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EXPERIMENTAL RESPONSE OF RC WALLS WITH OPENINGS UNDER CYCLIC LOADING

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Abstract

The Mw 8.8 earthquake in 2010 in Chile damaged several reinforced concrete (RC) structures, where many walls elements failed. This type of element is the preferred option used in residential buildings. According to the Chilean design practice, these walls usually have complex geometry and discontinuities in height, mainly in the first story or the first underground floor where architectural requirements impose openings at the base or present hanging walls. Nowadays, the Chilean codes do not provide special provisions for any kind of discontinuities.

This paper shows the results of an experimental study of walls specimens with an opening at the base, where inelastic deformation is expected. The main objective is giving design recommendations for modeling and detailing. In particular, information will be provided regarding evaluation of the maximum compressive strain, which is used currently for detailing using a displacement-based procedure for continuous (non-perforated) walls. Four walls are constructed with the same dimensions (2.65 m height, 0.9 m large and 0.15 m thickness) and different shapes of the opening (15% and 30% of the length, and 11% and 22% of the wall height) –always at the base- and tested under constant axial load of about $0.07f'_cA_g$, while cyclic lateral pseudo-static loading is applied at the top of the wall. The walls were made using typical materials in the common practice (concrete strength of 25MPa and steel yield stress of 420 MPa). One of the specimens presents slab elements at the base to be able to capture their influence in the wall response.

The results indicate that the lateral strength is similar in all cases, which implies that flexural yielding is achieved for all specimens that presented similar longitudinal reinforcement. However, displacement capacity varies with opening size. All specimens with openings have less ductility, where the specimen with wider and taller opening reduced its displacement capacity by about 30% compared to the continuous wall. The width of the opening was more influential than the height in the displacement capacity. The slab presented a beneficial effect in the displacement capacity.

Keywords: experimental study; slender wall; openings; slabs; cyclic loading.

1. Introduction

In Chile, the latest severe earthquake was in 2010 in the central-south area of the country with an Mw 8.8 magnitude. This event caused damage in several modern buildings, especially in walls, which are the main resistance system against earthquakes used in the country. Damage in walls includes concrete crushing, global and local buckling and fracture of flexural steel boundary reinforcement. Ex post analysis reveals that some of the reasons of these failures were lack of confinement at walls boundaries, the presence of discontinuities and elevated levels of axial load. The first reason occurs due to a relaxation in the country standard that allowed no confining in walls boundaries elements. The second is due to architectural requirements, which concentrate discontinuities in the first floor and first underground, where highlights door type discontinuities. Some damage in these areas can be seen in Fig.1.

Fig. 1: Damage on discontinuities A) Elevation view, B) Damage hightailed in A), C) D) Similar cases [8].

Despite the high use of reinforced concrete walls in high-rise buildings, there is a modest amount of experimental research relative on test of these elements, and also rarely considered some kind of discontinuity in the wall. In the Chilean design code, that follows mainly the ACI 318-08 code, the wall detailing of slender walls is based on a displacement-based design, which assumes a model of plastic hinge at the wall base that defines the transverse boundary reinforcement. However, the formulation of detailing is based on a rectangular wall without any discontinuity. Taylor and Wallace [9] tested scaled walls to show whether that displacement-based design is valid for walls with discontinuities. Although results indicate that target displacements can be achieved, there is no studies of the limitation of the displacement approach, or the impact of different size opening in walls. Previous analytical studies made by Ahumada [1] on modeling walls with base discontinuities determine that the opening influences the walls strain and plastic hinge length. Morales [7] show that the overall behavior of a wall with a large opening center at the wall base is similar to a wall supported by two separate columns. Also, opening generates a vertical strain concentration near the upper inner side of the opening (corner). Finally, it concluded that the vertical compression deformation can be obtained through a sectional analysis (flexural) which includes the opening obtaining error of about 20%,

Taylor and Wallace [8] study the displacement-based design applied in two approximately quarter scale wall and the use of strut and tie model for the selection of the horizontal shear reinforcement. Results show that slender walls with opening at the base have important ductility, which were designed based on a displacement-based approach based on a sectional analysis, and strut and tie model properly estimates the observed force in the

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transverse boundary reinforcement. Ali and Wight [2] test four scaled RC walls: three with staggered openings and one with no openings. The objective was to study the influence of the location of the openings. Results reveal that all specimens show stable behavior and great ductility. The staggered configuration is better option than "in line" openings, similar to coupled walls, because less detailing near the openings is required.

This paper shows the results of an experimental study of four slender reinforced concrete walls with different opening characteristics at the base in order to determine the influence of a central discontinuity in the wall behavior. In addition, the influence of the presence of slabs is studied in the area of discontinuity.

2. Description of experimental program

2.1 Walls description

Four RC walls were designed and constructed with opening at the base using common characteristics in Chile (Fig 2). The overall dimensions are 2.65 m high, 0.9 m long and 0.15 m thick. In addition, each wall has a pedestal that is 1.4 m long, 0.7 m wide and 0.4 m high and a beam that is 0.9 m long, 0.4 m wide and 0.3 m high. The specimens were differentiated by its opening size and the presence/absence of a slab: MR1 has a discontinuity of 135x300mm, in MR2 opening height is maintained and doubles its length resulting in a discontinuity of 270x300 mm, MR3 increases twice the height and long stays as same as for MR2 having a 270x600 mm discontinuity and MR4 has the same opening that MR3 but with two slabs of 600x900x65 mm centered located 300 and 600 mm from the base of the wall. The dimensions used are identical to those of Manríquez et al. [6] to compare the results to a base or common wall, W1.

The longitudinal reinforcement consists of 4 bars ϕ16 located at each boundary, confined with ϕ6 stirrups spaced every 70 mm until 900 mm from the beginning of the wall; then one side has no stirrups and the other one has ϕ6 stirrups spaced every 100 mm until the top of the wall. The longitudinal reinforcement at each edge of the discontinuity (opening) includes 2 ϕ10 bars. The horizontal reinforcing bar consists in ϕ8 bars spaced 200 mm in the vertical direction, decreasing the spacing in the opening to achieve a shear resistance similar to a case without opening. Vertical distributed reinforcement were ϕ8 bars and were spaced such that the bars are spliced with the bars located at the opening edge, simulating a spacing of 200 mm. Vertical and horizontal reinforcement are doubled at the top of the wall to ensure proper load transfer. Roughly, reinforcement quantity and layout, dimensions and material properties were selected to recall W1 wall design for comparison purposes (Fig. 3).

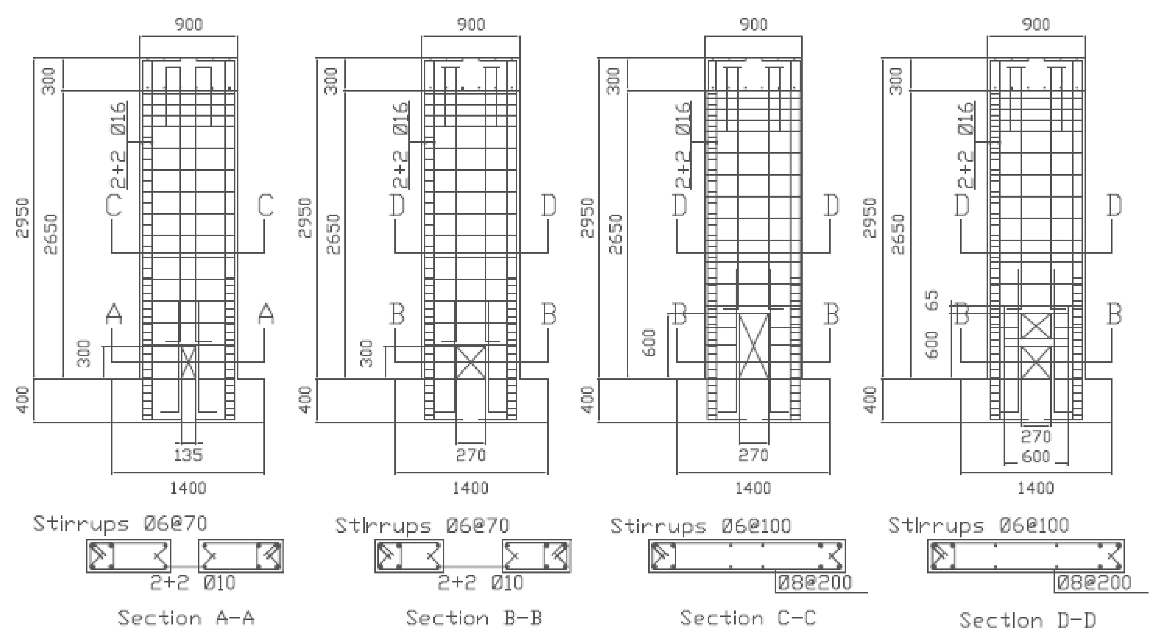

Fig. 2: Reinforcing bars (units in mm).

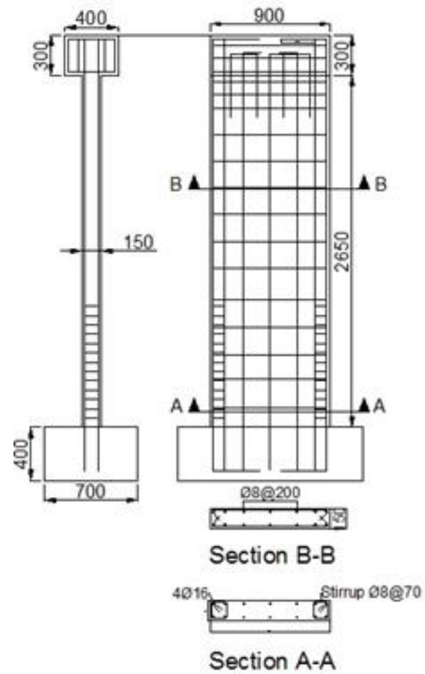

Fig. 3: Reinforcing bars W1 (units in mm) [6].

2.2 Materials

For all specimens the concrete quality was H30 (nominal compressive strength 25 MPa) having an average strength of 39.6 MPa for specimens MR1, MR2 and MR3 (tested at about 130 days of concrete hardening), and 41.2 MPa for specimen MR4 (tested at about 190 days). The steel used in the reinforcing steel is A630-420 (with a nominal yield stress of 420 MPa). The yield stress of the steel reaches an average value of 480 MPa. W1 has a compressive strength of 33.2 MPa and a yield stress average of 490 MPa [6]. Walls were built with materials properties and steel qualities typical of medium and high-rise buildings in Chile [5].

2.3 Instrumentation and data acquisition

In all specimens three types of devices are used to record the experimental data. About 15 strain gages are located on the reinforcing bars of each specimen in web horizontal bars near the discontinuity, boundary longitudinal bars and longitudinal bars at the side of opening. On one side of the wall around 30 LVDT's were installed, measuring top lateral wall displacement, internal flexural and shear deformations, besides of sensors located in the pedestal of the specimen recording possible sliding or rigid body rotations. On the other side of the walls a photogrammetry system is implemented. In this system 2 cameras captures images (globally and locally) of the entire test process and later get displacements and strains on wall sections at different drift levels.

2.4 Test setup

Each specimen was anchored to the strong floor using four rods in the pedestal (in MR2 six were used). An axial load of roughly $0.07f'_cA_g$ is applied by means of four hydraulic jacks on the top of the load transfer system and held constant the entire test, controlled by a load cell. The lateral displacement is applied by a hydraulic actuator attached to the reaction wall at 2.8 m height (measured from the base of the wall, not the base of the pedestal) and controlled to ensure the desired drifts. These drift are 0.1%, 0.2%, 0.3%, 0.4%, 0.6%, 0.9%, 1.35%, 2%, 3% and 4% of the height. Three cycles are performed for each drift level, and always cycle starts pulling the wall (against the reaction wall, which is defined as the negative direction). A steel frame is attached to the strong floor and uses four struts to secure out of plane stability in the wall (see Fig. 4).

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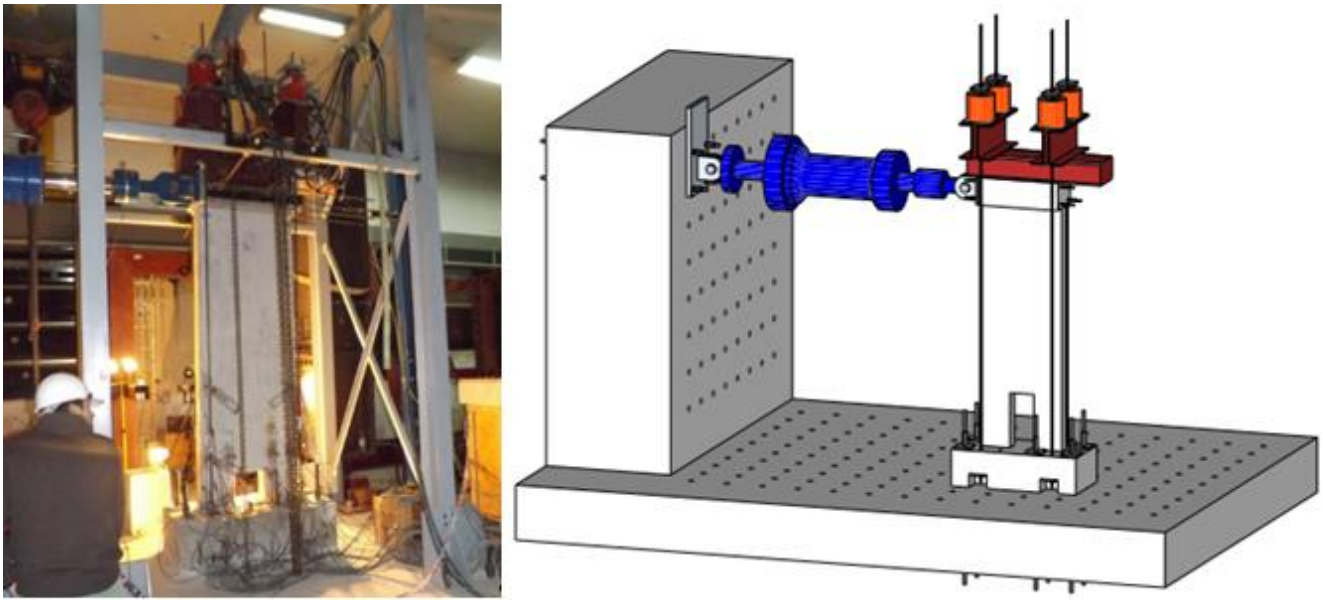

Fig. 4: Test configuration and general scheme.

3. Results

3.1 Overall behavior

All specimens have a similar behavior for the first drift levels, having horizontal cracks at the base and diagonal cracks distributed in height starting from a drift of 0.3%. Cracks, in general, are clearly visible at 0.6% drift.

For specimen MR1, the first considerable cracks appear in the 0.9% drift cycle near the top of the opening, and are horizontal. At 1.35% cracks widen, and new flexural (horizontal) cracks develop near the opening. At the second 3% drift cycle in negative direction there is concrete cover loss at wall boundary. In the negative direction of the third 4% drift there is compression failure in the boundary wall, with local buckling of the boundary reinforced bar and the rebar located at the opening. Finally, in the positive direction of the third 4% drift takes place a compression failure, with buckling of the boundary reinforced bar and the rebar located at the opening. Final configuration can be seen in Fig. 5a) and Fig. 6a).

Specimen MR2 does not show remarkable cracks until first 3% drift cycle. At that level (positive direction), there is a sudden concrete cover loss, besides of a shear crack (Fig. 5b). Failure occurs in the second 3% drift level in negative direction, with concrete cover loss in the inner face of the opening, together with concrete spalling and buckling of bars located at the boundary and opening edge (Fig. 6b).

In specimen MR3 during the first 3% drift cycle in the negative direction, a vertical crack appears near the inner face of the opening. The concrete cover loss happens in the first 3% drift cycle in positive direction, together with buckling of bars located at the boundary and opening edge. A notorious shear crack appears in one leg (side of the opening) of the wall, at the height of the opening. Finally, failure occurs in the second 3% drift cycle in the negative direction, with a brittle shear crack, similar to the other side of the opening (see Fig. 5c) and Fig. 6c).

The presence of slabs in MR4 makes a concentration of cracks below the second slab. The concrete cover loss happens in the first 2% drift cycle in the negative direction in the compressed boundary side, and during the second 3% drift cycle in the negative direction in the other compressed boundary side. At the second 2% drift cycle in the negative direction cracks can be seen in the first slab, coupling the two parts of the wall. In the second 3% cycle in the negative direction failure is reached with the presence of a shear crack, together with buckling of longitudinal bars (Fig 5d) and Fig. 6d).

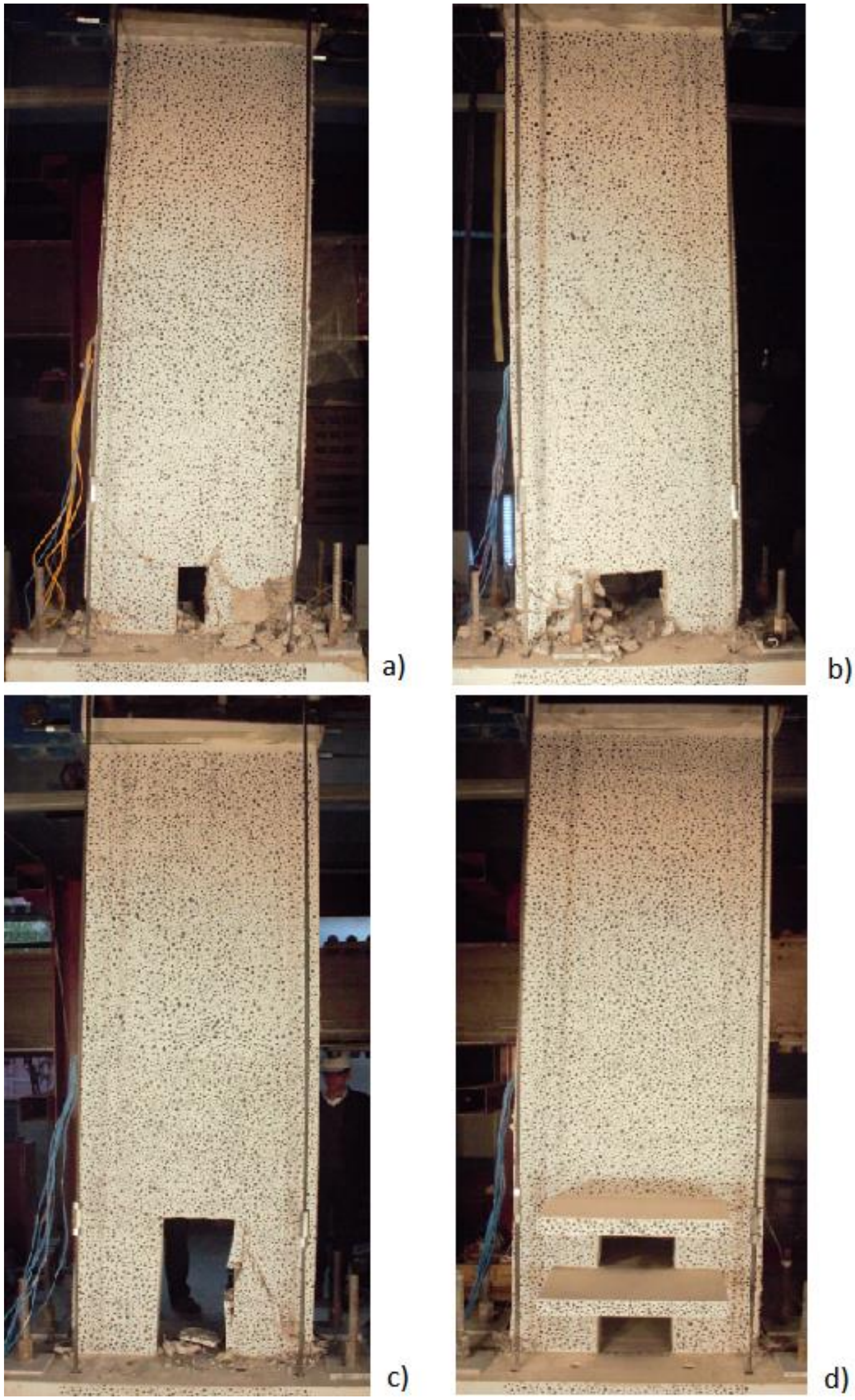

Fig. 5: Global deformation at final stage for specimens: a) MR1, b) MR2, c) MR3 and d) MR4.

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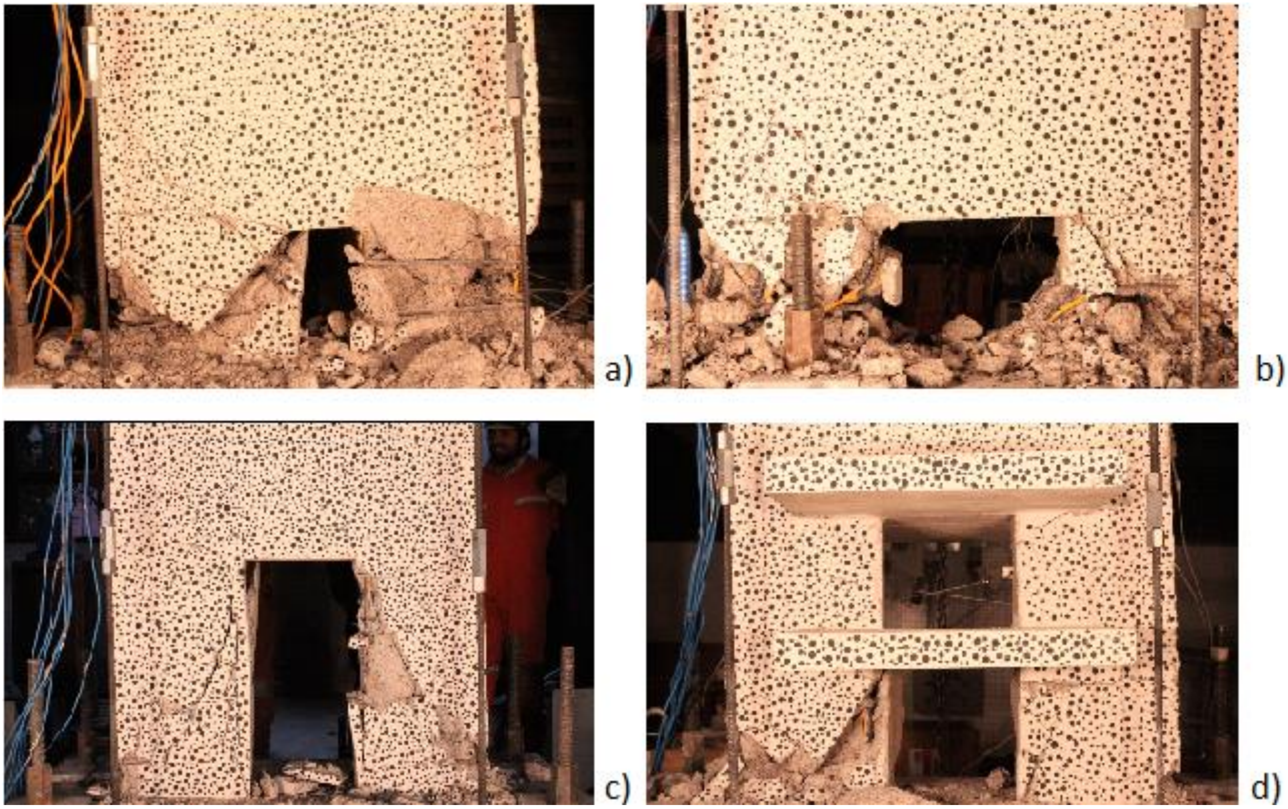

Fig. 6: Damage at wall base for specimens: a) MR1, b) MR2, c) MR3 and d) MR4.

3.2 Load versus displacement response

The lateral displacement (corrected by pedestal sliding and rotation) versus lateral load is shown in Fig. 7 for all specimens. The blue line shows the results for each wall, while grey line represented the results for W1 [6] , where can be seen stable behavior up to 4.0% drift (first important degradation). Overall results indicate that all specimens reach almost the same lateral strength, because yielding is achieved in flexure, as designed, where capacity is largely influenced by the boundary flexural reinforcement. The main difference is the displacement capacity reached by the specimens. Results of MR1 are shown in Fig. 7a), where stable behavior can be seen until last 4% drift cycle. Stiffness is similar in both loading directions, but there is a small difference in the lateral strength close to 5%. Sudden degradation occurs close to 4% drift while trying to reach 6% drift (the corrected maximum drift achieved – before a lateral force drop of 20% - was about 3.7%). The overall response is quite similar to the specimen without opening (grey line in Fig. 7). The larger (longer) opening in the specimen MR2 reduces considerably the displacement capacity (Fig. 7b). Both strength and stiffness are symmetric in each loading direction and similar to MR1. While reaching the first 3% drift cycle in the positive direction, degradation is observed (the corrected maximum drift achieved was about 2.7%). Fig. 7c) shows the response of specimen MR3. Similar to the other cases, stiffness and strength are symmetric and similar to MR1 and MR2. There is no great difference between MR3 and MR2. Failure is reached when trying to reach the second cycle of 3% drift in the negative direction; although degradation was already observed in the previous cycle (the corrected maximum drift achieved was about 2.6%). MR4 response is shown in Fig. 7d). Like the other specimens, strength and stiffness are symmetric and similar to the other walls. Nevertheless, there is a big improvement in the deformation capacity compared with the specimen without slab and the same opening size (MR3), but not as good as specimen MR1. Slabs allow finishing all three 3% drift cycles, having the wall a brittle failure trying to reach 4% (the corrected maximum drift achieved was about 3.2 %).

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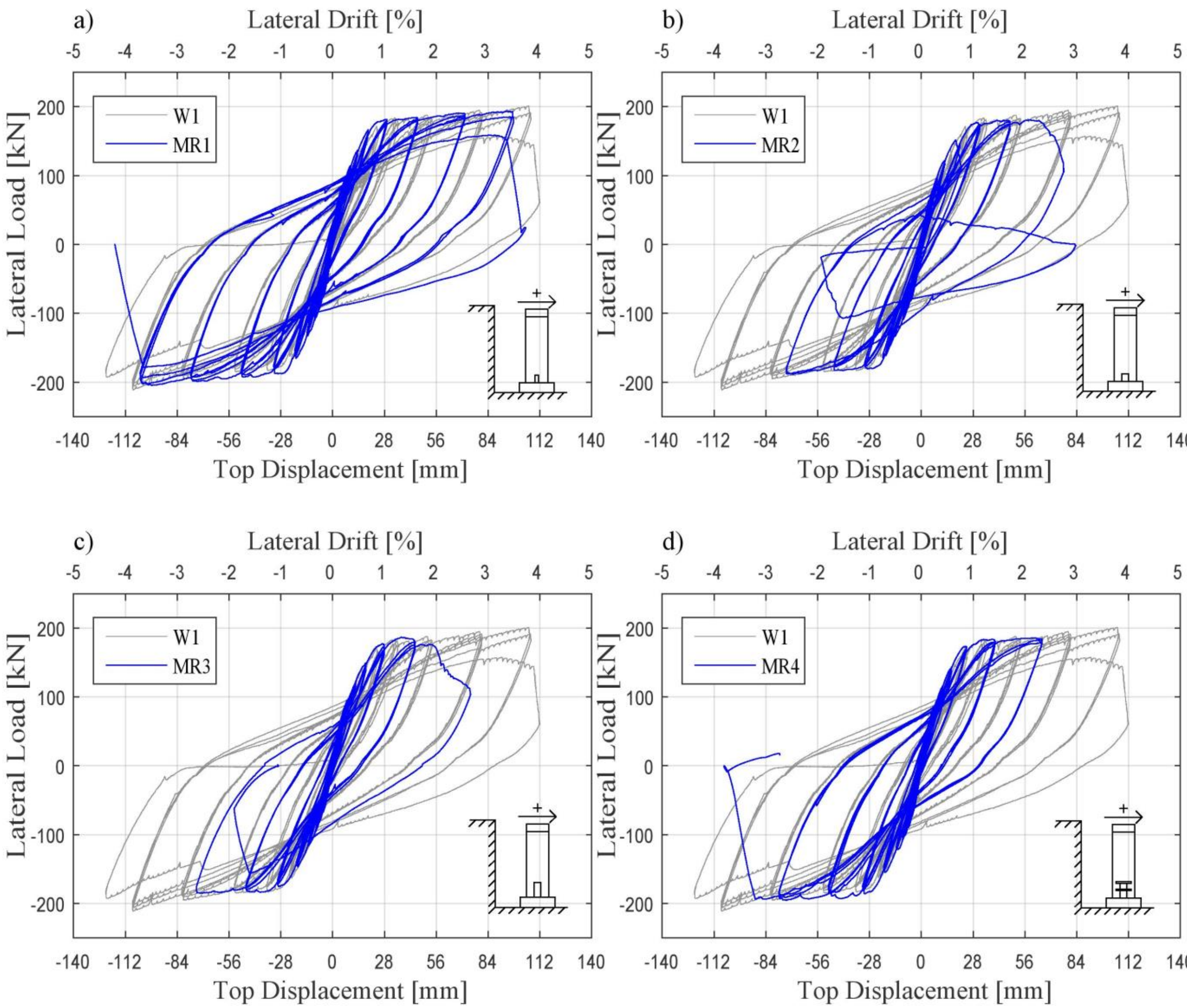

Fig. 7: Load versus displacement response of specimen - a) MR1, b) MR2, c) MR3 and d) MR4.

3.3 Photogrammetry

As an alternative of the use of LVDT's to obtain displacement and strain information from the test, a photogrammetry system is implemented, which consists in drawing black dots randomly in a white base in one face of the wall and taking pictures of the entire test. Displacement and strains are calculated using the open source software Ncorr [3], [4]. This paper summarizes a preliminary analysis of vertical strains at first cycle of 2% and 3% drifts. The "+" direction corresponds to the case when the wall is pushed and "-" when the wall is pulled against the reaction wall.

Figure 8 shows the results of MR1. Both 2% and 3% are similar in each loading direction, with a strain concentration at the base and at the upper area of the opening. Fig. 8 b) and d) reveals an important strain concentration near the upper area of the opening.

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Also, considering Fig. 8 to Fig. 10 it can be concluded that there is a significant concentration of tensile strain near the top corner of the opening, as mentioned by Morales [7], which means that there may be other critical zones apart from the boundary elements at the wall base that require detailing.

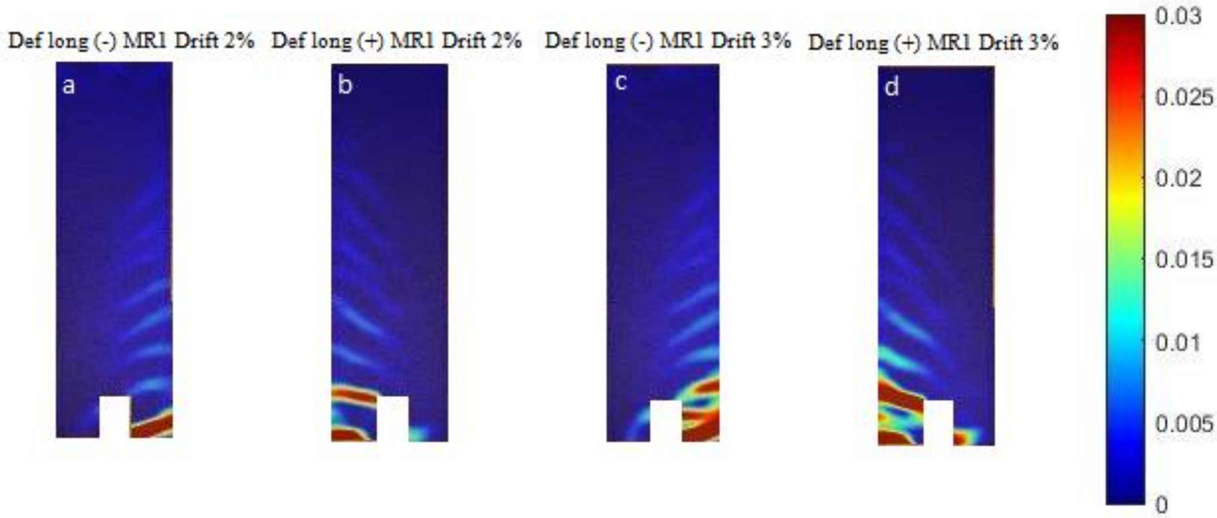

Fig. 8: Vertical strain distribution of specimen MR1 - a) drift 2% - b) drift 2% + c) drift 3% - d) drift 3% +.

Vertical strains in MR2 are shown in Fig. 9. The strain patron is similar to MR1, but the values of strains over the height are smaller, revealing a bigger concentration at the base for all four drifts. Again, Fig. 9c) and d) shows a strain concentration in the section change. Results are changed in direction because in MR2 the other face of the wall is used for photogrammetry, and discontinuity seems no centered because the anchor rod doesn't let obtain information in its projection (Fig. 6 b)

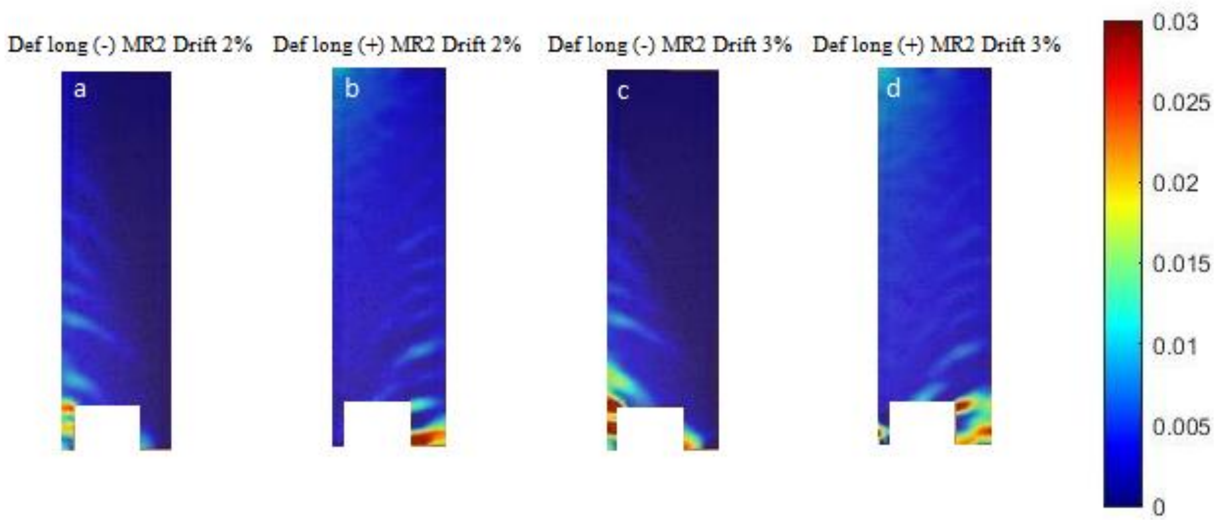

Fig. 9: Vertical strain distribution of specimen MR2 a) drift 2% - b) drift 2% + c) drift 3% - d) drift 3% +.

The response of MR3 can be seen in Fig. 10. Strain pattern is similar to MR1 and MR2, but adapted to the size of the opening. Again, Fig. 10 b) and d) shows a strain concentration near the upper zone of the opening, generating a potential buckling of the longitudinal reinforcing bars located near the opening. Fig. 10 c) reveals horizontal and almost uniform crack pattern on the tension side of the wall base. Slabs generate a significant loss of information in global photos, so that analysis of specimen MR4 was left out in this article.

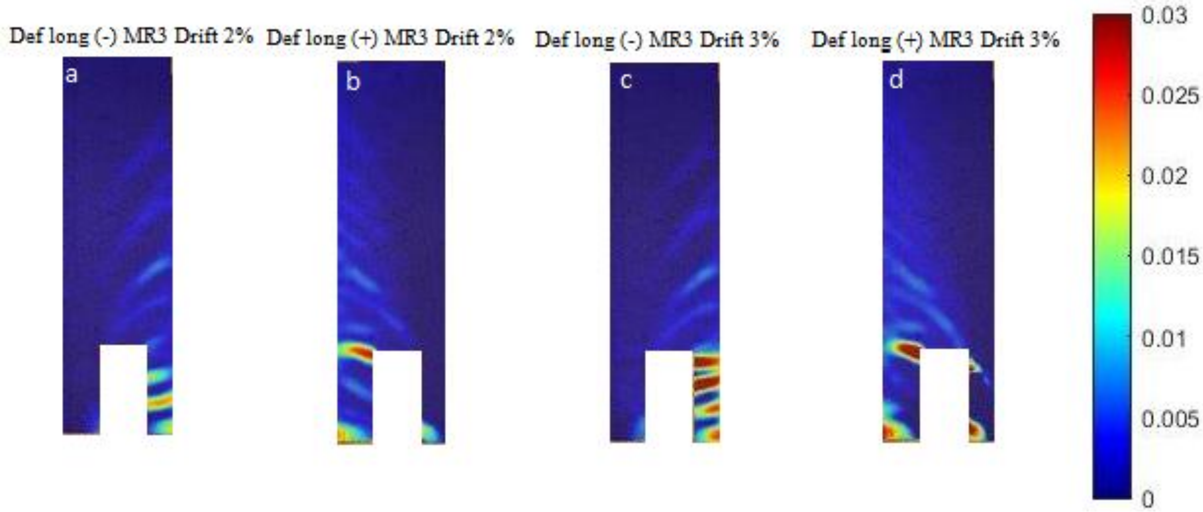

Fig. 10: Strain distribution MR3 a) drift 2% - b) drift 2% + c) drift 3% - d) drift 3% +.

4 Conclusions

This paper summarizes the experimental study of four scaled slender RC walls with central opening at the base. Four specimens are constructed and tested in cantilever with a cyclic lateral point load at the wall top. An axial load was also considered ($\sim 0.07f'_cA_g$). One of the specimens has two centered slabs near the base.

Walls are designed to have the same flexural strength, which is confirmed with the tests. The main global difference is the deformation capacity, being reduced with the size of the opening. Comparison between MR1 and MR2 and among MR2 and MR3 reveals that width is more influential than height in the displacement capacity degradation. Since the influence of the openings affects the deformation capacity and not strength, proposals for design improvement should be focused on detailing. Fig. 7d) reveals that slabs have a remarkable influence in the wall response: despite having a taller opening, MR4 has a similar behavior as MR2 (with the same opening width but half the height compared to MR4). This suggests that experimental and analytical studies should consider the slab impact in discontinuous walls.

Photogrammetry analysis reveals that the main flexural-shear cracks developed within the discontinuous zone (at the base until the top of the opening) and narrower shear (diagonal) cracks over the opening zone. The presence of the opening also shows large tensile strains in the upper zone of the opening, making longitudinal reinforcing bars close to the opening more susceptible to buckling. This indicates that buckling constrain should be considered close to opening areas where plastic hinge formation is expected. Constrains could be cross ties or stirrup spacing six times the diameter of the opening reinforcement bar.

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