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EXPERIMENTAL STUDY ON THE BEHAVIOR OF CONFINED MASONRY WALLS SUBJECTED TO OUT-OF-PLANE CONCENTRATED LOADS

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Abstract

This paper presents the results of an experimental study on the out-of-plane seismic behavior of confined masonry walls. Three full-scale confined walls were tested in the laboratory under concentrated reverse cyclic loads. The variable studied was the wall axial stress. Walls were constructed using hollow clay bricks laid in half running bond. Mortar used in construction was in proportion by volume 1:2:7 (Portland cement: lime: sand). The geometry and reinforcement details for the concrete confining elements were based on those minimum specified in the Mexico City Masonry Technical Norm. The wall test setup consisted of three parts: an axial load system, a support system, and an out-of-plane load system. The support system allowed the out-of-plane horizontal displacement and restricted the rotation at the top of the wall. Based on the results obtained in this work, it is concluded that the final cracking pattern of walls was in general similar. The out-of-plane behavior of walls was linear elastic until the formation of the first horizontal masonry cracks. After that, the behavior was nonlinear. This nonlinear behavior was related to the presence of new horizontal cracks in the wall panel, horizontal cracks in the vertical confining elements and yielding of the flexural reinforcement of the wall. As the axial load increased the out-of-plane strength also increased. This was related to the additional vertical displacement restriction provided by the axial load.

Keywords: confined masonry walls; out-of-plane strength; seismic loads; axial load

1. Introduction

The out-of-plane strength of masonry walls can be related to two types of loads: distributed loads acting on the wall surface or concentrated loads applied at the top of the wall. In the first case, distributed loads can be related to seismic forces due to wall self-weight or uniform pressures due to wind forces. In the second case, concentrated loads are related to seismic forces due to floor self-weight. For the case of masonry walls subjected to distributed loads, there are some research studies for unreinforced walls [1-7], reinforced walls [8-10], infill walls [11-16], and confined walls [17-22]. Similarly, for the case of masonry walls subjected to concentrated loads, there are few research studies for reinforced walls [23, 24], and infill walls [25-27].

Based on these studies, it is concluded that the main variables that affect the out of plane behavior of masonry walls are wall support conditions, wall aspect ratio (height over length), wall slenderness ratio (height over thickness), axial stress, wall openings, compressive strength of masonry, stiffness of the surrounding elements, and previous damage as a result of in-plane loads. Another conclusion is that wall cracking pattern depends on the type of load applied to the wall. For example, for rectangular walls with distributed loads, wall cracking pattern is defined by horizontal, vertical and diagonal cracks [21], but for concentrated loads, only by horizontal cracks [25-27]. This out-of-plane cracking pattern is similar to that observed on confined walls after earthquakes [28-31].

The objective of this paper is to study the out-of-plane seismic behavior of confined walls subjected to concentrated loads (one-way bending). As far as the authors know, there is no previous research on confined walls subjected to this type of load in the literature. Results of three confined masonry walls subject to out-of-plane concentrated loads are presented. The variable studied was the wall axial stress. Based on the results obtained in this work, it is concluded that the final cracking pattern of walls was in general similar. The out-of-plane behavior of walls was linear elastic until the formation of the first horizontal masonry cracks. After that, the behavior was nonlinear. This nonlinear behavior was related to the presence of new horizontal cracks in the wall panel, horizontal cracks in the vertical confining elements and yielding of the flexural reinforcement of the wall. As the axial load increased the out-of-plane strength also increased. This was related to the additional vertical displacement restriction provided by the axial load.

2. Experimental Program

Three full-scale confined walls were considered in this study (walls M1 to M3). The geometry of walls was 3.49 × 2.55 m (length × height). Walls were constructed using hollow clay bricks with nominal dimensions of 0.12 × 0.12 × 0.25 m (thickness × height × length). Bricks had multiple vertical cells. Walls were constructed in half running bond by a qualified worker. Mortar used in construction was in proportion by volume 1:2:7 (Portland cement: lime: sand). Mortar was placed on both the face shells and the head joints. Average thickness of the mortar joint was equal to 10 mm. Cross-section dimensions and steel reinforcement details of confining elements (CE) for the walls are presented in Fig. 1. Longitudinal reinforcement (LR) consisted of deformed steel bars with nominal yield strength of 412 MPa. Transverse reinforcement (TR) consisted of plain steel bars with nominal yield strength of 228 MPa. All requirements used for the confining elements were based on those minimum specified in the Mexico City Masonry Technical Norm [32].

Walls were tested using axial stresses of 0.11, 0.23 and 0.35 MPa, respectively. These stresses correspond to interior walls of 1, 2 and 3 stories high, respectively. Each wall was subjected to constant axial stress and reverse cyclic out-of-plane concentrated loads until failure. Axial stress was applied first and later the concentrated loads. The wall test setup was divided into three parts: an axial load system, a support system, and an out-of-plane load system. The axial load system was formed by two swivel beams, two simple supported spreader beams, four steel threaded bars and two hydraulic actuators with capacity of 117 kN. Axial stress was maintained constant by using a mechanical "load maintainer" [33]. The support system consisted of a reinforced concrete slab, two structural steel frames, and four steel wheels. The concrete slab was connected along the length of the wall by using steel threaded bars. Wheels were placed between the concrete slab and the structural frames. This support system allows the out-of-plane horizontal displacement and restricts the rotation at the top of the wall. Walls were attached to the laboratory strong floor by using concrete blocks and steel threaded bars.

The out-of-plane load system consisted of a reaction steel frame, a two-way hydraulic actuator and a connection steel beam. The walls, as tested, represent interior bearing walls subjected to out-of-plane seismic loads. The total length of the top slab parallel to the direction of loading was defined by the midlength of the left and right spans. Views of the wall test set up are presented in Fig. 2.

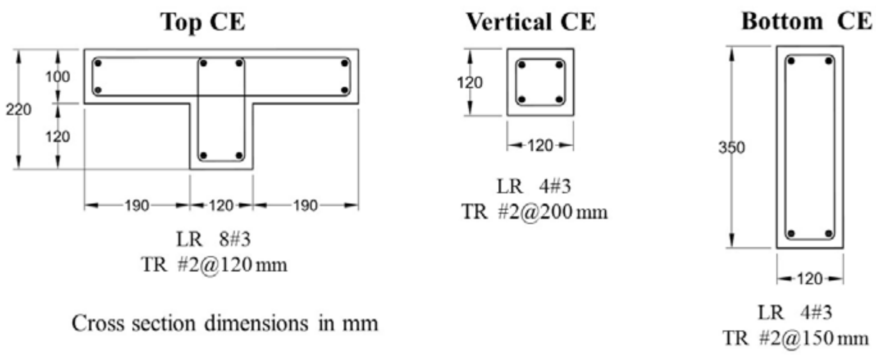

Fig. 1 – Geometry and steel reinforcement details of confining elements

Fig. 2 – Views of wall test set up

Axial load was measured using four donut load cells with capacities of 44 and 111 kN. Out-of-plane load was measured using a pin load cell with a capacity of 400 kN. Axial and out-of-plane loads were verified by using pressure transducers with capacities of 69 and 34.5 MPa, respectively. Out-of-plane horizontal displacements at top of the wall were measured using 127 and 381 mm linear potentiometers. Relative displacements between the concrete slab and the wall, the concrete slab and the steel frames, and the wall and the strong floor were measured using 25mm and 50 mm linear potentiometers. Strain gauges were attached at the top and bottom parts of the longitudinal reinforcement of vertical confining elements. The out-of-plane loading history used for the walls consisted of six initial reverse cycles controlled by load and subsequent cycles controlled by displacement. Walls were first loaded to the east direction and later to the west direction. Loading history was based on that proposed in the Mexico City Masonry Technical Norm [32].

3. Experimental Results

The average axial compressive strength of concrete was equal to 17.92, 14.92 and 18.70 MPa for walls M1 to M3, respectively. Corresponding coefficients of variations were equal to 0.03, 0.02 and 0.02, respectively. The average axial compressive strength of units was equal to 18.9 MPa with a coefficient of variation of 0.14. The average axial compressive strength and modulus of elasticity of masonry were equal to 6.48 and 5705 MPa, respectively. Corresponding coefficients of variations were equal to 0.05 and 0.12, respectively. All values were calculated using gross properties of corresponding cross-sections.

The behavior of the confined walls was in general similar. Horizontal cracks were observed first in the two bottom brick courses of the west wall face and between the two top brick courses of the east wall face, while loading to the east direction. When the load was reversed, horizontal cracks formed between the two bottom brick courses of the east wall face and between the two top brick courses of the west wall face. These horizontal cracks, initially, did not form along the entire length of the wall. Yielding of the flexural reinforcement was observed at the top and bottom ends of the vertical confining elements. Yielding was observed in both loading directions. Horizontal cracks were observed along the top and bottom parts of the vertical confining elements over a length of about 0.45 m. A vertical crack, located at the wall center, was observed for walls M1 and M3. Crushing of masonry was observed at the two top corners of the wall panel in both wall faces. Failure of walls was related to crushing of concrete at the top and bottom ends of the vertical confining elements. Testing of walls was stopped at a maximum out-of-plane top displacement of 175 mm because the hydraulic actuator ran out of stroke. The final cracking patterns of the west face of the walls are presented in Fig. 3. The out-of-plane load – drift ratio curves for the walls are presented in Fig. 4. Drift ratios reported were calculated using the out-of-pane displacements measured at top of the walls. Out-of-plane strengths were equal to 10.95, 11.22 and 14.07 kN for walls M1 to M3, respectively. Corresponding drift ratios were equal to 2.4%, 2.8% and 2.6%, respectively.

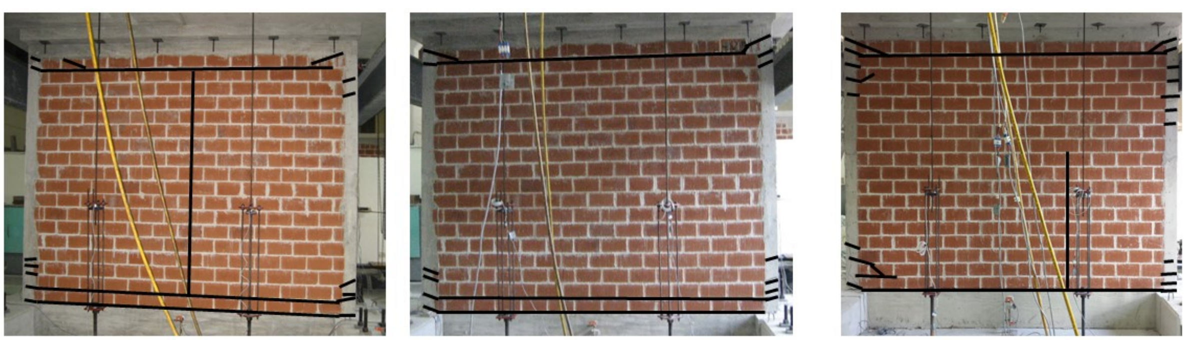

Fig. 3 – Final cracking patterns of walls

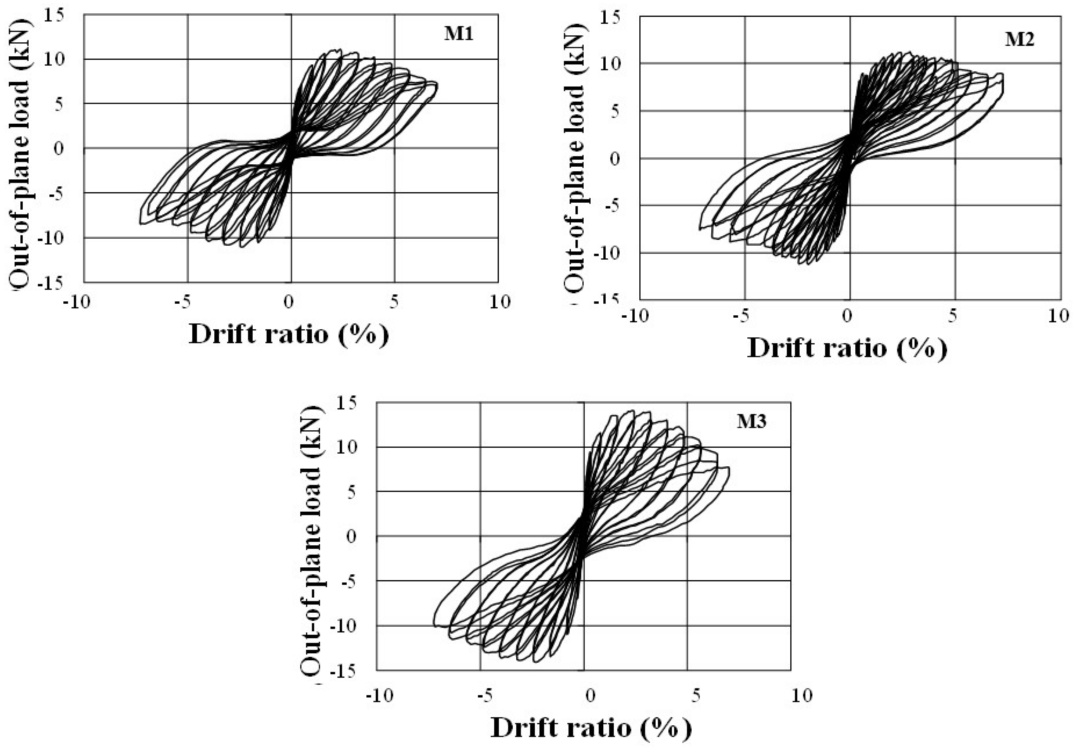

Fig. 4 – Out-of-plane load – drift ratio curves for the walls

4. Discussion of Results

The final cracking pattern of walls was in general similar. Horizontal cracks were observed first between the two top and the bottom brick courses on both wall faces. Horizontal cracks were not formed between the top brick course and the top confining element because concrete penetrated in the brick cells during pouring. The length of these horizontal cracks was initially smaller than the wall length. Horizontal cracks were observed later at the top and bottom parts of the concrete confining elements. A vertical crack was observed for walls M1 and M3 at the end of the tests. This vertical crack was related with the relative displacement observed between the wall panel and the bottom horizontal confining element. This displacement caused an out-of-plane bending of the wall panel about the vertical direction.

The out-of-plane behavior of each wall was linear elastic up to the formation of the first horizontal cracks. After this, the behavior was nonlinear. This nonlinear behavior was related to the presence of new horizontal cracks in the wall panel, horizontal cracks in both vertical confining elements and the yielding of the flexural reinforcement of these elements. After the out-of-plane strength was reached, the wall strength decreased. This reduction was associated with the progressive crushing of masonry observed in the two top brick courses.

Fig. 5 shows the ascending envelope curves of walls. In this figure, circular markers represent the out-of-plane strength of the walls. Fig. 5 shows that as the axial stress increased the out-of-plane strength increased. This was related to the additional vertical displacement restriction provided by the axial stress. The slight difference in the out-of-plane strength between walls M2 and M1 is associated with the lower axial compressive strength of concrete of wall M2 compared with M1. The ratio between the out-of-plane strength of wall M3 and M1 was 1.28.

Fig. 5 shows that the out-of-plane strength of the walls was associated with drift ratios between 2.4% and 2.8%. In-plane allowable drift ratios for confined masonry walls [32] are smaller than out-of-plane drift ratios observed in this work; therefore, out-of-plane and in-plane strengths cannot be added. The out-of-plane strength contribution must be calculated using the drift ratio associated with the in-plane strength. Even though maximum wall drift ratios were greater than 5.0% (Fig. 5), walls did not collapsed. Vertical confining elements provided enough out-of-plane support for the walls to avoid snap through of wall segments.

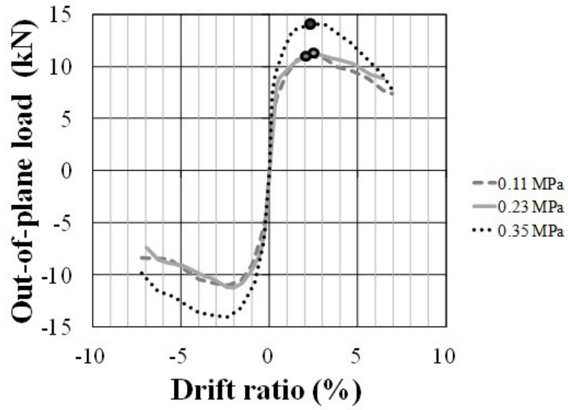

Fig. 5 – Ascending envelope curve of walls

5. Conclusions

Three confined walls were tested in the laboratory under reverse cyclic loads. Based on the experimental results obtained in this work, the following conclusions are presented.

The final cracking pattern of walls was in general similar. Horizontal cracks were observed first between the two top and bottom brick courses on both wall faces. Horizontal cracks were observed later at the top and bottom parts of the concrete confining elements. For walls M1 and M3, a vertical crack at the center of the wall was observed at the end of the tests.

The out-of-plane behavior of walls was linear elastic until the first masonry cracks. After that, the behavior was nonlinear. This nonlinear behavior is related to the presence of new horizontal cracks in the wall panel, horizontal cracks in vertical confining elements and the yielding of the flexural reinforcement of these elements.

For the three walls with the same aspect ratio, as the axial stress increased the out-of-plane strength increased. This was related to the additional vertical displacement restriction provided by the axial load.

The out-of-plane strength of the walls was associated with drift ratios greater than those related to the in-plane strength of confined masonry walls; therefore, the out-of-plane and in-plane strength cannot be added. The out-of-plane strength contribution must be calculated using the drift ratio related to the in-plane strength.

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