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BEHAVIOR OF CONFINED MASONRY SHEAR WALLS WITH LARGE OPENINGS

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SUMMARY

Significant research has been carried out in different countries to study the behavior of confined masonry walls. However all the specimens of the tests reported had not openings, which is a typical feature of walls of actual buildings. In order to study the behavior of lightly reinforced confined masonry shear walls with openings, sixteen full-scale specimens were tested. Eight specimens were of concrete masonry units and eight of hollow clay brick masonry units. The specimens were designed to have shear failure with diagonal cracks in the masonry panel. The test parameters were the masonry unit type (concrete and clay) and the size of openings (four cases).

Test results include the evaluation of the deformation capacity, energy dissipation characteristics and stiffness and strength degradation, cracking shear, maximum shear strength and the interstory drift associated to different limit states. Comparisons with the behavior of previously tested confined masonry walls without openings are also made.

The results show that masonry unit type and size of the openings control the behavior and that confined masonry walls, even with large openings, have a significant deformation capacity. They also show that it is conservative to consider the shear capacity proportional to the net transverse area of the walls.

INTRODUCTION

Structural masonry is one of the most inexpensive construction systems for low to medium rise buildings in Latin America. In these buildings, masonry shear walls are the only structural element of the gravitational and seismic lateral resistance system.

In many Latin American countries, **confined masonry** is one of the most popular construction system, consisting of a masonry panel framed with concrete beams and columns. The masonry panel is made first, and then the concrete of columns and beams is poured against the boundaries of the masonry panels.

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Due to the complexity of the problem, the behavior of confined masonry shear walls is still not well known, in spite of masonry experimental research programs conducted in many countries. One of the less known aspect is the effect of the openings (their size) on the seismic behavior of the walls. These openings correspond to windows and doors of the façade of the buildings.

To assess the effect of the openings on the seismic behaviors, sixteen specimens of confined masonry walls with central openings of different sizes were tested under lateral controlled deformation cycles. Eight specimens were of hollow concrete masonry units and eight of hollow clay masonry units. The main parameters studied were strength, stiffness, deformation capacity and energy dissipation capacity of the walls [1].

EXPERIMENTAL PROGRAM

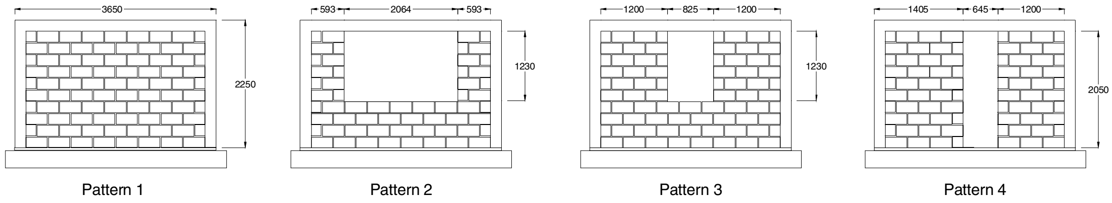
Characteristic of the specimens

To determine the characteristics of the specimen, 164 Chilean dwelling projects were reviewed [2].

All the specimens had a panel with openings of different sizes, two columns and a beam on top. The bond pattern was of the running bond type. The openings had no special concrete confinement elements around its borders. The hollows of the masonry units were not filled with mortar or grout, except in the hollow close to the openings where a vertical reinforcement bar was placed.

The walls of concrete masonry units were 3650 mm width and 2250 mm height. The walls of clay units were 3600 mm width, and 2200 mm height. The thickness in both cases was 140 mm (the width of the units). Figure 1 shows the dimensions of the four patterns of the specimens (there were 2 specimens for each pattern).

Concrete masonry walls



Hollow clay brick masonry walls

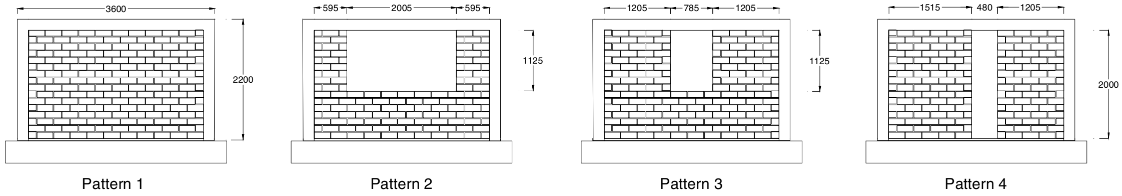


Figure 1: Wall dimensions

The longitudinal reinforcement of the confinement columns and beam was 4 bars of 10 mm diameter, and the transverse reinforcement was a hoops of 6 mm diameter at 150 mm spacing. The vertical reinforcement in the border of the openings was 1 bar of 10 mm diameter, placed in the first hollow close to the opening. The steel was 420 MPa yield strength in all cases. A reinforcement of 2 bar of 4.2 mm diameter (steel welded wire fabric) 500 MPa yield strength was placed under the first course below the window openings, see Figure 2.

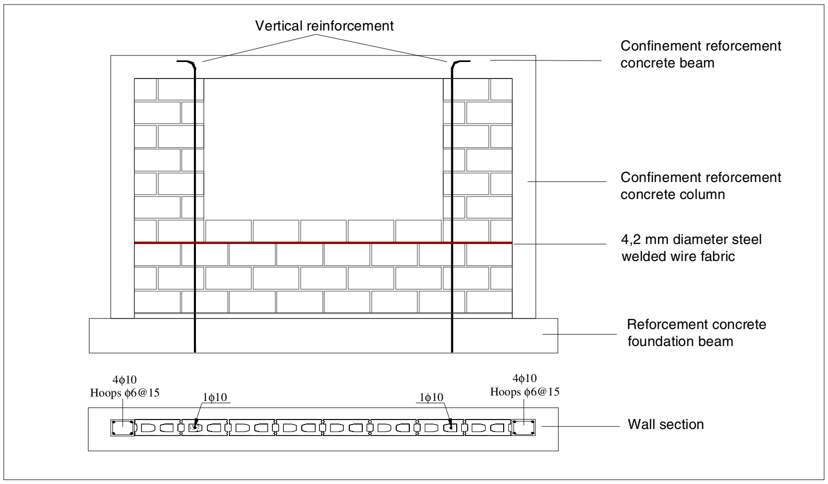


Figure 2: Wall reinforcement

The proportion of the mortar used was 6.5 liters of water per each 45 kg sack of premixed mortar. The proportion of the concrete of the columns and beams was 4.2 liters of water per each 35 kg sack of premixed concrete of 8mm maximum size. The grout poured into the hollows close to the opening (where a reinforcement bar was placed) was 5.5 liter of water per each 45 kg sack of premixed concrete of 8 mm maximum size. Table 1 shows the mean strength of the materials used.

Table 1: Strength of the materials

Material	**Strength**	**Mean value [MPa]**
Mortar	Compressive Strength	18.87
Fill concrete	Compressive Strength	31.72
Concrete	Compressive Strength (28 days)	23.9
Steel A 63-42H	Yield Strength	553
Steel AT56-50H	Yield Strength	587

The properties of the units are shown in Table 2. Figure 3 shows the masonry units used. The mechanical properties of the masonry are shown in Table 3. The compression strength was determined testing prisms of masonry, see Figure 4, and the basic shear strength, testing square masonry wall segments in diagonal compression, see Figure 5, according to the procedure of Chilean standards NCh1928 [3] and NCh2123 [4].

Tabla 2: Properties of Unit

Dimensions / Properties	**Concrete masonry Unit**	**Hollow clay brick masonry unit**
	Mean value	**Mean value**
Length	392 mm	291 mm
Width	140 mm	141 mm
Thickness	189 mm	115 mm
Hollow	35.6 %	50.7 %
Compressive Stregth	9.68 MPa	25.9 MPa

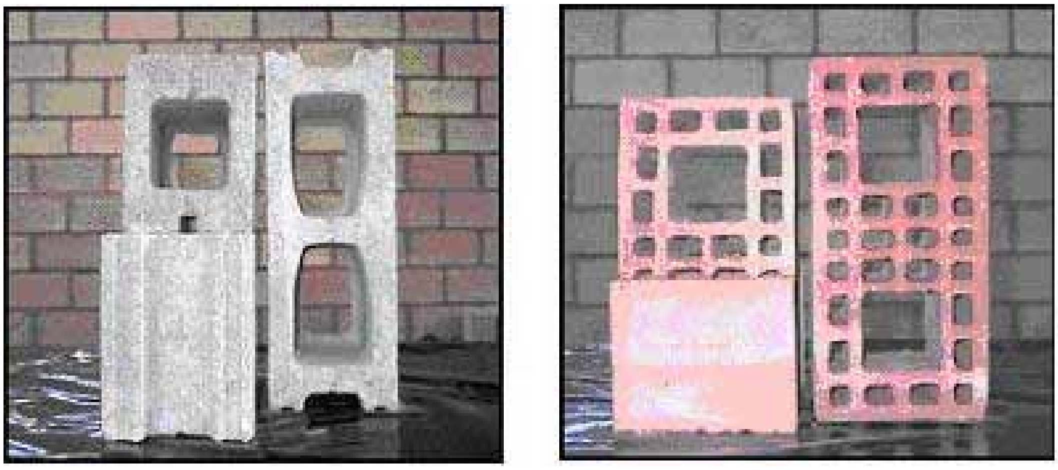


Figure 3:Concrete masonry unit (left) and hollow clay brick masonry units (right)

Tabla 3: Properties of Masonry

Indice	**Symbol**	**Type of unit**	
		Concrete masonry Unit	**Hollow clay brick masonry unit**
		[MPa]	[MPa]
Compressive Strength[1]	f'_m	6,04	6,89
Basic Shear Strength[1]	τ_m	0,49	0,55
Elastic Modulus[1]	E_m	7114	4849
Shear Modulus	G_m	1005	528

[1] Base on gross area

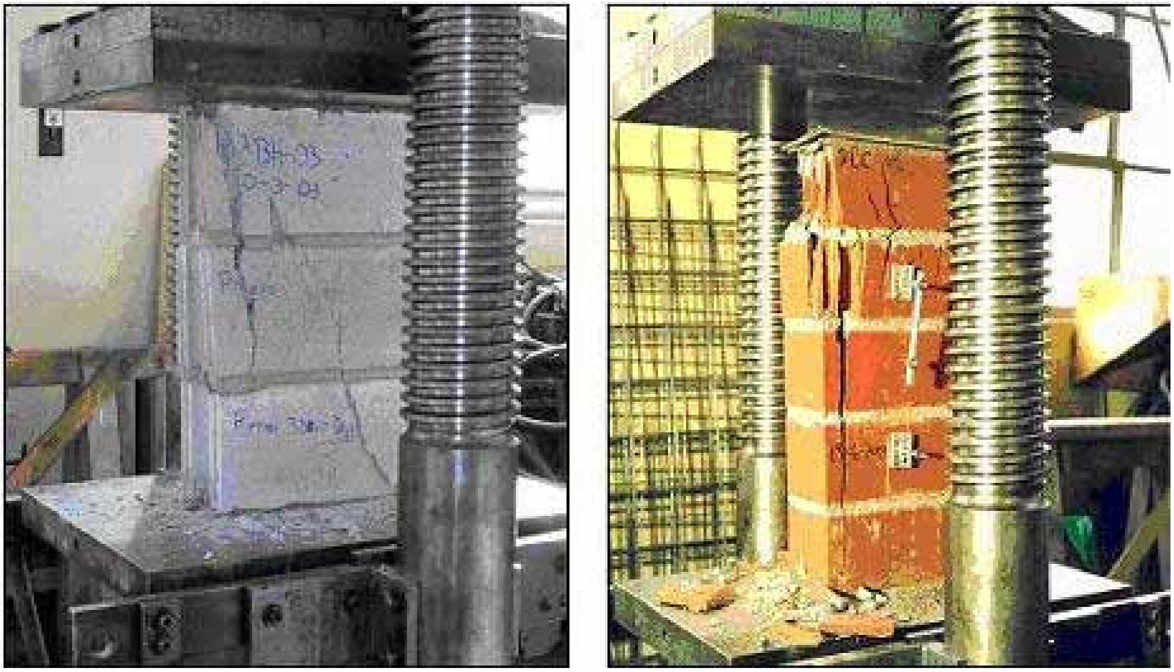


Figure 4:Axial compression test of masonry prism of concrete masonry units (left) and hollow clay brick masonry units (right)

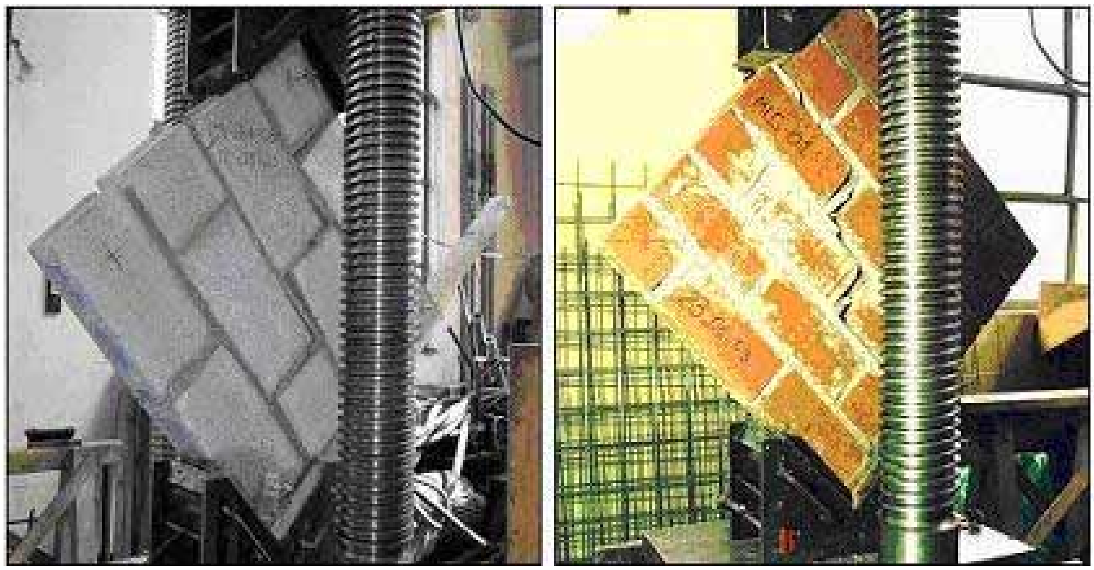


Figure 5:Diagonal compression test of masonry wall segments of concrete masonry units (left) and hollow clay brick masonry units (right). It can be seen in both cases that the cracks propagate through the mortar joint

Parameters studied

The parameters studied in this experimental program were the type of the units (concrete and clay) and the size of the openings. The ratio between the opening area and the total area of the wall, α, and the ratio between the net transverse area (discounting the opening) and the total transverse area, β, are indicated in Table 4

Table 4: Parameters α y β

Concrete masonry wall		
Pattern	α %	β
1	0	1.00
2	31	0.44
3	12	0.77
4	16	0.82

Hollow clay brick masonry wall		
Pattern	α %	β
1	0	1.00
2	28	0.44
3	11	0.78
4	12	0.87

For each case, 2 specimens were tested. The quantities evaluated were: strength capacity, stiffness, deformation capacity and energy dissipation capacity.

Construction

The specimens were built upon a reinforced concrete foundation beams, where the vertical bars of the walls were anchored.

The concrete was poured in the columns from a height of 2.20 m. After each 0.3 m of height, the concrete was vibrated. Before concreting the top beam, the construction joint in the columns were scarified and washed out.

To cure them, the specimens were covered with polyethylene film. The mortar joints of the concrete masonry unit specimens were wetted twice a day. In the case of hollow clay brick masonry unit specimens, the units and the mortar joints were wetted for seven days.

Testing procedures

The testing set up is shown in Figure 6. A horizontal cyclic load was applied along the axis of the top beam, and controlled by displacement. There was no vertical load applied. The displacement history is shown in Figure 7. Two cycles at each deformation level were applied.

During testing, the development of cracks and damage were registered. Five level of damage were defined: (i) first visible cracking in the columns, (ii) first visible cracking in the masonry panel, (iii) beginning of diagonal cracking, (iv) primary and secondary diagonal cracking in the wall segments in both sides of the openings, and (v) formation of the final cracking pattern.

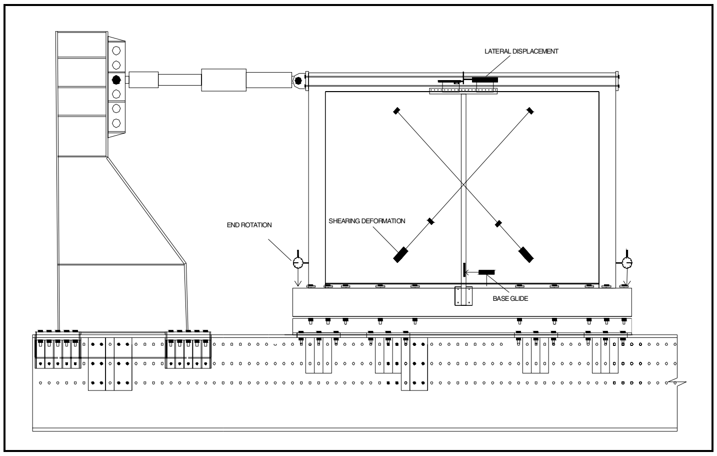


Figure 6: The testing set up

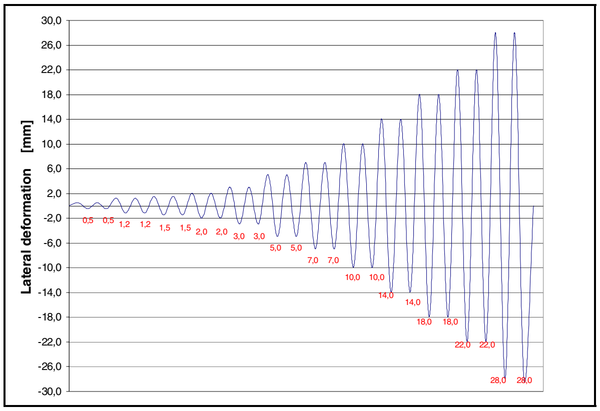
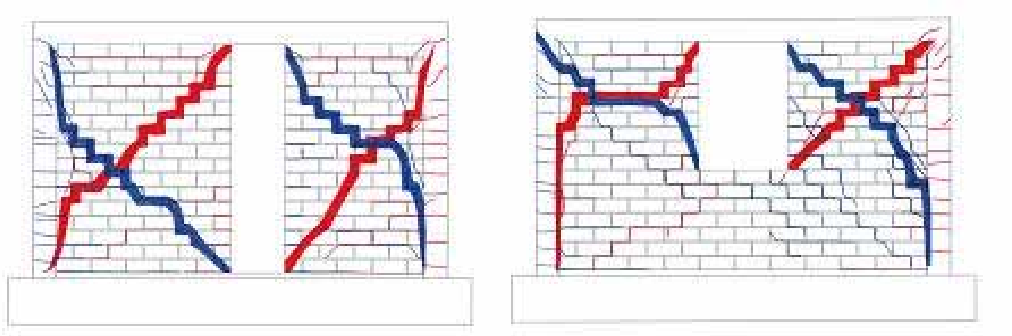


Figure 7: Displacement history

RESULTS

Qualitative behaviors of the specimens

All the specimens failed in shear. There appeared two failure mechanisms (shown in Figure 8): diagonal cracking and mixed cracking. The first mechanism corresponds to a diagonal crack spanning at least half of the width of the specimen. The second mechanism corresponds to a crack that develops horizontally and then diagonally, or vice versa, with similar spans in each case. In both mechanisms, the cracks propagate though the mortar joint due to a low adherence between the mortar and the masonry units. This situation appears more often in concrete masonry unit specimens.



Diagonal cracking Mixed cracking

Figure 8: Failure mechanisms

The first cracks appeared horizontally in the confinement columns, and in the lower courses of the masonry panels. While the horizontal reinforcement under the openings is not broken, the damage concentrates in the wall segments in both sides of the openings, see Figure 9. In the specimens with no horizontal reinforcement under the openings (pattern 4), the strength degradation and the width of the cracks was notorious once the diagonal cracks reached the vertical bar reinforcement close to the openings, see Figure 10.

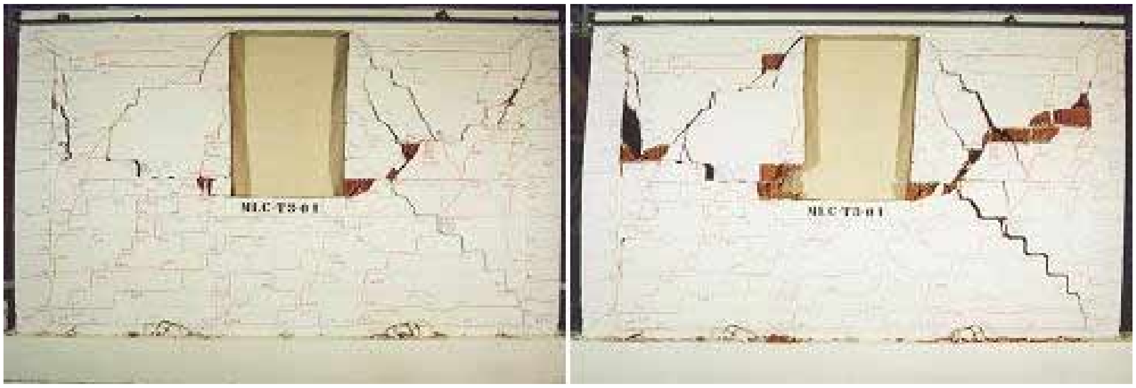


Figure 9: Damage of hollow clay brick masonry wall (pattern 3) before the fracture of horinzontal reinforcement under the opening (left) and after its (right)

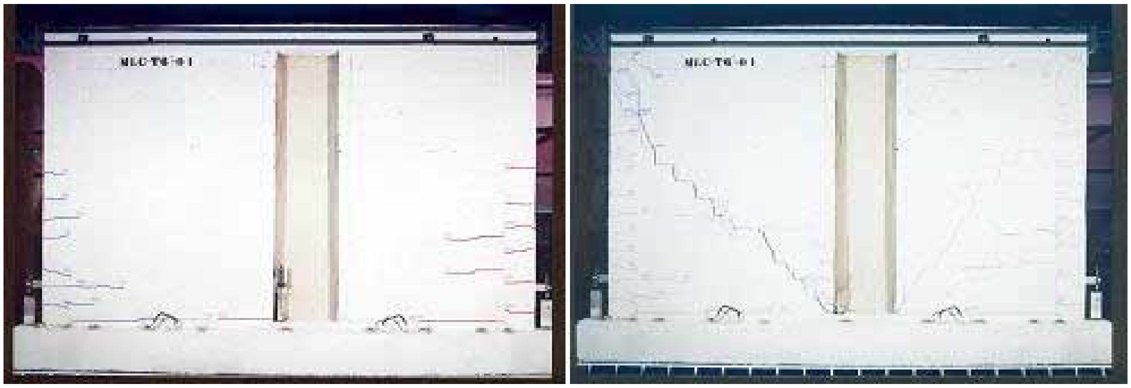


Figure 10: Damage of hollow clay brick masonry wall (pattern 4) before diagonal cracking (left) and after its (right)

Strength capacity

Table 5a and 5b show (a) the load corresponding to the primary diagonal cracking (i.e. the diagonal crack developed in the pier or wall segment adjacent to the opening when the boundary column works as a tie in a virtual strut and tie model), and (b) the maximum load capacity of the specimens. Figure 11 shows the envelope of the hysteretic load-deformation curves, based on the first cycle of each deformation level. In these curves, the lateral load H is scaled in terms of Ho, the smaller maximum lateral load corresponding to the specimen without openings.

Table 5a: Strength capacity of concrete masonry walls

Load for primary diagonal cracking				
Pattern	**Specimen 1**		**Specimen 2**	
	+	**-**	**+**	**-**
	kN	kN	kN	kN
1	67	23	70	65
2	61	48	45	49
3	78	53	77	65
4	49	75	60	60

Maximum load				
Pattern	**Specimen 1**		**Specimen 2**	
	+	**-**	**+**	**-**
	kN	kN	kN	kN
1	124	109	130	130
2	79	68	87	78
3	154	104	113	112
4	122	96	109	80

Table 5b: Strength capacity of hollow clay brick masonry walls

Load for primary diagonal cracking				
Pattern	**Specimen 1**		**Specimen 2**	
	+	**-**	**+**	**-**
	kN	kN	kN	kN
1	143	150	114	141
2	61	77	83	77
3	116	157	122	126
4	100	123	110	147

Maximum load				
Pattern	**Specimen 1**		**Specimen 2**	
	+	**-**	**+**	**-**
	kN	kN	kN	kN
1	172	152	199	183
2	85	87	96	100
3	135	157	141	152
4	100	127	126	147

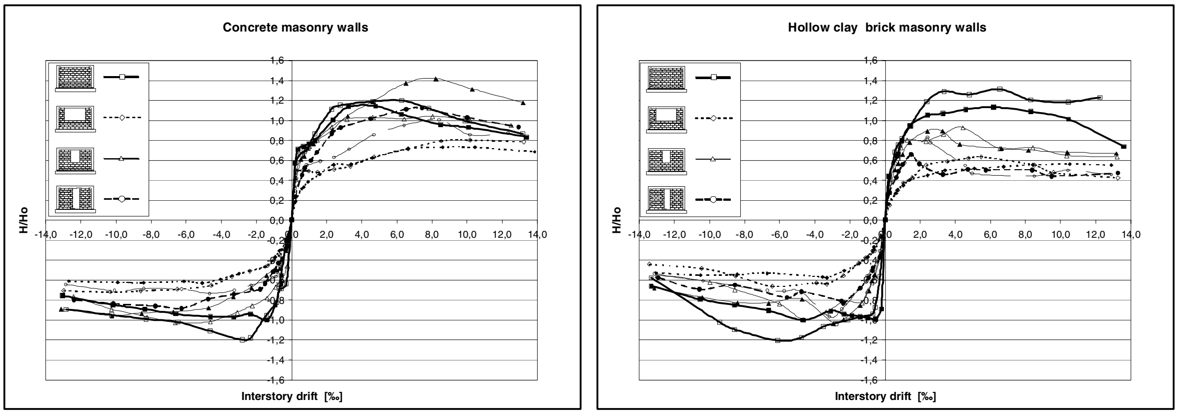


Figure 11: Envelope of the hysteretic cycles

Strength degradation

Figure 12 shows the strength degradation from maximum horizontal load to the load level of the last cycle applied to the specimens. It can be seen that the hollow clay brick masonry unit specimens present larger strength degradation than the concrete masonry unit specimens, although the former specimens reach larger maximum horizontal load. Figure 12 also shows that specimens with opening pattern 2 and 3 have the smaller strength degradation.

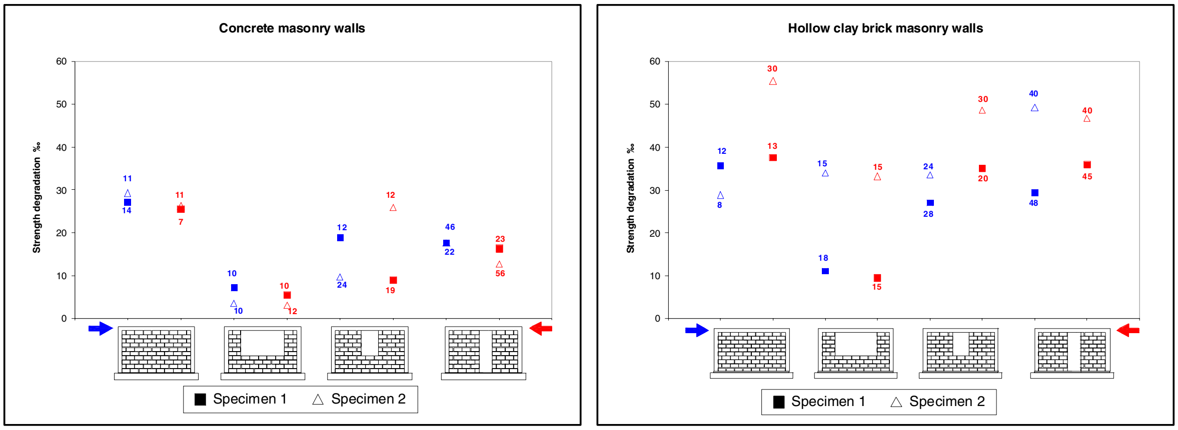


Figure 12: Strength degradation

Stiffness

Table 6 shows the lateral stiffness for the first cycle of the second level of deformations applied to the specimens (initial stiffness). Figure 13 shows the stiffness degradation as a function of the interstory drift. The curves are shown up to an interstory drift of 8.0‰.

The stiffness was defined taken the slope of the line joining the maximum positive and negative deformation of the cycle. In these curves the stiffness was scaled in terms of Ko, the smaller stiffness of the first cycle of the second level of deformations applied to the specimens without openings.

Figure 13 also shows that the stiffness degradation is striking for interstory drift lesser that 2.0‰, due to the cracking in the confinement columns and in the masonry panel, and the concrete masonry walls present a small rate of the stiffness degradation for any interstory drift value.

Table 6: Initial stiffness

Concrete masonry wall		
Pattern	Specimen 1	Specimen 2
	kN/mm	kN/mm
1	44	49
2	23	25
3	36	42
4	30	35

Hollow clay brick masonry wall		
Pattern	Specimen 1	Specimen 2
	kN/mm	kN/mm
1	60	82
2	28	29
3	57	66
4	50	48

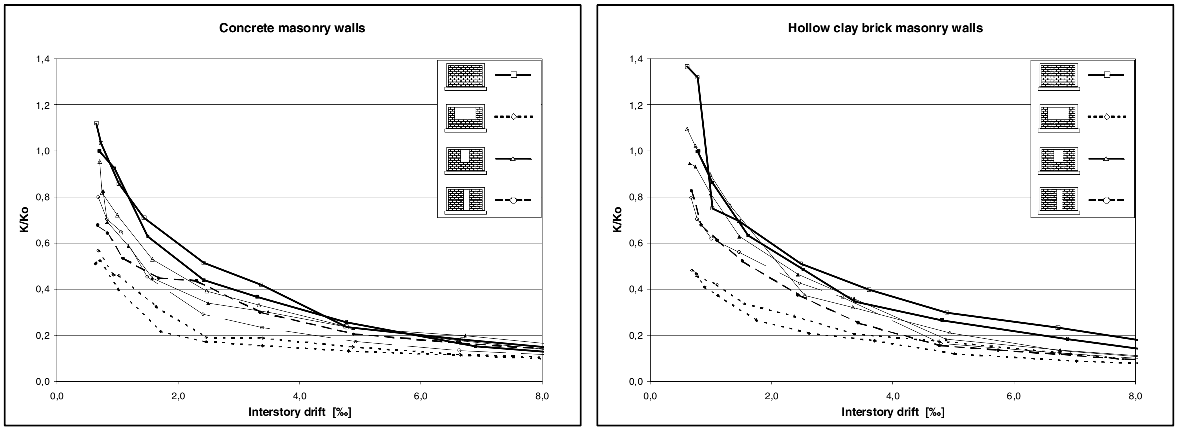


Figure 13: Stiffness degradation

Deformation capacity and damage

Figure 14a and 14b show the interstory drift associated to the different levels of damage for the concrete masonry unit specimens. They also show under every point the corresponding crack width. For clarity, Figure 14a shows the beginning of diagonal cracking (BDC) and primary diagonal cracking (PDC), and Figure 14b shows the primary diagonal cracking level again and the maximum load level (MLL). It can be seen that (a) under 1.0‰ interstory drift, all the specimen have reached the beginning of diagonal cracking level with crack widths in the range of 0.1 to 0.4 mm, (b) under 1.5‰ interstory drift, all the specimens have reached the primary diagonal cracking level with crack widths in the range of 0.1 to 0.8 mm, and (c) the maximum horizontal load is associated to interstory drift larger than 2.0‰.

Figure 15a and 15b show the interstory drift associated to the different levels of damage for the hollow clay brick masonry unit specimens. It can be seen that (a) under 1.5‰ interstory drift, all the specimen have reached the beginning of diagonal cracking level with crack widths in range of 0.1 to 0.8 mm, (b) under 2,0‰ interstory drift, all the specimen have reached the primary diagonal cracking level with crack widths in the range of 0.2 to 2.0 mm, and (c) the maximum horizontal load is associated to interstory drift larger than 2.0‰.

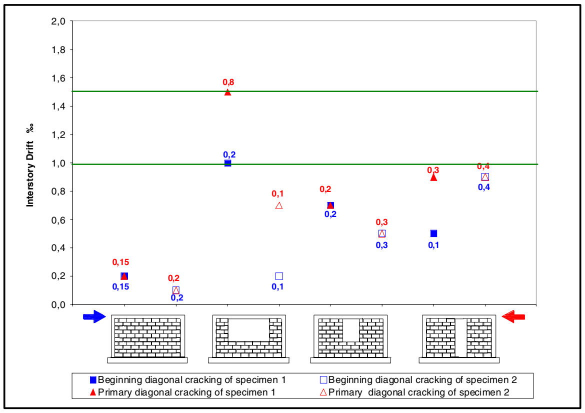


Figure 14a: Interstory drift and crack width for BCD and PDC damage level of concrete masonry walls

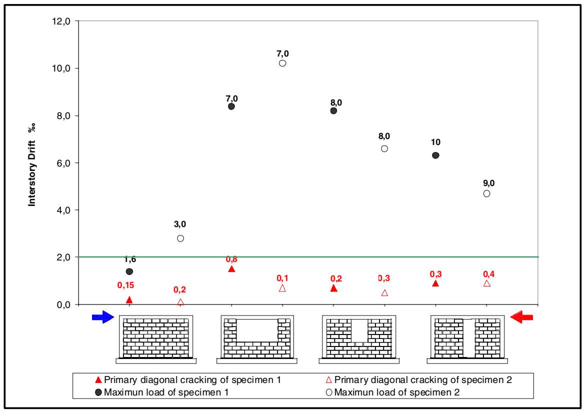


Figure 14b: interstory drift and crack width for PDC and MLL damage level of concrete masonry walls

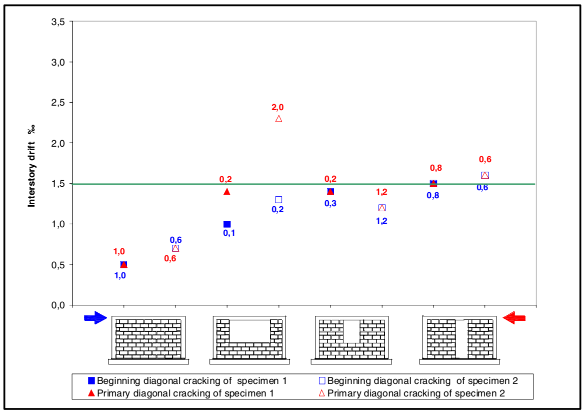


Figure 15a: Interstory drift and crack width for BCD and PDC damage level of hollow clay brick masonry walls

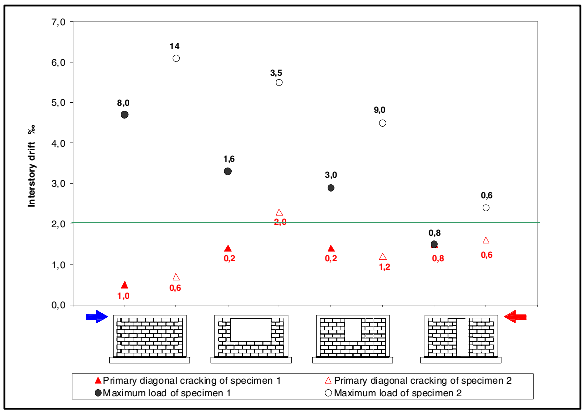


Figure 15b: interstory drift and crack width for PDC and MLL damage level of hollow clay brick masonry walls

Figure 16 a,b and Figure 17 a,b show the interstory drift associated to crack widths of 1.5 mm and 3.0 mm, for concrete masonry units and hollow clay masonry units, respectively. The tests indicate that for these specimens with small horizontal reinforcement in the masonry panel, the crack widths are quite large for small interstory drift. In order to keep the crack widths under 1.5 mm, the interstory drift ratio should be no larger than 1.0‰, whereas to keep the crack widths under 3.0 mm, the interstory drift should be no larger than 2.0‰.

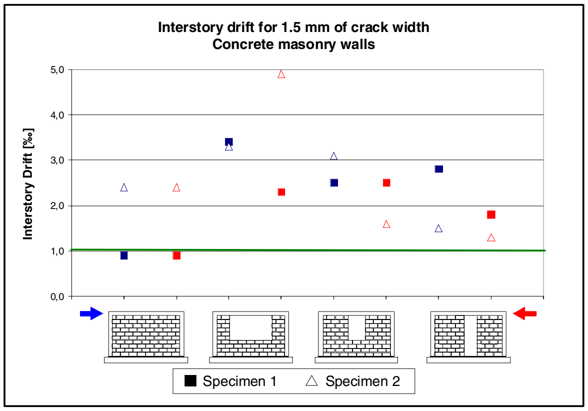


Figure 16a: Interstory drift for 1.5 mm of crack width for concrete masonry walls

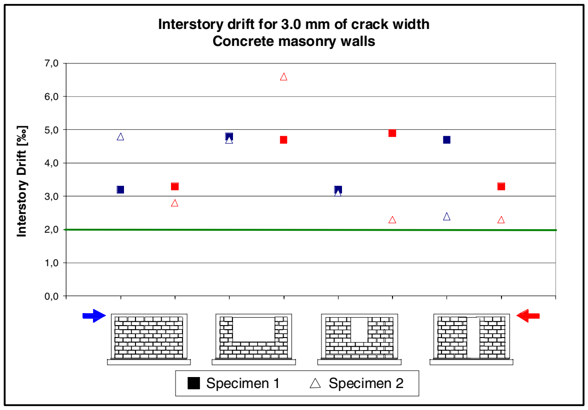


Figure 16b: Interstory drift for 3.0 mm of crack width for concrete masonry walls

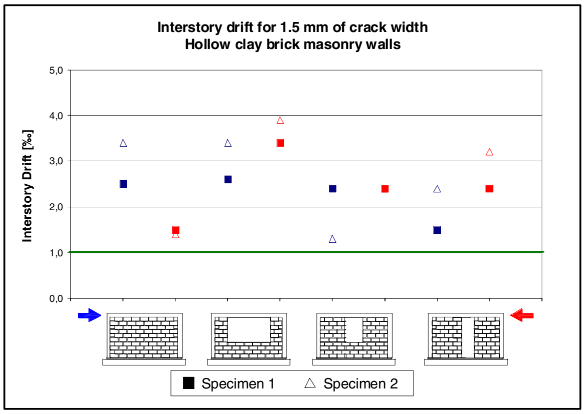


Figure 17a: Interstory drift for 1.5 mm of crack width for hollow clay brick masonry walls

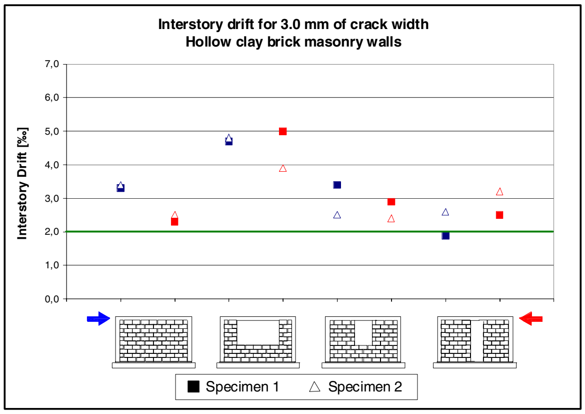


Figure 17b: Interstory drift for 3.0 mm of crack width for for hollow clay brick masonry walls

Energy dissipation capacity

Figure 18 shows the accumulated energy dissipation for each level of deformation (including both cycles) as a function of interstory drift. This energy has been scaled in terms of the smaller total accumulated energy dissipation (Eo) of the specimens without openings. Table 7 shows the total accumulated energy dissipation for all the specimens. From this table it can be seen that energy dissipation capacity of concrete masonry walls is smaller than brick masonry walls, between a 25% to 40%, when the interstory drift is 10.5 ‰. The Figure 18 shows that in concrete masonry walls this capacity is less sensitive to the opening of small size.

Table 7: Total accumulated energy dissipation when interstory drift is 10.5‰

Concrete masonry wall		
Pattern	**Specimen 1**	**Specimen 2**
	kN mm	kN mm
1	9192	10164
2	5538	5706
3	9004	8351
4	9047	10187

Hollow clay brick masonry wall		
Pattern	**Specimen 1**	**Specimen 2**
	kN mm	kN mm
1	15924	17120
2	7737	7487
3	10474	14800
4	12341	15092

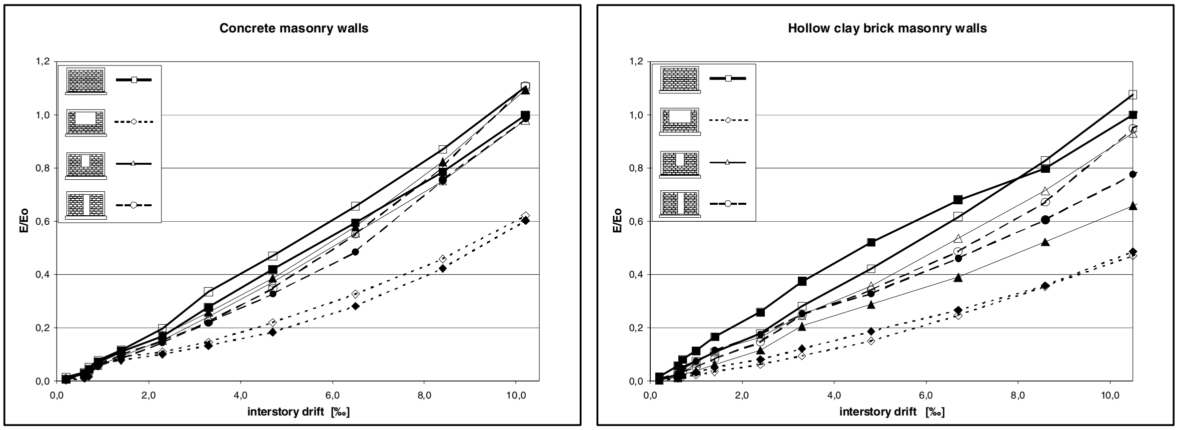


Figure 18: Accumulated energy dissipation when interstory drift is 10.5‰

Maximum shear and size of openings

Figure 19 shows the maximum horizontal load H scaled in terms of Ho, as a function of β. It can be seen that the shear capacity decreases as the net transverse area decreases. The line H/Ho=β can be considered as a lower bound for the shear capacity of both type of wall with centered openings. An exception is the walls with opening pattern 4, where the virtual strut in both lateral panels is steep. On the contrary, in the case of pattern 3, the wall segment below the opening can accommodate a virtual diagonal strut with a smaller slope than in pattern 4, pointing out the significance of the spandrel below the opening. In relation to pattern 2, Figure 19 reflects that H/Ho is well above the line H/Ho=β, which reflects the contribution of the confinement column to shear capacity.

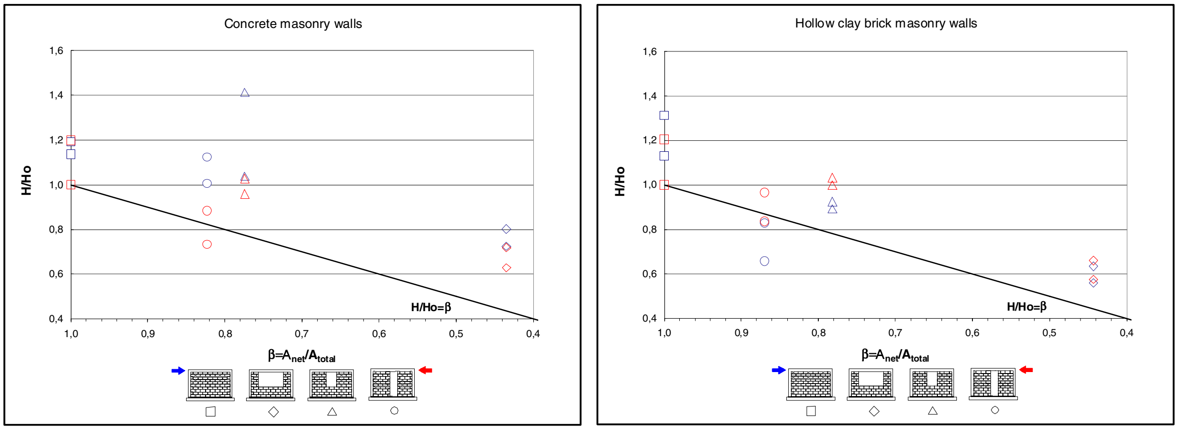


Figure 19: load versus β

CONCLUSIONS

The load-deformation behavior of the specimens with opening is non lineal, having an initial lineal elastic zone. The load-deformation capacity depends on the inclination of the diagonal struts that can be developed in the specimens with openings, and on the tensile capacity of the confinement column or vertical reinforcement in the border of the opening that work as ties of virtual strut and tie models.

The stiffness of specimens with an opening ratio of 11% of the total wall area is close to that of the specimens without openings. The stiffness degrades strikingly with the subsequent cycles due to cracking. The rate of the stiffness degradation is smaller as the opening size increases, especially in the concrete masonry walls.

The shear capacity of the specimens was reached for the interstory drift range of 2.0‰ to 4.0‰. For walls with larger openings, the maximum strength decreases and is reached for interstory drift larger than 4‰.

It is conservative to consider the shear capacity proportional to the net transverse area of walls with window openings.

The tests indicate that for these specimens with small horizontal reinforcement in the masonry panel, the crack widths are quite large for small interstory drift. In order to keep the crack widths under 1.5 mm, the interstory drift ratio should be no larger than 1.0‰, whereas to keep the crack widths under 3.0 mm, the interstory drift should be no larger than 2.0‰.

The tests also indicate that the confinement concrete frame keeps the integrity of the specimens under interstory drift ratios as large as 13‰ in spite of large damage (large crack widths and large strength and stiffness degradation), see Figure 20. It is interesting to note that this large deformation level cannot be reached in lightly reinforced partially grouted masonry walls [5].

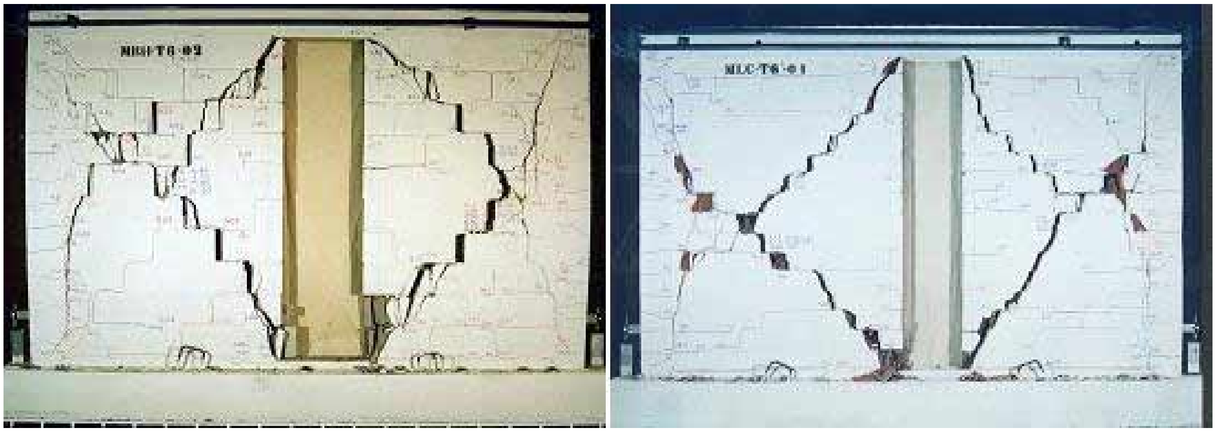


Figure20: Damage level for 13‰ interstory drift

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REFERENCES

[1] Ogaz, O., Experimental study about confined masonry walls with openings and small amount of reinforcement around the opening under cyclic lateral load, Civil Engineering Thesis, Department of Civil Engineering, University of Chile, Santiago, Chile, 2004. Adviser: M. Astroza I. (In Spanish)
[2] Guzmán, F., Study of seismic behavior of one and two story masonry low-income housing with mixed type of reinforcement, Civil Engineering Thesis, Department of Civil Engineering, University of Chile, Santiago, Chile, 2002. Adviser: F. Yáñez U. (In Spanish)
[3] INN, Norma Chilena Oficial NCh2123.Of1997 : Confined masonry - Requirements for structural design, Instituto Nacional de Normalización, Santiago, Chile, 1997. (In Spanish)
[4] INN, Norma Chilena Oficial NCh1928.Of1993 : Reinforced masonry –Requirements for structural design, Instituto Nacional de Normalización, Santiago, Chile, 1993. (In Spanish)
[5] Astroza, M., A. Holmberg, C Luders and F. Yáñez, Experimental study of lightly reinforced partially grouted masonry walls under cyclic lateral load, XI Iberoamerican Seminar on Earthquake Engineering, Mendoza, Argentina, 2003. (In Spanish)