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SOME TOPICS ON THE SEISMIC BEHAVIOR OF CONFINED MASONRY STRUCTURES

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ABSTRACT

The influence of horizontal reinforcement placed within the mortar joints and the effect of the walls′ aspect ratio are two concepts which have not been thoroughly evaluated on wall behavior and on the design of confined masonry structures (brick masonry load-bearing walls confined by light reinforced concrete bond-beams and tie-columns) by current Latinamerican regulations. In this paper, both effects are analyzed for walls subjected to lateral load. This evaluation is based on results of recent studies made by some latinamerican researchers.

KEYWORDS

Confined masonry structures, reinforced masonry, horizontal reinforcement, wall′s aspect ratio, diagonal cracking.

INFLUENCE OF HORIZONTAL REINFORCEMENT

An option to improve the seismic response of confined masonry walls, is to place reinforcement within the mortar joints anchored into the tie-columns (it is not possible to place vertical reinforcement through solid bricks).

Table 1 shows masonry properties and reinforcement steel percentages of some full-scale models tested by latinamerican researchers and studied in this paper; v′ represents the specimen shear resistance, σ is the vertical stress applied to the model and p_v and p_h are transverse steel percentages at the end of tie-columns and horizontal along walls, respectively.

Table 2 shows measured values for walls stiffness, shear stresses and distortions. Wall stiffness was calculated as $K=v/d$; v_u represents the maximum shear stress of the model and d_u is the distortion corresponding to v_u .

Hernández and Meli (1976) tested models using horizontal reinforcement; the model number 2 increased v_u as much as 60% with respect to wall without reinforcement. The ultimate distortion for walls with horizontal reinforcement (walls 2 and 3), was 33% and 114% greater than those of walls without reinforcement.

Table 1. Masonry properties and reinforcement steel percentages

Reference	Model	v' (MPa)	σ (MPa)	$p_v f_y$ (MPa)	p_h %	$p_h f_y$ (MPa)
Hernández and Meli (1976)	1[1]	0,26	0	2,39	0	0
	2[1]	0,26	0	2,39	0,067	0,39
	3[1]	0,26	0	1,94	0,067	0,39
San Bartolomé (1990)	MR1[1]	0,86	0	1,17	0	0
	MR2[1]	0,86	0	1,17	----[3]	-----
	MR3[1]	0,86	0	1,17	0,16	0,40
	MR4[1]	0,86	0	1,17	0,16	0,40
	MR5[1]	0,86	0	1,17	0,08	0,20
Sánchez *et al.* (1992)	WBW[2]	0,98	0,49	2,16	0	0
	WBW-E[2]	0,69	0,49	2,16	0,1	0,49
	WBW-B[2]	0,78	0,49	2,16	0,09	0,52
Beijing Institute (1987)	1[2]	-----	0,59	0,55	0,167	0,69
	2[2]	-----	0,78	0,55	0,074	0,30
	3[2]	-----	0,78	0,55	0,165	0,68
	4[2]	-----	0,59	0,55	0,083	0,34
U. de Los Andes-Yamín *et al.* (1993)	1[2]	0,19	0	0,70	0,11	0,25
	2[1]	0,22	0	0,70	0,11	0,25
	3[2]	0,30	0	0,70	0	0
	4[1]	0,50	0	0,70	0	0
Aguilar *et al.* (1994)	M-3/8-Z6[2]	0,29	0,49	1,92[4]	0,20[6]	0,82
	M-0-E6[2]	0,29	0,49	1,92	-------	-------
	M-5/32-E20[2]	0,29	0,49	0,58	0,071[4]	0,42
	M-1/4-E6[2]	0,29	0,49	1,92	0,18[4]	1,06

NOTE: 1 MPa=10.19 kg/cm^2

[1] Wall built with industrial bricks

[2] Wall built with craftsmanship bricks

[3] Half-height beam reinforced with 2#4

[4] Helicoidal transverse reinforcement

San Bartolomé (1990) found little increases in the maximum shear resistance (about 10%), when horizontal reinforcement was used.

The behavior of wall WBW-E was not modified substantially with the horizontal reinforcement made with welded-joint wires used by Sánchez *et.al* (1992); moreover, transverse wires showed fragile faults in welded joints of transverse wires. V_u increases 60% with horizontal reinforcement in wall WBW-B, the increasing deformation capacity with d_u/d_{ag}=6,73. The response envelope for these models is indicated in Fig. 1.

In models tested at Universidad de Los Andes (1993), it was not observed defined effect with horizontal reinforcement; in this case, the steel percentage was about 50% in relation to others. These walls did not have any post-cracking deformation capacity.

In four models tested by Aguilar *et al.*, cracking shear v_{ag} and distortion d_{ag} values, were similar. The presence of horizontal reinforcement increased as much as 25% the maximum shear strength and 83% the deformation capacity for v_u. Horizontal reinforcement did not modify the stiffness models.

Table 2. Shear stresses, distortions and walls stiffness

Model	v_{ag} (MPa)	d_{ag} x 10^{-4}**	K_{ag} (MPa)	v_u (MPa)	d_u x 10^{-4}**	K_u (MPa)	v_u/v_{ag}
1	0,21	10,0	206,0	0,24	105,0	23,35	1,19
2	0,26	6,5	392,4	0,39	140,0	28,06	1,54
3	0,26	7,0	364,3	0,34	225,0	15,21	1,35
MR1	0,48	7,0	691,6	0,64	62,1	102,7	1,32
MR2	0,52	5,1	1 023,5	0,80	41,7	193,1	1,55
MR3	0,39*	5,7	687,2	0,53	17,1	310,2	1,35
MR4	0,48	6,0	795,9	0,71	50,8	138,9	1,47
MR5	0,48	4,3	1 110,1	0,72	61,3	116,9	1,49
WBW	0,49	13,0	445,9	0,55	60,0	91,5	1,12
WBW-E	0,51	11,0	463,7	0,61	29,0	211,1	1,20
WBW-B	0,53	12,0	480,7	0,88	74,0	118,6	1,67
1	0,49	2,3	2 132,6	0,98	24,7	397,2	2,0
2	0,66	8,6	764,3	0,77	34,3	223,1	1,16
3	0,78	11,3	694,5	0,83	26,3	317,1	1,06
4	0,52	8,0	649,9	0,62	60,4	102,3	1,19
1	0,17	33,0	50,5	0,21	52,0	39,6	1,24
2	0,24	32,0	73,6	0,25	38,0	64,5	1,04
3	0,20	47,0	41,7	0,23	55,0	41,0	1,15
4	0,31	20,0	157,0	0,31	20,0	157,0	1,0
M-3/8-Z6	0,48	21,6	222,2	0,59	53,3	110,7	1,23
M-0-E6	0,33	13,3	248,1	0,47	40,0	117,5	1,42
M-5/32-E20	0,43	16,7	257,5	0,56	60,0	93,3	1,30
M-1/4-E6	0,34	13,0	261,5	0,53	73,3	72,3	1,56

* flexural fault

** averages values from positive and negative cycles, graphically obtained from the models′ hysteresis loops

WALLS′ ASPECT RATIO

Most of the walls tested by different researchers have been square. When the aspect ratio of the wall modifies, stress distribution changes and so, its resistance could be affected in an important way. For cantilever tests, as the wall becomes slender, flexural deformations becomes more important, and even when the type of failure does not change, it is possible that shear strength decreases.

Experimental results shown in table 3 confirm this hypothesis. For walls tested in cantilever there is a strength increases when height/length ratio (H/L) changes from 1 to 0,5 and a decreases when ratio varies from 1 to 2,5. Unfortunately, the information is too limited to infer a reliable empirical equation.

Table 3. Effect of walls´ aspect ratio in walls´ shear resistance

Reference	Specimen	H/L	v_{ag} (MPa)	v_{ag}/v_o
Meli (1979)	Simms 1	0,5	0,98	1,43
	Simms 2	1	0,69	1
	Williams 1	0,5	1,63	1,42
	Williams 2	1	1,15	1
	Williams 3	2	0,95	0,83
Torrealva and Macciotta (1:2 scale, 1986)	A1*	0,5	0,58	1,07
	B1*	1	0,54	1
	C1*	1,75	0,29	0,55
	D1*	2,5	0,26	0,48
	A2**	0,5	0,52	0,82
	B2**	1	0,63	1
	C2**	1,75	0,41	0,64
	D2**	2,5	0,25	0,40
Diez *et al.* (1988)	MRG1	1	0,43	1
	MRE1	2	0,42	0,99
	MRG2	1	0,48	1
	MRE2	2	0,37	0,77

v_{ag}=diagonal cracking shear stress
v_o=diagonal cracking shear stress of square specimen (H/L=1)
* monotonous lateral load
** cyclical lateral load

D1 and D2 specimens tested by Torrealva and Macciotta (1986, with an intermediate slab), tried to represent a two-story wall subjected to lateral load operating at the second level. As flexural moment is given by M=VH, then M/(VL)=(VH/VL)=H/L. In this walls (D1 and D2) shear failure was observed only at first level, where flexural moment was bigger; both stories were subjected to the same shear force. In other words, the M/VL ratio for the first level was double in relation to the second. This concept must be considered, because the M/VL ratio could be greater than 1 in multi-story buildings.

Figure 2 shows experimental results obtained by Meli (1979), Macciotta and Torrealva (1986), and Diez *et al.* (1988); Vo represents the square model (H/L=1) shear strength and V represents the shear strength supported by specimen in study; as H/L (or M/VL) ratio increases V/Vo ratio decreases.

The equation V/Vo=1,35-0,35(H/L) which is plotted in the same figure, was obtained by linear regression, using the results presented in this paper; the correlation coefficient is equal to -0,79.

In this matter, the simplified method proposed by mexican regulations (NTC-RCDF, 1987), suggest considering $V/Vo=(1{,}33L/H)^2$ when H/L>1,33. San Bartolomé (1990), suggests that V/Vo=L/H when

H/L>1; it is important to point out that the recommendation given by mexican code suppose that contribution of walls to resist shear decreases due to flexural effects.

Stiffness degradation was studied on specimens tested by Diez *et al.* (1988), in relation to secant stiffness corresponding to angular distortion of 0,2, 0,4, 0,8 and 1%. Reference level for defining this ratio was the stiffness corresponding to an angular distortion of 0,2%. Table 4 shows the stiffness ratio values. The stiffness degradation rate decreases as wall's slenderness increases (behavior is different, because of flexural effects are more important).

Table 4. Effect of walls' aspect ratio on stiffness degradation

Reference	Model	H/L	$K_{0,2\%}$ (kN/m)	$K_{0,4\%}/K_{0,2\%}$ %	$K_{0,8\%}/K_{0,2\%}$ %	$K_{1\%}/K_{0,2\%}$ %
Diez	MRG1	1	24 627	43,0	20,0	9,5
et al.	MRG2	1	31 445	50,5	26,0	18,0
(1988)	MRE1	2	10 787	70,5	43,5	35,0
	MRE2	2	11 398	65,0	42,0	29,0

CONCLUSIONS

Horizontal reinforcement does not increases the cracking shear stress and neither the cracking stiffness. Nevertheless, it helps to produce a more uniform distribution of damage (Sánchez *et al.*, 1992, Aguilar *et al.*, 1994) . Wall's behavior after cracking depends on type and percentage of horizontal reinforcement.

The presence of horizontal reinforcement shows increase in the ultimate shearing strength as much as 60% for standardized percentages $p_h f_y$ from 0,4 MPa to 1,06 MPa (see table 2 and Fig. 1). Stiffness degradation is not affected for this concept (Sánchez *et al.*, 1992); The energy dissipation is similar for walls with horizontal reinforcement and for walls without it (Alvarez and Alcocer, 1994).

The mexican code (NTC-RCDF, 1987), allows to increase the shear strength of masonry walls as much as 25%, if it is used a minimum specific horizontal reinforcement. This considers that walls with horizontal reinforcement have larger deformation capacity (ductility factor about 2,5, Hernández and Meli, 1976) than walls without reinforcement (ductility factor equal to 2). The rest of latinamerican regulations do not consider the influence of this reinforcement.

The ultimate shear strength of walls with horizontal reinforcement could be estimated with (1), obtained by a linear regression using the information presented in tables 1 and 2, although the correlation coefficient is hardly equal to 0,42

$$v_u/v_{ag}=1,20+0,338p_h f_y \qquad (1)$$

The shear strength of masonry walls decreases as aspect ratio H/L increases. For taking into account this effect as a first approximation, can be used Eq. 2

$$V/Vo=1,35-0,35(H/L) \qquad (2)$$

where Vo represents the square model (H/L=1) shear strength and V represents the shear strength supported by specimen in study.

Current codes from América Latina (México, Perú, Colombia, Chile y Argentina), do not consider the effect of walls′ aspect ratio. This concept must be considered, because the M/VL ratio could be greater than 1 in multi-story buildings. Moreover, the stiffness degradation rate decreases as walls slenderness increases. However, more research is needed to obtain information which allows to calibrate suitable equations.

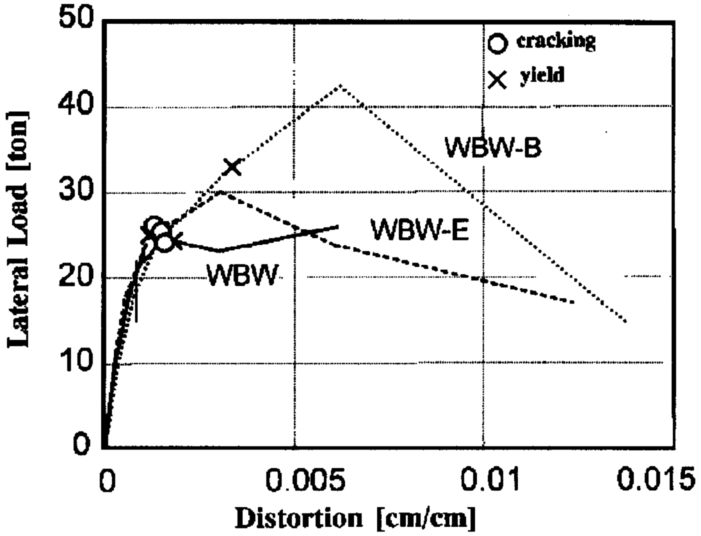

Fig. 1. Influence of horizontal reinforcement on shear strength. Response envelopes.

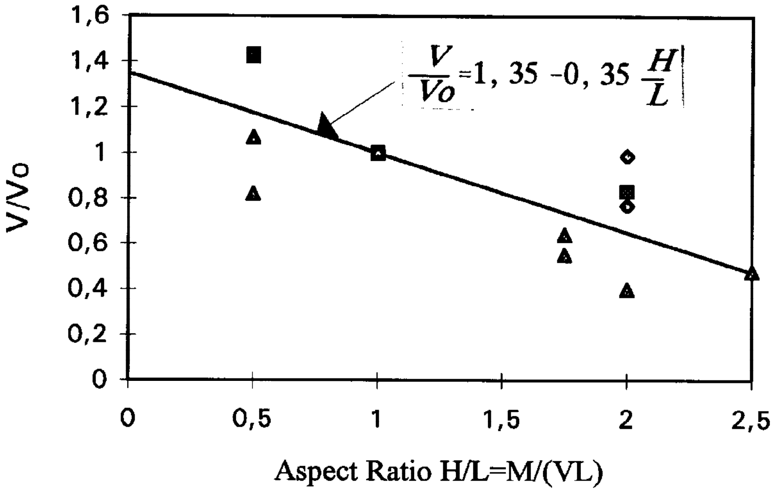

Fig. 2. Effect of walls′ aspect ratio on shear strength

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