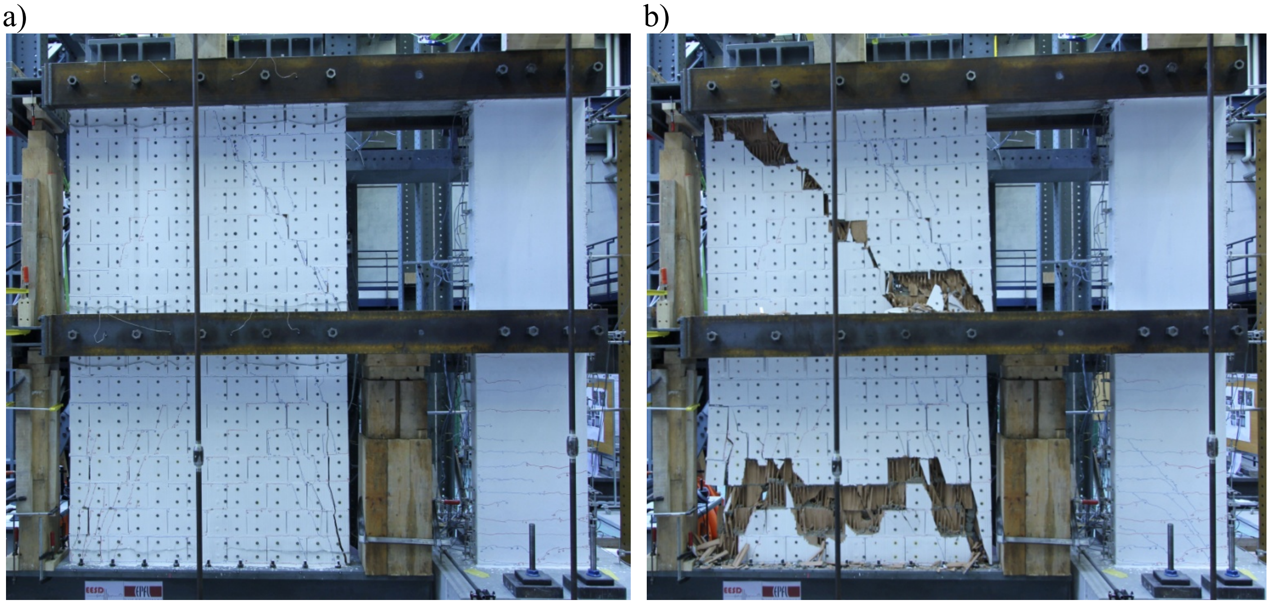

Figure 9: crack pattern at: (a) δ=+0.5%, (b) δ=+1%.

CONCLUSIONS

The paper presents a quasi-static cyclic test on a mixed structure composed of a URM wall and a RC wall which were coupled through RC beams. The test unit behaved differently when loaded in the positive and negative direction because the axial forces in the URM and RC walls varied depending on the loading direction. The final axial load failure occurred in the first storey of the URM wall and was followed by the failure in the second storey of the URM wall. The coupling of the URM wall to the RC wall produced a distribution of the damage along the whole height of the URM wall, whereas in uncoupled URM wall structures deformations are mainly concentrated at the first storey. The total base shear of the structure did not decrease until the end of the test when the URM wall lost its axial load bearing capacity. The positive stiffness of the system is due to the presence of the RC wall which withstood higher drift limits. At the failure of the URM wall, the RC wall was far from its failure. The variation of axial force in the two walls was of about 190 kN, representing roughly 50% of the axial load applied to the URM wall.

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