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EXPERIMENTAL STUDY TO AVOID THE SLIDING FAILURE IN REINFORCED MASONRY WALLS UNDER LATERAL LOADS

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ABSTRACT

An experimental study was conducted at the Structures Laboratory of the Pontifical Catholic University of Peru in order to find ways to control or to avoid the sliding failure of reinforced masonry walls under seismic lateral loads. This type of failure is very dangerous because: the vertical bars can be cut, the reduction of the cross section is significant, and the wall can be broken into two parts, generating eccentricity of the vertical loads.

Five fully grouted masonry walls were constructed using concrete blocks. Variations included: the use of additional dowels to support the sliding shear force, the use of different components of the grout, the vertical reinforcement distribution, the use of continuous bars or vertical bars with overlaps, the treatment of the foundation beam, the use of special blocks at the first layer and some other construction details. The five walls were built to full scale and subjected to cyclic lateral load of increasing displacement amplitude, until failures were attained. Conclusions are drawn in terms of the construction process and the vertical reinforcement, indicating which parameters had influence in preventing sliding and which did not. Recommendations are given regarding the findings reached.

KEYWORDS: sliding, failure, concrete blocks, tests, seismic resistance, wall

INTRODUCTION

In reinforced masonry buildings subjected to strong earthquakes, a sliding failure (or shear friction failure) may occur, due to several reasons. Such failure is very dangerous, because the vertical bars can be cut, the reduction of the cross section is significant, and the wall can be broken into two parts, generating eccentricity of the vertical loads (Figure 1). An experimental research was conducted at the Structures Laboratory of the Pontifical Catholic University of Peru (PUCP) in order to find how to prevent the sliding failure of reinforced masonry walls under seismic lateral loads. At least, the aim was that such failure be produced for drifts higher than the allowed by the Peruvian Seismic Code [1], which is 0.005. This unsought sliding failure appeared in previous research studies on seismic behavior of reinforced masonry walls at the PUCP [2]. The research presented here was done to study how to deal with this problem. Firstly, the factors that have influence on the sliding failure were analyzed. Then, some solutions were proposed and applied to five different walls. These walls were constructed of fully grouted concrete blocks and were subjected to increasing lateral cyclic loads, until failure was observed.

Figure 1: Sliding failure in masonry walls, Chile (1985) and Northridge (1994)

FACTORS THAT HAVE INFLUENCE IN THE SLIDING FAILURE

Six possible factors that may influence the sliding failure were studied and are summarized hereafter. In all cases, the masonry units are concrete blocks.

The first factor is the lack of adhesion between block and mortar. If the blocks have a high initial suction, the mortar placed on top will harden quickly, losing much of the adhesion required with the following layer. This produces a potential sliding surface.

The second factor may be the overlap of vertical reinforcement. In the traditional construction process of reinforced masonry walls, dowel bars are left anchored to the foundation; after the wall is finished, the vertical bars are installed, overlapping with the dowels. The surface in which the dowels end, becomes a weak plane were the sliding failure may occur. To avoid the problem with the overlaps, in some countries a special H-shape block is used (Figure 2), that lets the vertical bars be continuous. If conventional blocks are used with continuous vertical bars, the placement of the masonry units is slow due to the time required to insert and lower the blocks through the bars.

Figure 2: The use of H-shape blocks (left) avoid the overlap of bars and reduces the placement time when using conventional blocks (right).

A third factor may be the poor adhesion between the foundation and the grout. This could be produced by: a) inadequate treatment of the foundation surface; b) grout segregation, due to a high amount of water, inadequate compacting, pouring from too high, etc.

The grout drying shrinkage is the fourth factor. When this happens, the grout may separate from the block and the reinforcement bar, and it losses effectiveness to resist flexure and shear. The amount of dust in the sand and the amount of water required by the grout increases this factor.

The uniform distribution of vertical reinforcement is the fifth factor. Traditionally, the vertical reinforcement is uniformly distributed along the wall. If the reinforcement at the wall ends consists of the same bars along the rest of the wall, it may not be enough to control the wall base rotation when it is subjected to high seismic forces. This fact provokes the crushing of the wall ends, and favours the horizontal flexural cracks to extend towards the middle of the wall. As the seismic load is cyclic, the horizontal cracks end up in a sliding failure (Figure 3).

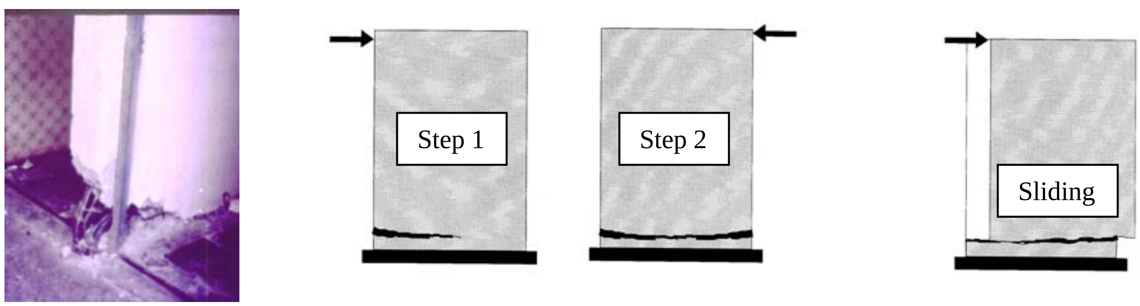

Figure 3: Flexure failure becomes a sliding failure

The sixth and last factor analyzed is the use of longitudinal and vertical strips of mortar over the block. It has been observed that the grout is unable to fill all the space between the strips. Therefore, the union of block and mortar is not strong enough and cracks may develop easily.

POSSIBLE SOLUTIONS TO AVOID THE SLIDING FAILURE

A brief review of possible solutions to avoid the sliding failure is given in this section. The idea was to find alternatives that are economic as well as feasible to perform at field. Among several others, the following can be mentioned: a) deepen the slots on the upper base of the foundation to 6 mm minimum; b) to concentrate more steel reinforcement at the end of the wall, keeping a minimum ratio of 0.001 at the mid zone of the wall; c) placing the first layer blocks inverted upside down, with added openings to be filled with the grout; d) change the mix proportion of the grout, from cement: sand: stones 1:2.5:1.5 (traditional) to 1:3:1, that is, reducing the amount of stones to avoid the grout segregation; e) use pozzolanic cement; f) addition of lime to the grout mix; g) watering the cells previous to grouting, curing the joints after placing the blocks till grout pouring and watering the wall for one week after grouting; h) add dowels in the cells without vertical bars, properly anchored to the foundation.

PRELIMINARY GROUT SPECIMENS

Ten different grout mixes were prepared to study which were suitable for use in the improved wall specimens. A wall pier was constructed using ten half blocks, with a height of 2.4 m, using a transparent plastic formwork. Traditional grout was prepared with Portland cement, common sand, and stones in a proportion of 1:2.5:1.5, with 250 mm (10") slump. Variations included the sieving of the sand, the use of 1:3:1 mix proportion, the addition of 1/10 lime proportion, the use of pozzolanic cement, watering the cells prior to grouting, etc. After the visual inspection of this grout specimen it was decided which grout to use in each wall. The traditional grout was chosen for wall W1; the sieved sand and 1:3:1 proportion was chosen for wall W2, pozzolanic cement and keeping the other characteristics similar of W2 grout were used for wall W3; and walls W4 and W5 had a grout similar to the one used in W3, plus watering of the cells prior to grouting.

CONSTRUCTION OF WALL SPECIMENS

A total of five full-scale walls were constructed. All had several common characteristics, as follows: dimensions were 2.4x2.4x0.14 m; wall thickness was 0.14m; the concrete blocks featured slots to allow the horizontal reinforcing bars; the mortar mix was 1:1/2: 4 cement: lime : coarse sand; the cement for the mortar was Portland type I and the sand was sieved between meshes ASTM #4 and #200; all joints were 10 mm thick; the reinforcing bars steel had yield point at 420 MPa (60 ksi); the grout was prepared in a mixer machine; the slump was controlled to be 250 mm (10"); the walls were constructed in two days by the same qualified labour men; all blocks of the first layer had cleaning openings of 75x100 mm (3"x4") in each cell; the grout was poured in two layers, each one was compacted with a 16 mm (5/8") bar with an interval of 30 minutes between layers; the horizontal reinforcement was 1-9.5mm (3/8") bar each 0.20 m, a ratio of 0.0025, while the vertical reinforcement total ratio was 0.0024. Finally, both foundation beam and collar beam had the same cross section, concrete quality and reinforcement.

For wall W1 the traditional construction sequence was followed. For the rest of the walls, table 1 show the variations used in their construction. Figures 4 to 9 show the wall characteristics and some aspects of the construction. The inverted blocks of the first layer used in walls W3 and W4 should be especially noted.

Table 1: Characteristics of Wall Specimens

Characteristic	W1	W2	W3	W4	W5
Foundation slots	normal	deep	deep	Deep	deep
Distribution of vertical reinforcement	uniform	concentrated at ends	concentrated at ends	concentrated at ends	concentrated at ends
Sieving the sand of the grout, meshes #4 y #200	no	yes	yes	yes	yes
Type de vertical joint	strips	full	full	full	strips
Overlap of vertical reinforcement	100% in the same section	alternated h = 0.7 m and 0.95 m	alternated h = 0.7 m and 0.95 m	alternated h = 0.7 m and 0.95 m	continuous, no overlaps
Grout cement-sand-stones	1: 2 ½: 1 ½	1: 3: 1	1: 3: 1	1: 3: 1	1: 3: 1
Cement of the grout	Portland I	Portland I	Pozzolanic IP	Pozzolanic IP	Pozzolanic IP
Treatment by curing the joints, watering the inner cells and walls	no	no	no	yes	yes
Added dowels	no	no	no	yes	yes
Block of first layer	normal	normal	inverted	inverted	H

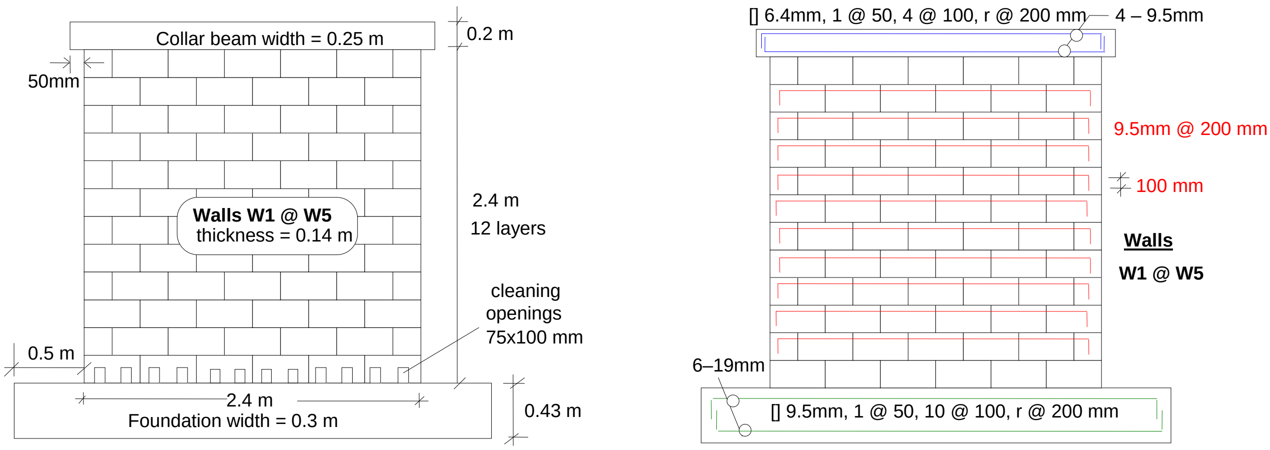

Figure 4: Common characteristics of the five walls

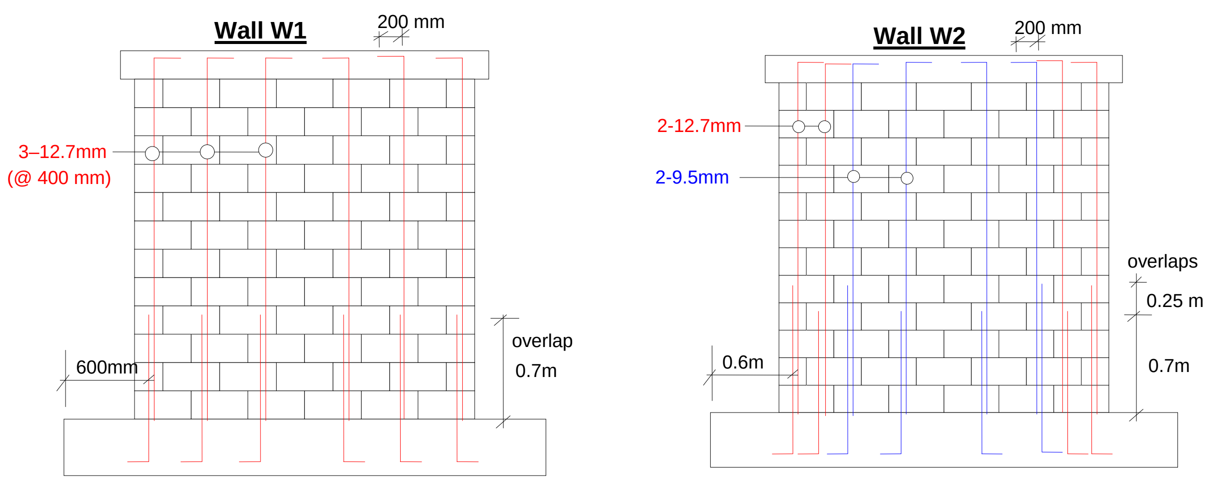

Figure 5: Vertical reinforcement of walls W1 and W2

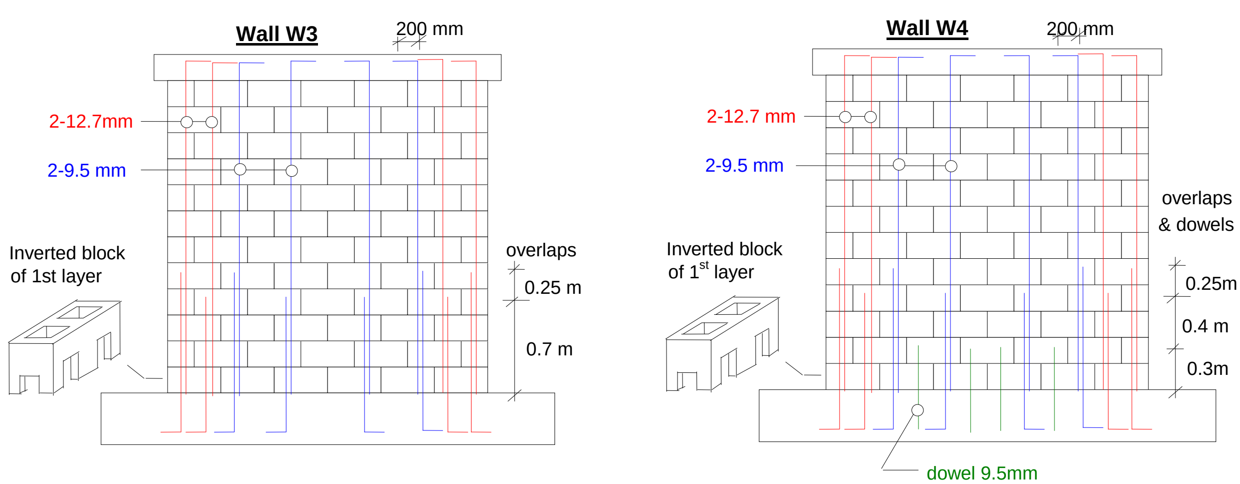

Figure 6: Characteristics of walls W3 and W4

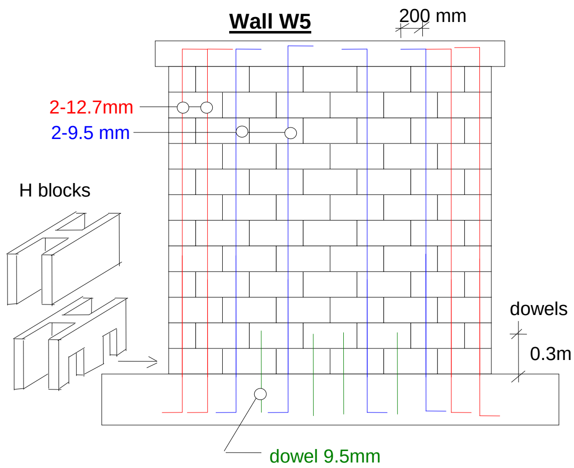

Figure 7: Characteristics of wall W5

Figure 8: Construction of walls W1 (left), W3 (centre) and W5 (right)

Figure 9: Treatment by watering of walls W4 and W5

MATERIAL TESTS

The control tests on the materials included grout compression strength of 9 samples; in all cases, the resistance was over the Peruvian Masonry Code minimum [3]. Six masonry prisms 3-layers each were constructed and subjected to axial compression and six small walls 4-layers each were constructed and subjected to diagonal compression. Of these, 3 prisms and small walls were filled with traditional grout while the other 3 were filled with the 1:3:1 grout with pozzolanic cement IP, as used in walls W4 and W5. Also, they had the same treatment by watering already mentioned in Table 1. The average and characteristic compressive resistance f_m and f'_m, and the average and characteristic shear resistance, v_m and v'_m results are shown in Table 2. Characteristic values of f'_m and v'_m, were taken as the average minus one standard deviation.

Table 2: Masonry prisms resistance

Specimen	Resistance	Grout 1: 2 ½ : 1½ Cement I	Grout 1: 3: 1 Cement IP
Prisms	Average f_m	10.4 MPa	8.4 MPa
	Dispersion	3.0 %	6.0 %
	Characteristic f'_m	10.1 MPa	7.9 MPa
Small walls	Average v_m	1.31 MPa	1.25 MPa
	Dispersion	8.6 %	3.5 %
	Characteristic v'_m	1.20 MPa	1.21 MPa

CYCLIC LATERAL LOAD TESTS

The five walls were subjected to cyclic lateral load tests with the setup shown in Figure 10. The horizontal displacement of the collar beam (named D1) was controlled with ten steps of increasing amplitude (Table 3). Hysteretic curves for walls W1 and W4, and envelopes of the first cycle of the five walls are shown in Figure 11.

Table 3: Cyclic lateral load steps

Step	1	2	3	4	5	6	7	8	9	10
D1 (mm)	0.25	1.00	2.50	5.00	7.50	10.00	12.50	15.00	17.50	20.00
No. Cycles	1	2	3	3	3	3	4	4	4	4

Figure 10: Test setup for cyclic lateral load

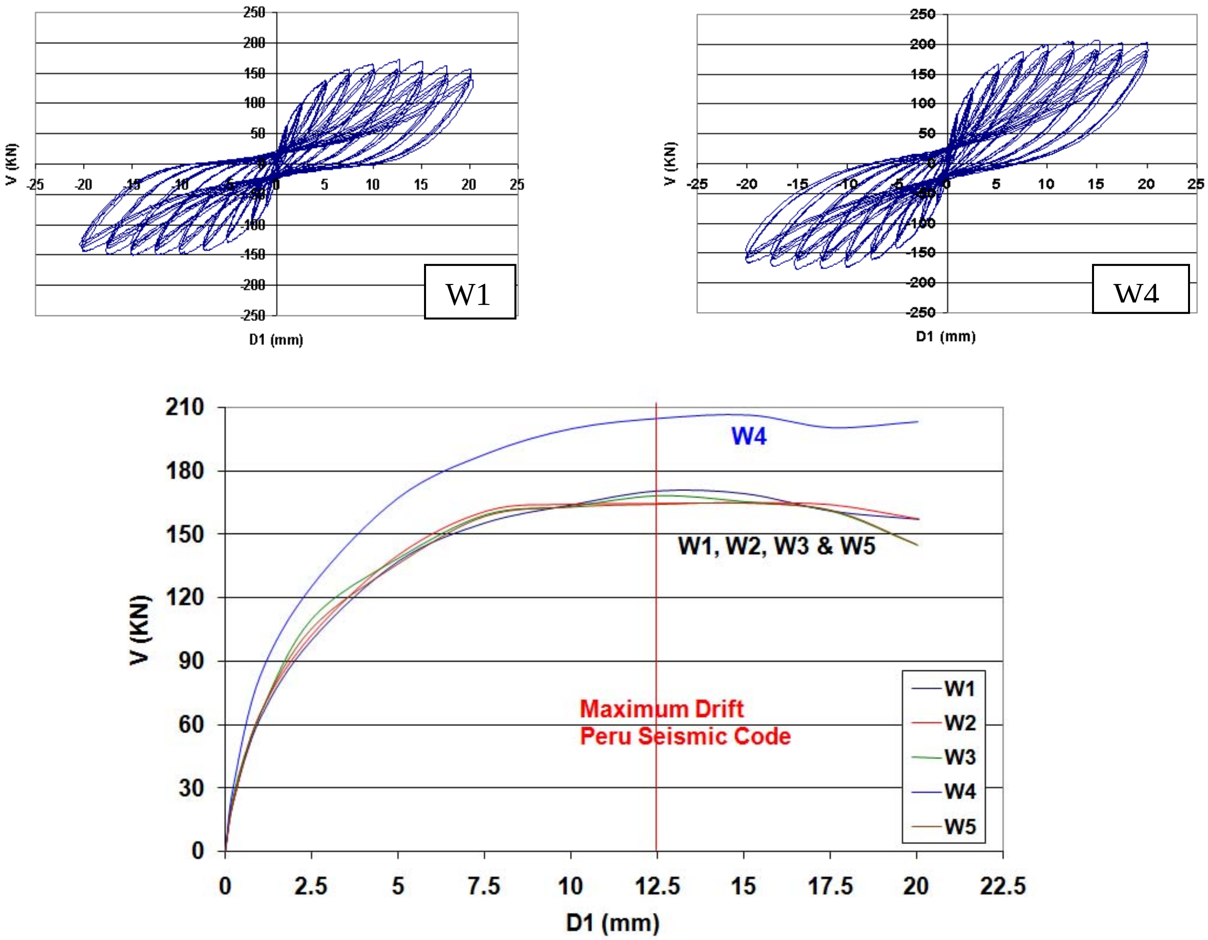

Figure 11: Hysteretic curves and envelopes

DESCRIPTION OF TEST BEHAVIOUR OF THE WALLS

The behaviour of the walls during the cyclic lateral load tests is summarized focusing on the sliding problem. The maximum drift of 0.005 allowed by the Peruvian Seismic Code for masonry structures was attained during step 7 of the test, for D1=12.5 mm. Therefore, if the sliding failure was reached at a higher step it would be unimportant. However, due to other factors, such as the relation between the test model and a wall in a building subjected to real earthquakes, it would be recommended to use a safer drift limit as 0.006, which was reached in step 8 of the test, for D1=15 mm.

In wall W1 two sliding planes were observed: the first one was located at the foundation and was produced during step 5; the second occurred at the fifth layer base, were the dowels end, and was produced during step 7. For walls W2 and W3, the sliding occurred at the foundation during steps 5 and 7, respectively. Wall W4 had no sliding at any step. Finally, wall W5 had sliding at the third layer base, were the dowels end, during step 9. According to the above mentioned criteria, walls W1, W2, W3 are unsafe, while wall W5 could be improved and wall W4 had the best behavior. The added amount of vertical reinforcement in wall W4 appears to have a significant influence in this behavior. In figure 12, details of the five walls are shown, at the end of step 8 for walls W1, W2 and W3, and at the end of step 10 for walls W4 and W5.

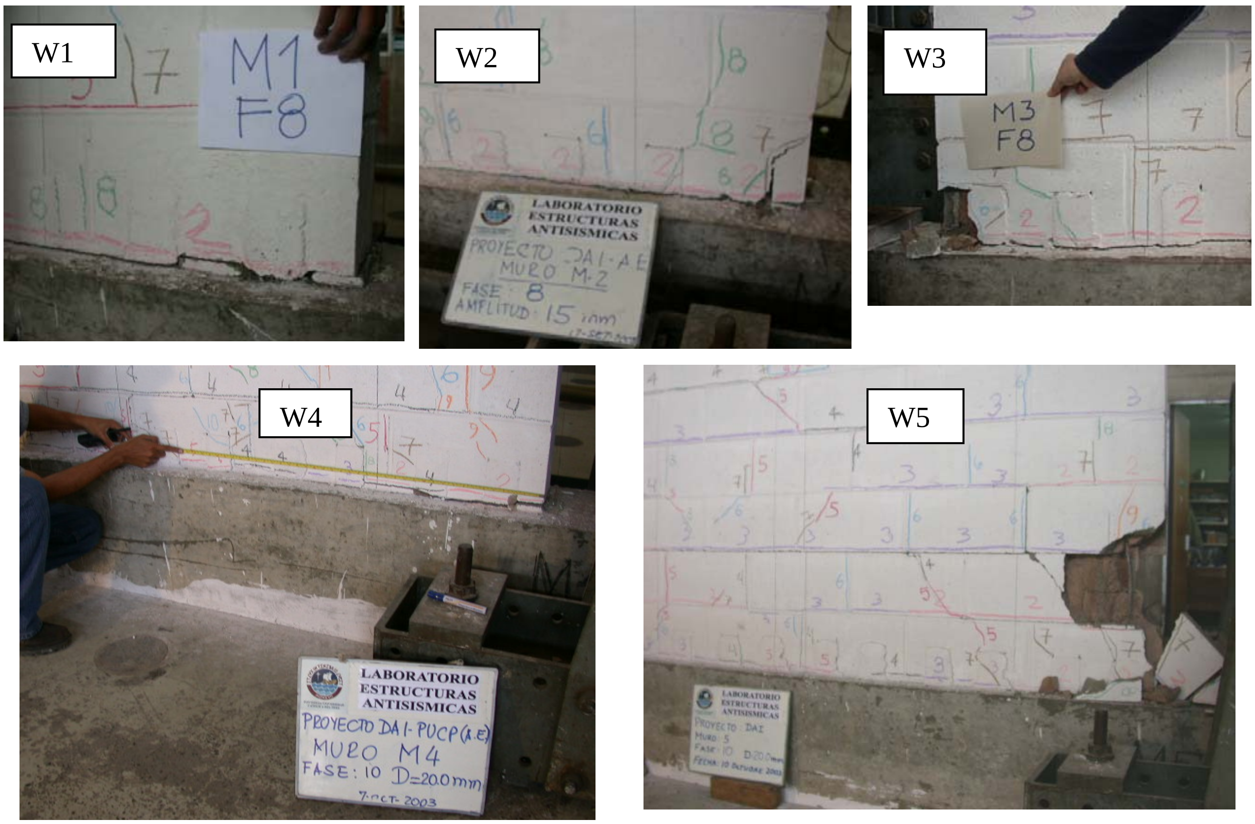

Figure 12: Walls showing sliding failure at different steps of the test, except W4.

The use of deep slots at the foundation, used in walls W2 to W5, improved the adhesion of the foundation with the mortar. However, the horizontal cracks at the base developed at the joint block-mortar, due to the low adhesion between these two elements.

The use of inverted blocks at the first layer so that grout could fill more area, did not increase the wall shear resistance. It could be observed that the grout base was covered by a smooth layer of humid cement of the same grout.

The reduction of stone proportion in the grout, keeping the slump at 250 mm (10”), was useful to reduce the problem of segregation of the stones in the base of the grout.

The treatment by watering done to walls W4 and W5, as well as the use of pozzolanic cement IP, improved slightly the adhesion between blocks and grout. The drying shrinkage of the grout was lowered in both cases. However, this improvement did not increased the resistance in wall W3 because it failed by sliding.

Regarding the vertical reinforcement, several findings were obtained, as follows. The use in wall W1 of traditional bars of equal height with overlaps at the same section produced two sliding failure surfaces, which is very dangerous. In walls W2 and W3, the use of overlaps at different heights made that the only sliding surface was the one at the base. In wall W4, the use of dowels of different lengths plus extra dowels at the cells without vertical reinforcement, improved significantly the seismic behavior. A similar conclusion was also reported in reference [4], in which stronger dowel bars were effective to prevent the sliding failure at the bottom of the tested fully grouted masonry wall. Wall W4 had a mixed final failure combined of flexure and shear, with an increased maximum resistance force of 21% respect to wall W1. Furthermore, wall W4 was the only one in which the vertical bars at the wall end did not buckle. In the other four walls buckling of those bars occurred (Figure 13).

Figure 13: Inspection after the test, buckling of bars at the end of the walls

CONCLUSIONS

The main objective of this research study which was the control of the sliding failure was achieved. The wall in which this occurred had a less dangerous failure at the end of the test. This could be done by using extra 9.5 mm (3/8”) dowels in those cells free of vertical flexural reinforcement, and that those dowels have different lengths over the foundation, let us say 300 and 500 mm. The dowel separation could be every 200 mm, which is the cell spacing, and anchored 300 mm into the foundation.

It must be mentioned that any improvement in such reinforced masonry walls will be not effective or will not increase it resistance, unless the sliding failure is avoided.

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