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Effect of vertical axial loads and repeated lateral forces on seismic behavior of confined concrete masonry walls

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ABSTRACT

In order to investigate the effect of applied vertical axial loads and height of repeated lateral forces on seismic behavior of confined concrete masonry walls, twelve different wall specimens with and without wall reinforcement are tested under constant vertical axial loads and alternately repeated lateral forces. Test results indicated that both of applied vertical axial loads and height of lateral forces give a large effect on the seismic behavior of confined concrete masonry walls. In addition, it is also shown that the vertical and horizontal wall reinforcements provided in the confined concrete masonry walls play an important role for developing higher strength and better ductility.

1. INTRODUCTION

Confined concrete masonry walls, which are defined as concrete masonry walls confined by reinforced concrete (R/C) columns and beams, are widely accepted as the structural bearing walls in Latin American countries as well as the People's Republic of China. Confined masonry walls shown in Figure 1 are composed of hollow concrete-block or brick masonry units which are confined by cast-in-place R/C small columns and beams (and/or floor slabs) along the perimeter of each masonry wall. These structural wall systems are very popular and have been frequently designed and constructed in those earthquake countries. It is noted, however, that the masonry wall panels in this wall system are usually not reinforced by any wall reinforcing bars (Re-bars) in both horizontal and vertical directions.

In order to develop more seismic confined concrete masonry walls, the authors have conducted numerous experimental studies including several parameters such as reinforcing details in confining column sections and amount of wall reinforcements (Yoshimura et.al. 1995, Yoshimura et.al. 1996, Liu et.al. 1997). Main objective of the present study is to investigate the effect of applied vertical axial loads and height of repeated lateral forces (or height of the inflection point in flexural deformation of the wall) on seismic behavior of confined concrete masonry walls experimentally. Four confined concrete masonry wall specimens with two different types of wall reinforcing details are newly tested under constant vertical compression or tension axial loads and alternately repeated lateral forces. And, all the test results obtained from the twelve specimens including eight former specimens are compared each other in this paper.

2. TEST SPECIMENS

Twelve confined concrete masonry wall specimens with two different types of wall reinforcements were designed and constructed as being listed in Table 1 and Figure 2. All the specimens are approximately one-half scale models of one-bay-one-story masonry walls using hollow concrete block masonry units with Grade C in the Japanese Industrial Standard (JIS). Thickness of all the masonry walls are 10cm, and all the masonry walls are confined by the cast-in-place R/C confining columns with 10cm x 10cm cross-sections along their extreme edges of the wall. These specimens are classified into two test series, L-series and H-series, depending on the adopted test setup as shown in Figures 3(a) and 3(b). Each of the specimen is designated by a four symbol code, such as L1-H40V40-HC. The first letter "L" or "H" represents that the height of repeated lateral forces is "**L**ow" or "**H**igh" as shown in Figures 3(a) or 3(b), respectively. Based on the calculation results on the height of the inflection point in the first story masonry bearing walls in case when the five story masonry buildings are subjected to lateral earthquake forces (Liu et.al. 1997), the heights of repeated lateral forces adopted for the test are determined as 0.67 of the wall height (*h* in Figures 2 and 3) for L-series specimens and 1.11 of the wall height for H-series specimens, respectively. The second numeral "1" after the letter "L" or "H" represents that the only one longitudinal Re-bar with bar-size of D19 (or #6) is provided in each of the confining R/C column-section, which is

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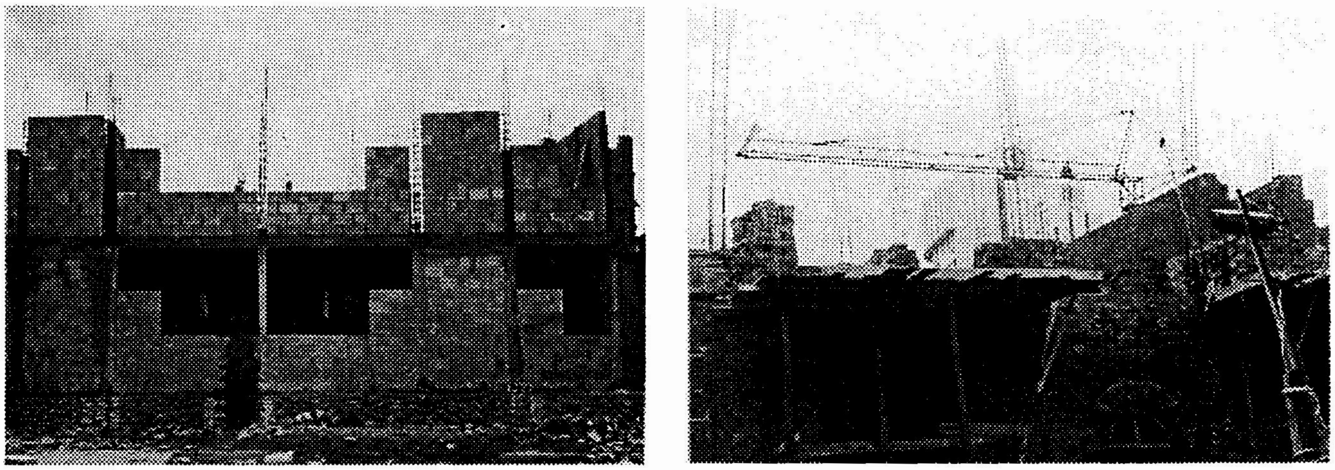


Figure 1. Confined concrete masonry walls (under construction in Mexico and P.R.of China)

transversely reinforced by circular spiral hoops of D6 (#2) as shown in Figure 2. The third and fourth symbols such as "H40" or "V40" indicate that the horizontal or vertical Re-bars are respectively provided in the masonry wall where spacings of these wall reinforcements are 40 cm and 40 cm, respectively. In case of the "H0V0" specimens, there is no wall Re-bars in both horizontal and vertical directions. The final letter "HC" or "LC" represents that the constant vertical axial load applied to the specimens are respectively "**H**igh **C**ompression" or "**L**ow **C**ompression", while in case of "T", constant vertical **T**ension axial load is applied to the wall specimens. Based on a theoretical study for investigating the vertical axial loads induced in the first story masonry bearing walls of the five story buildings (Yoshimura et.al. 1998), the values of vertical axial loads are determined as 1.80MPa for "HC" specimens, 0.84MPa for "LC" specimens and -0.11MPa for "T" specimens, respectively. Mechanical properties of materials used for all the specimens are shown in Table 2.

Among those specimens presented in Table 1 and Table 2, the L1-H0V0-LC and the L1-H40V40-LC specimens are respectively the same as the L1-H0V0 and the L1-H40V40 specimens which were already tested and presented (Yoshimura et.al. 1996). Also, the H1-H0V0-LC and H1-H40V40-LC specimens are respectively the same as the H1-H0V0 and the H1-H40V40

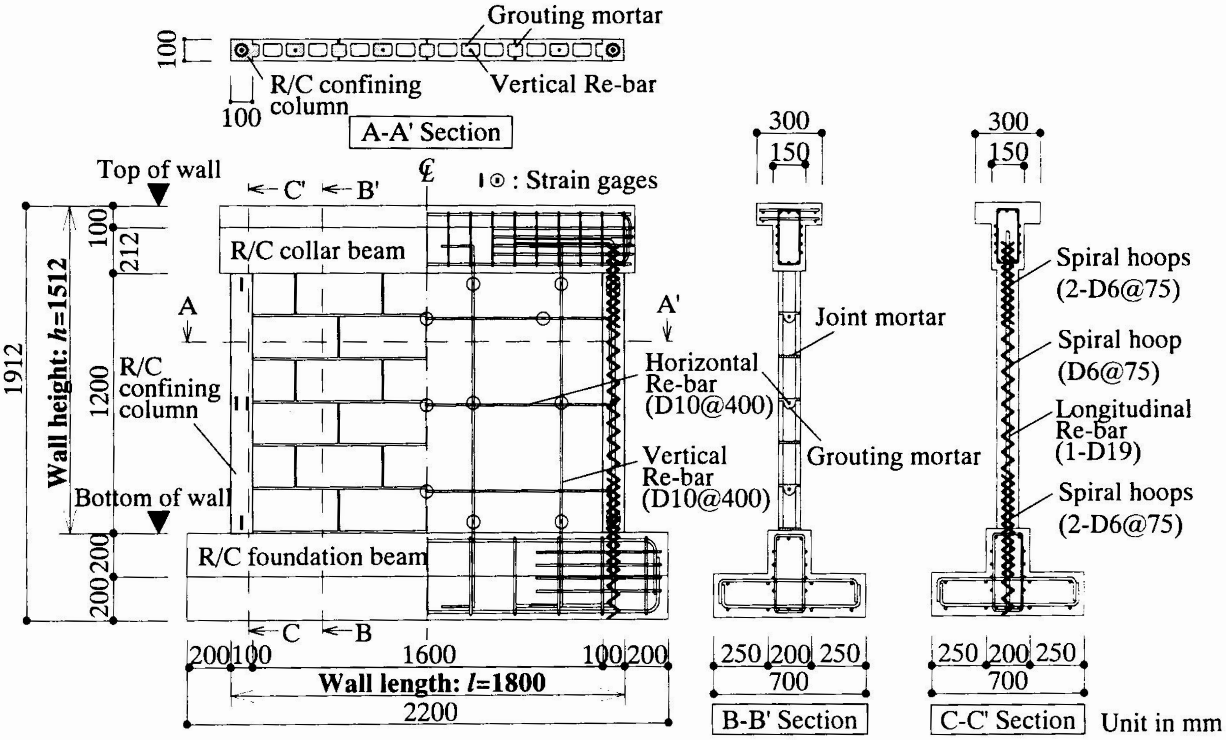


Figure 2. Test specimens

Table 1. List of specimens

Specimens		Height of applied lateral forces	Wall reinforcing bar		Axial stress σ_0 (MPa)
			Horizontal bar	Vertical bar	
L-series	L1-H0V0-HC	0.67×*h* (*h* : Wall height)	None	None	1.80
	L1-H40V40-HC		D10(#3) @400*	D10(#3) @400*	
	L1-H0V0-LC		None	None	0.84
	L1-H40V40-LC		D10(#3) @400*	D10(#3) @400*	
	L1-H0V0-T		None	None	-0.11
	L1-H40V40-T		D10(#3) @400*	D10(#3) @400*	
H-series	H1-H0V0-HC	1.10×*h* (*h* : Wall height)	None	None	1.80
	H1-H40V40-HC		D10(#3) @400*	D10(#3) @400*	
	H1-H0V0-LC		None	None	0.84
	H1-H40V40-LC		D10(#3) @400*	D10(#3) @400*	
	H1-H0V0-T		None	None	-0.11
	H1-H40V40-T		D10(#3) @400*	D10(#3) @400*	

* Spacing of bars in mm

Table 2. Mechanical properties of concrete, prism, joint mortar and reinforcing bars

Specimens	Compressive strength of concrete (MPa)		Compressive strength of prism (MPa)	Compressive strength of joint mortar (MPa)	Yield strength of Re-bar (MPa)		
	Column	Beam			D6 (#2)*	D10 (#3)	D19 (#6)
L1-H0V0-HC	23.3	24.0	18.4	45.4	448	376	347
L1-H40V40-HC	26.5	28.4	17.5	43.6	448	376	347
L1-H0V0-LC	30.6	31.2	18.8	30.4	434	377	354
L1-H40V40-LC	33.2	31.1	16.8	34.9	434	377	354
L1-H0V0-T	24.5	23.4	18.4	43.7	448	376	347
L1-H40V40-T	unmeasured	unmeasured	17.5	38.2	448	376	347
H1-H0V0-HC	33.8	17.5	13.4	36.6	448	376	347
H1-H40V40-HC	20.0	18.8	13.4	37.5	448	376	347
H1-H0V0-LC	32.2	31.8	18.7	36.1	448	376	323
H1-H40V40-LC	33.7	35.6	19.2	41.7	448	376	323
H1-H0V0-T	28.1	25.5	12.3	21.7	448	376	347
H1-H40V40-T	29.6	26.5	12.3	32.1	448	376	347

* 0.2% offset yield strength

specimens (Liu et.al. 1997), and the H1-H0V0-HC, H1-H40V40-HC, H1-H0V0-T and H1-H40V40-T specimens were already tested and presented as the same name (Yoshimura et.al. 1998). In this paper, all the twelve specimens including those above eight specimens are listed in Table 1.

3. TEST SETUP

Test setup adopted for L-series and H-series tests are respectively shown in Figures 3(a) and 3(b). As mentioned before, the height of the repeated lateral forces applied to the L-series specimens is 0.67 of the wall height (*h*), while in the H-series specimens 1.11 of the wall height is adopted. Corresponding constant vertical axial load was applied by a hydraulic jack, and alternately repeated lateral forces were applied by another double-acting hydraulic jack as shown in Figure 3. One auxiliary jack installed between Loading frame and Reaction frame is for counterbalancing and setting the test specimens. Important displacements and strains in reinforcing bars and wall surface were measured by displacement transducers and strain gages, and all the informations measured were processed simultaneously by a personal computer.

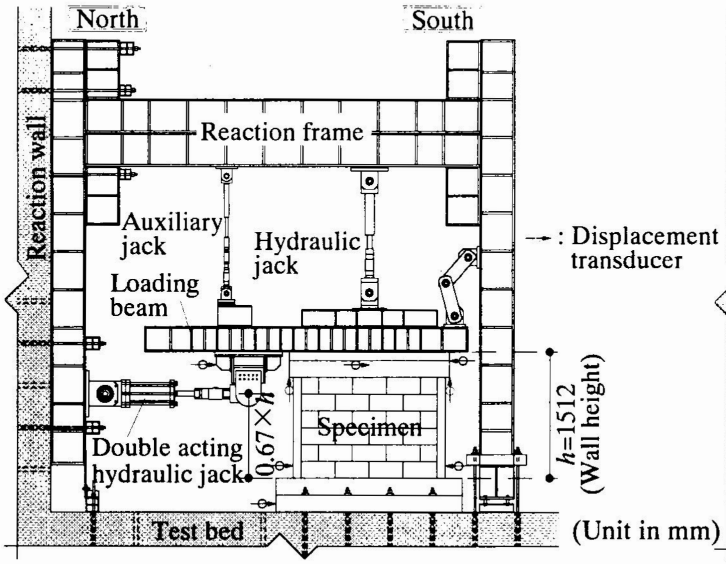


Figure 3(a). Test setup for L-series test

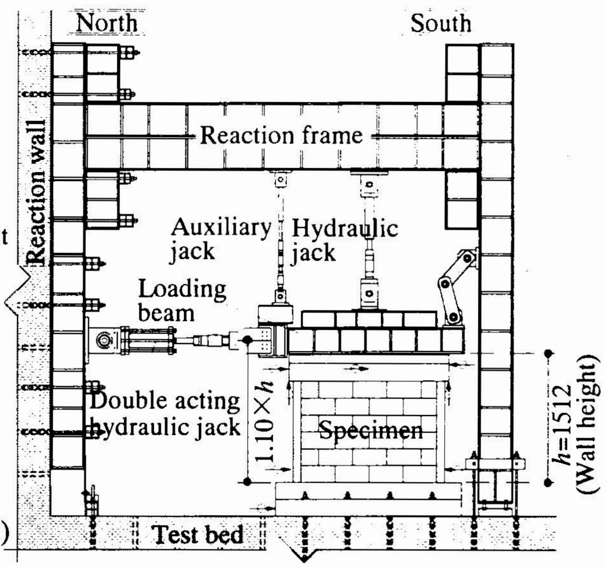


Figure 3(b). Test setup for H-series test

4. TEST RESULTS AND DISCUSSIONS

Complete hysteresis loops between applied lateral force (Q) versus story drift (R) relations obtained from the four specimens which are subjected to high compression and tension vertical axial loads in L-series specimens are shown in Figures 4(a) through 4(d), where story drift (R) is defined as the interstory displacement between top and bottom of the wall divided by the wall height of the specimen. Dotted lines in Figures 4(c) and 4(d) represent the theoretical lateral strengths determined by the ultimate flexural moment capacity at the bottom of each wall, and dashed lines in Figures 4(a) through 4(d) are the ultimate lateral strengths in shear failure mode of the masonry wall with flexural reinforcement in its wall-edges (or R/C confining columns), which are calculated by the existing equations to predict the ultimate flexural and shear strengths of the Reinforced Hollow Concrete-brock Bearing Walls (Architectural Institute of Japan 1990). Envelope curves obtained from the Q-R hysteresis loops of all the twelve specimens are shown in Figure 5, where lateral forces (Q) are given by the simple average calculated from the North- and South-side loading curves. Two light dashed lines parallel to the horizontal axes represent the allowable lateral shear force provided by the current AIJ (Architectural Institute of Japan) Design Standard for Hollow Concrete-block Masonry Structures (Architectural Institute of Japan 1994). In addition, theoretical ultimate lateral strengths for all the twelve specimens are also shown in Table 3 together with the expected failure modes and observed test results.

The findings from the test results can be summarized as;

(1) Most of the L-series specimens failed in shear failure mode in the region of the story drift of $0.2\text{x}10^{-2}$rad to $0.3\text{x}10^{-2}$rad before developing their flexural moment capacities. On the contrary, all the H-series specimens failed in flexural failure mode in the region of the story drift of $0.2\text{x}10^{-2}$rad to $0.3\text{x}10^{-2}$rad, and finally failed in shear failure mode. Ultimate lateral strengths carried by the L-series specimens are generally higher than the H-series specimens. It is noted that ductility (or deformability) developed by the L-series specimens are considerably smaller than the H-series specimens.

(2) Ultimate lateral strengths carried by the confined concrete masonry wall specimens became gradually higher with the increase of the vertical axial load applied to the specimen. On the contrary, ductility developed by the specimens became gradually smaller with the increase of the vertical axial load applied to the wall specimen.

(3) The L1-V0H0-LC specimen without any vertical wall Re-bars did not failed in flexural or shear failure mode but failed in sliding failure mode. The sliding failure occurred between bottom of the masonry wall panel and top surface of the R/C foundation beam at the story drift of $0.15\text{x}10^{-2}$rad.

(4) Most of the ultimate lateral strengths and failure mode of the specimens which are subjected to low compression vertical axial load are well predicted by the existing theory on masonry walls. While, some of the specimens which are subjected to high compression or tension axial loads, their ultimate lateral strengths and failure modes can not be well predicted by the existing theory.

(5) In case of the masonry wall specimens having both vertical and horizontal wall Re-bars, their ultimate lateral strengths

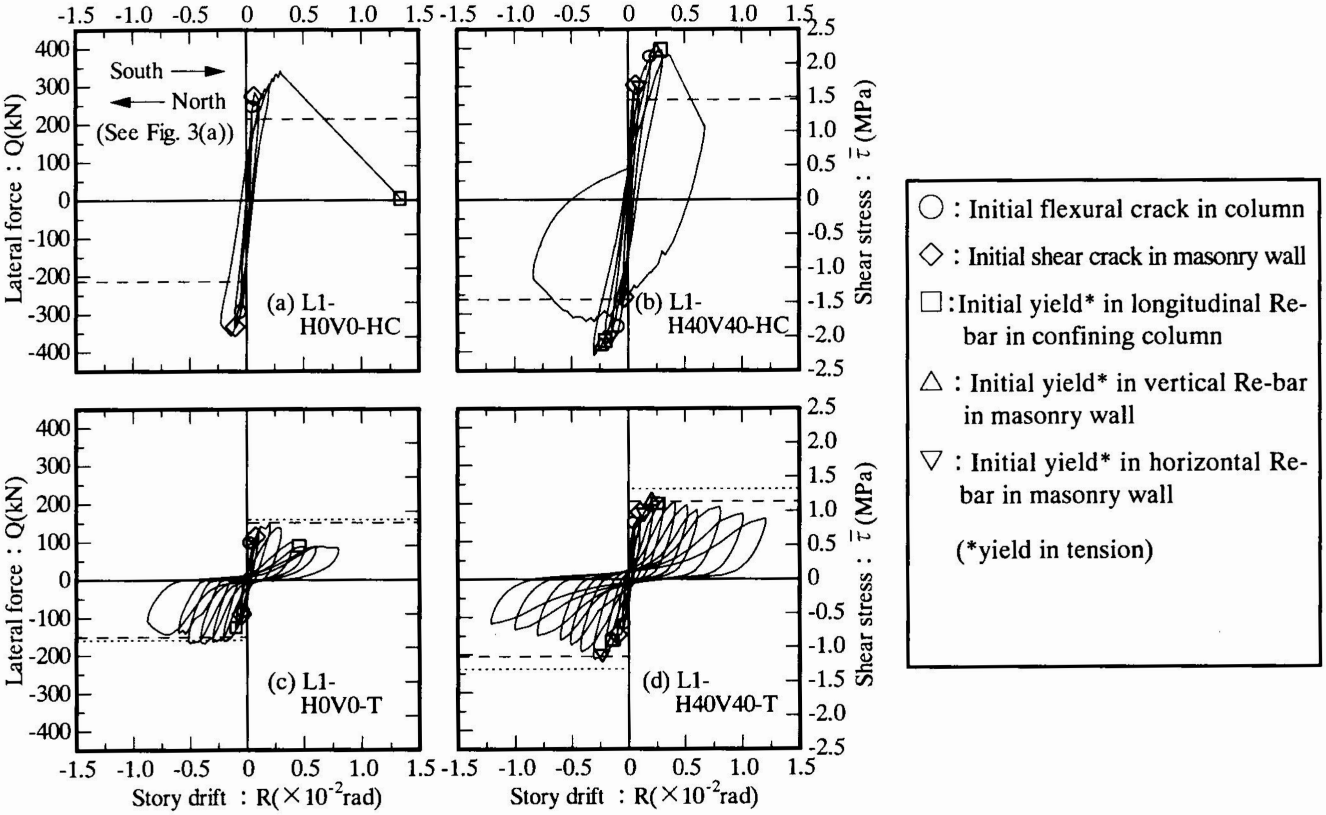
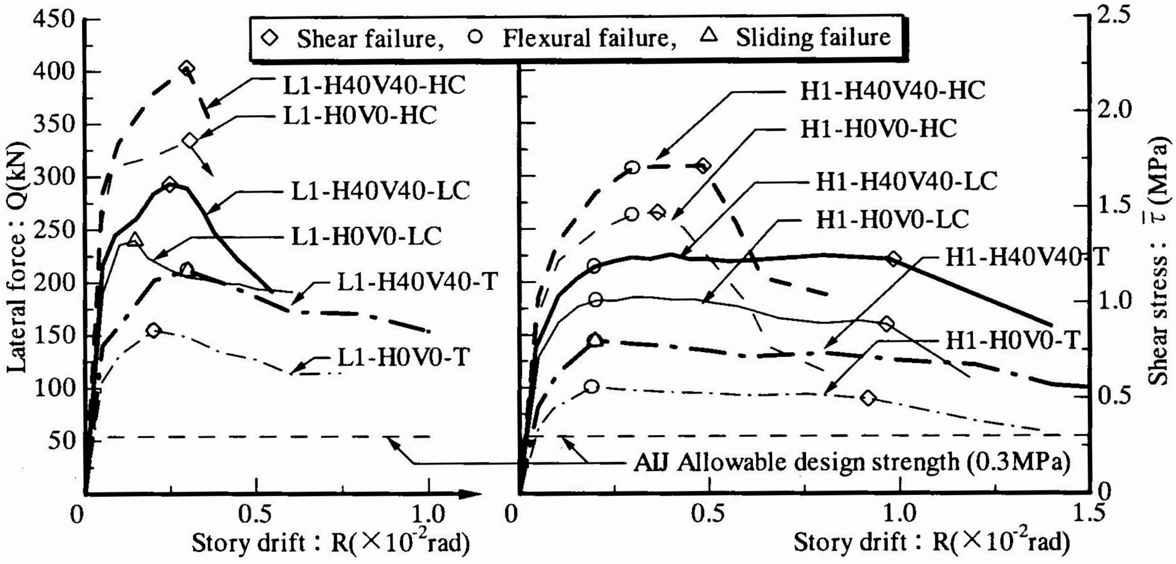


Figure 4. Q-R Hysteresis loops



(a) L-series specimens (b) H-series specimens

Figure 5. Q-R Envelope curves

become higher than the other specimens without any wall Re-bars. For example, the ultimate lateral strength carried by the H1-V40H40-T specimen is 1.43 times higher than that of the H1-V0H0-T specimen, both of which are subjected to the vertical axial tension load.

(6) Ultimate lateral strengths obtained from the confined concrete masonry wall specimens are at least more than 1.8 times of the AIJ allowable design strength.

Table 3. Predicted and observed ultimate lateral strengths and failure modes

Specimens	Theoretical prediction			Test result	
	Ultimate lateral strength		Predicted failure mode*	Ultimate lateral strength (Average value) Q (kN)	Observed failure mode*
	Flexure mode Q_u (kN)	Shear mode Q_{su} (kN)			
L1-H0V0-HC	455	214	S	350	S
L1-H40V40-HC	539	263	S	403	S
L1-H0V0-LC	310	186	S	243	SL
L1-H40V40-LC	413	231	S	293	S
L1-H0V0-T	156	155	S	155	S, F→S
L1-H40V40-T	238	205	S	211	F → SL
H1-H0V0-HC	269	190	S	266	F → S
H1-H40V40-HC	324	232	S	309	F → S
H1-H0V0-LC	173	185	F	186	F → S
H1-H40V40-LC	229	247	F	229	F → S
H1-H0V0-T	93	131	F	101	F → S
H1-H40V40-T	148	173	F	145	F → SL

* F : Flexural failure mode, S : Shear failure mode, SL : Sliding failure mode

5. CONCLUSIONS

In case of the confined concrete masonry bearing walls which are subjected to both vertical axial loads and alternately repeated lateral forces, their seismic behavior including ultimate lateral strength and deformation capacity are remarkably affected by the values of applied vertical axial loads and height of repeated lateral forces. In addition, the vertical and horizontal reinforcement in masonry walls play an important role for expecting higher ultimate lateral strength and better ductility.

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