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EFFECT OF VERTICAL AND HORIZONTAL WALL REINFORCEMENT ON SEISMIC BEHAVIOR OF CONFINED MASONRY WALLS

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ABSTRACT

In order to investigate the effect of vertical and horizontal wall reinforcing methods on seismic behavior of confined masonry walls, eight confined masonry wall specimens with different details in wall reinforcement are tested under a constant gravity load and alternately repeated lateral forces. Test results indicate that the vertical and horizontal wall reinforcing bars provided in confined masonry walls play an important role for developing higher strengths and better deformability.

KEYWORDS

Confined masonry walls; Wall reinforcement; Vertical wall Re-bars; Horizontal wall Re-bars; Seismic behavior; Laboratory tests;

INTRODUCTION

Confined masonry walls, which are defined as masonry walls confined by reinforced concrete (R/C) columns and beams, are widely accepted as seismic structural walls in Latin American countries. Confined masonry walls shown in Fig.1 are composed of hollow concrete-block masonry units which are confined by cast-in-place reinforced concrete small columns and beams (and/or floor slabs). These structural wall systems are very popular and are frequently designed and constructed in Mexico and other Latin American countries. It is noted, however, that the masonry wall panels in Fig. 1 are not reinforced by any wall reinforcing bars (Re-bars) in both horizontal and vertical directions. In addition, four longitudinal Re-bars and many transverse Re-bars are provided into very narrow cross-sectional spaces of all the R/C confining columns as is observed in detail illustration in Fig. 1.

In order to investigate the effect of vertical and horizontal wall reinforcement and reinforcing details adopted in the R/C confining columns on seismic behavior of confined masonry walls, eight different specimens were designed and tested under a constant gravity load and alternately repeated lateral forces. Test results indicate that the presence of vertical and horizontal wall Re-bars give a large effect on seismic behavior of confined masonry walls. Also it is shown that there is a possibility for improving the complicated reinforcing method adopted in R/C confining columns to much more simpler details. Main objective of the present study is to develop more seismic masonry walls in Latin American countries.

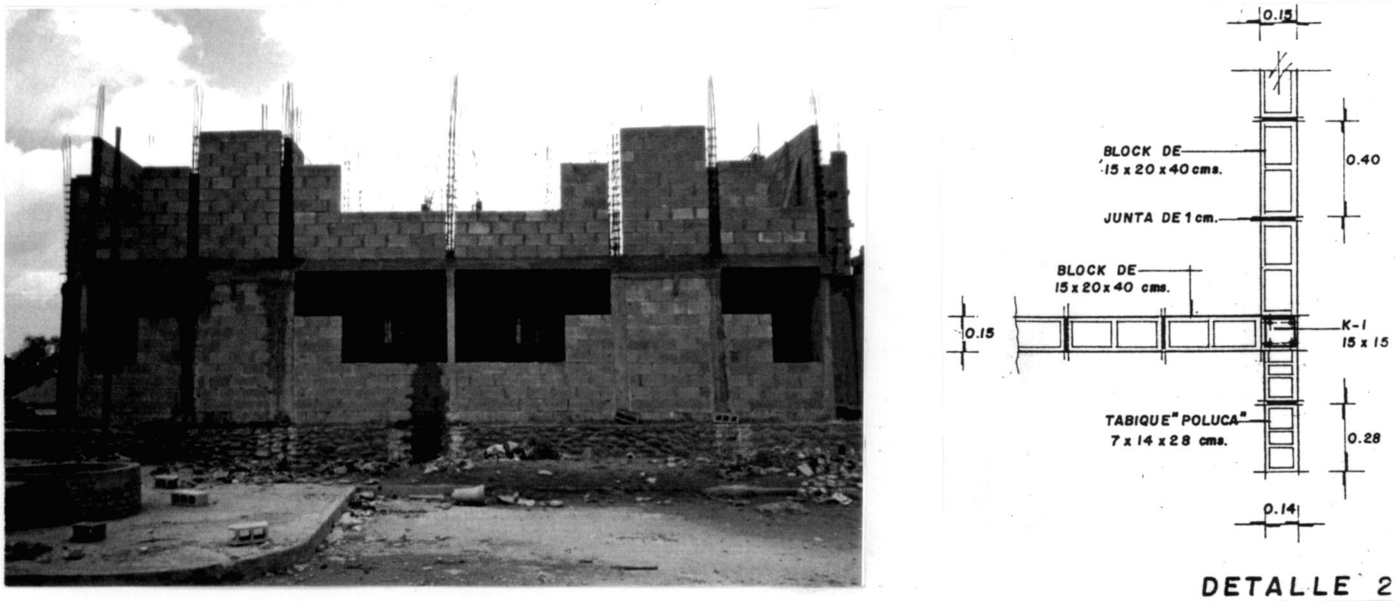


Fig. 1. Confined masonry walls using hollow concrete-block masonry units.
(Las Losas Project under construction in Villahermosa, Mexico)

PRELIMINARY INVESTIGATIONS

Before starting the experimental study presented in this paper, nine other different specimens were already tested to investigate the effect of confinement given by R/C confining columns on seismic behavior of confined masonry walls (Yoshimura and Kikuchi, 1995).

In the first phase of the above experiments, seismic behavior of a confined masonry wall specimen was compared with those of a masonry wall without any confining columns and an R/C ductile moment resisting frame having the same cross-sectional details with the confined masonry wall specimen. One of the important test results obtained was that the confined masonry wall system is very excellent structural system both in strength and deformation capacity, because the confined masonry wall specimen showed remarkably higher strength and ductility than those obtained from the superposition of the pure masonry wall and R/C frame specimens.

In the second phase of the study, four confined masonry walls with different cross-sectional details of R/C confining columns were tested. This test is to investigate the effect of size and shape, and reinforcing details of R/C confining columns on seismic behavior of confined masonry walls. Although all the masonry walls were sufficiently reinforced by wall Re-bars in both horizontal and vertical directions, all the specimens showed very excellent seismic resistance and deformability. In addition to those specimens, two different specimens including a repaired and rehabilitated specimen were tested in the third phase of the study. The investigation presented in this paper is the fourth phase of the experiment, where reinforcing details in masonry walls and R/C confining columns are main experimental parameters.

SPECIMENS

Eight different confined and unconfined masonry wall specimens listed in Table 1 and Fig. 2 were designed and constructed. 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 Japanese Industrial Standard. Thickness of all the masonry walls is 10cm, and except for 0-H40V40 Specimen, all other masonry walls are confined by R/C confining columns with 10cm x 10cm cross-sections in their extreme edges of the wall.

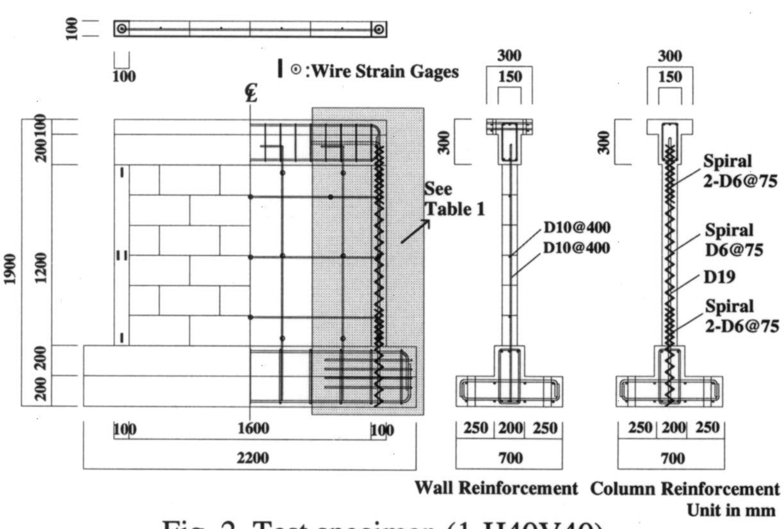
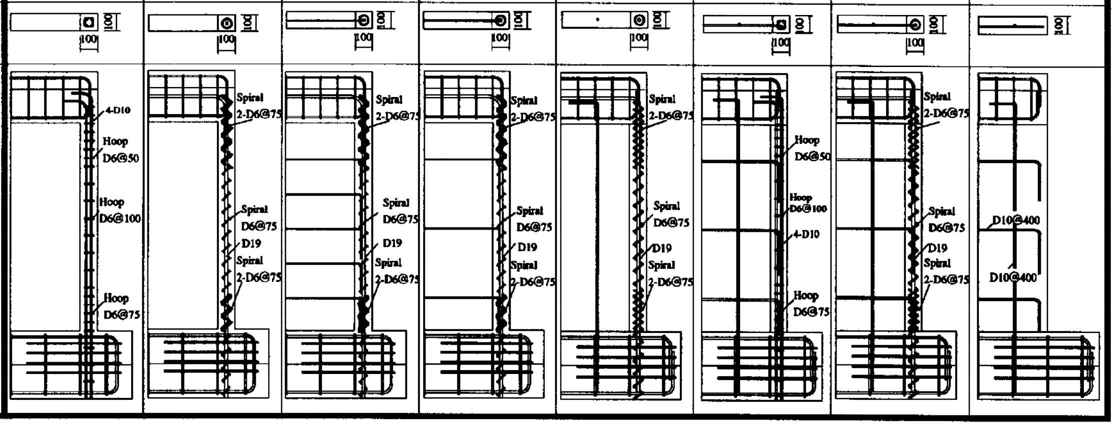


Fig. 2. Test specimen (1-H40V40).

Table 1. List of specimens.

Specimen	4-H0V0	1-H0V0	1-H20V0	1-H40V0	1-H0V40	4-H40V40	1-H40V40	0-H40V40
Horizontal Wall Re-bars	None	None	D6@200	D10@400	None	D10@400	D10@400	D10@400
Vertical Wall Re-bars	None	None	None	None	D10@400	D10@400	D10@400	D10@400
Longitudinal Column Re-bars	4-D10	1-D19	1-D19	1-D19	1-D19	4-D10	1-D19	None
Column Hoop	D6@100	D6@75	D6@75	D6@75	D6@75	D6@100	D6@75	None
Horizontal Cross-section								
Details of Reinforcement								



[Bar-size:D6=#2 , D10=#3 , D19=#6 ; All units in mm]

Each of the specimens is designated by a three symbol code, such as 4-H40V40 and 1-H0V0. The first numerals, "4" and "1", represent the total number of longitudinal reinforcing bars (Re-bars) provided in each of the column-section. The second symbol such as "H40" shows that the horizontal Re-bars are provided in the masonry wall where spacing of these wall reinforcement is 40cm. In case of the specimen "H0V0", there are no wall reinforcement in both horizontal and vertical directions.

Specimen (4-H0V0) in Table 1 is a model of one of the typical confined masonry walls in Mexico as shown in Fig. 1, in which there is no wall reinforcement provided in the masonry wall panel but both of the R/C confining columns are reinforced by four longitudinal Re-bars with bar-size of D10 (or #3) and transverse Re-bars of D6 (or #2). In Specimen (1-H0V0), only one longitudinal Re-bar having the same cross-sectional area with (4-H0V0) is provided in each column, which is transversally reinforced by spiral hoops.

In Specimens (1-H40V0) and (1-H20V0), only horizontal Re-bars are provided in the masonry walls, while Specimen (1-H0V40) has wall Re-bars only in vertical direction. The masonry walls in (4-H40V40) and (1-H40V40) are reinforced both in vertical and horizontal directions. Other reinforcing details are same for all of the specimens.

Among these specimens, five specimens with only one longitudinal Re-bar in their R/C column sections are designed in order to investigate the possibility for simplifying the reinforcing details in the typical R/C confining column-sections adopted in Mexico. It is noted that the amount of shear reinforcement becomes double near the top and bottom of all the R/C columns as shown in Table 1.

Specimen (0-H40V40) is a pure masonry wall specimen without any R/C confining columns, but its masonry wall is reinforced by 40cm spacing Re-bars in both horizontal and vertical directions. Mechanical properties of materials used for specimens are shown in Tables 2 and 3.

Table 2. Mechanical properties of Re-bars.

Bar size	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
D6	434 *	583	22
D10	377	541	21
D19	354	562	19

* 0.2% offset yield strength

Table 3. Compressive strengths of concrete, prism and mortar.

Specimen	Concrete (MPa)		Prism (MPa)	Joint Mortar (MPa)
	Column	Beam		
4-H0V0	31.7	32.6	14.7	33.9
1-H0V0	30.6	31.2	18.8	30.4
1-H20V0	31.9	30.0	17.3	29.6
1-H40V0	32.4	29.9	14.7	31.2
1-H0V40	31.4	29.5	17.4	37.8
4-H40V40	29.3	28.8	17.6	34.9
1-H40V40	33.2	31.1	16.8	34.9
0-H40V40	···	28.1	17.0	37.4

TEST SETUP

Test setup adopted is shown in Fig. 3. Constant gravity load was applied by a hydraulic jack with a capacity of 343kN, and alternately repeated lateral forces were applied by a double-acting hydraulic jack with 980kN capacity. Corresponding constant gravity load applied to the wall was 0.84MPa per gross horizontal area of the wall. Longitudinal axis of the applied lateral forces was kept constant so as to be located at 70 percent of the height of specimen measured from the top surface of the foundation beam, which is the corresponding height of applied lateral forces to the former tests in Oita University (Yoshimura and Kikuchi, 1995). An auxiliary jack installed between loading- and reaction-beams is for counterbalancing and setting the test specimen. Important displacements and strains in reinforcing bars were measured by transducers and wire strain gages, and processed simultaneously by a personal computer.

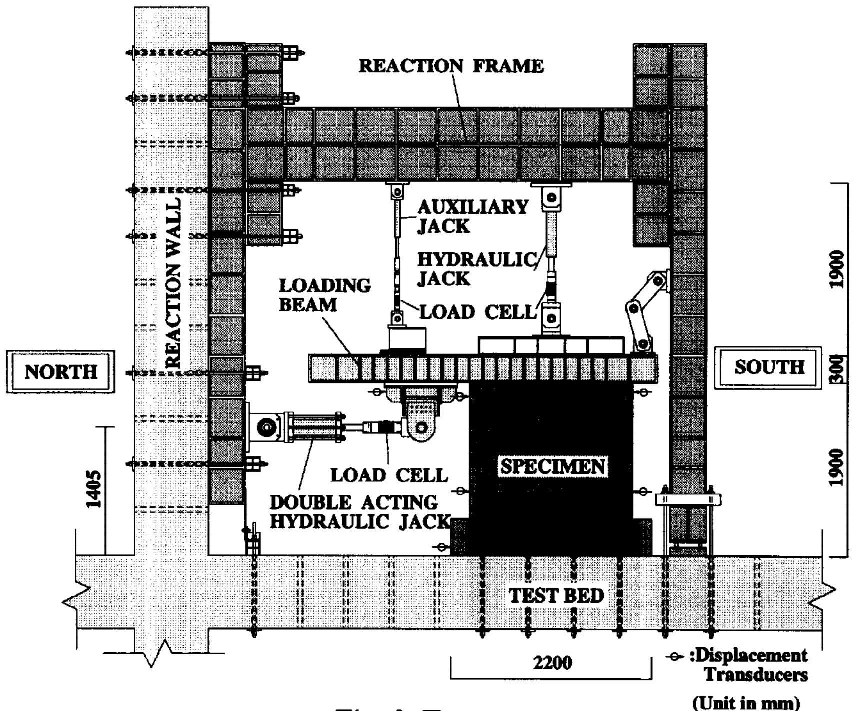


Fig. 3. Test setup.

TEST RESULTS AND DISCUSSIONS

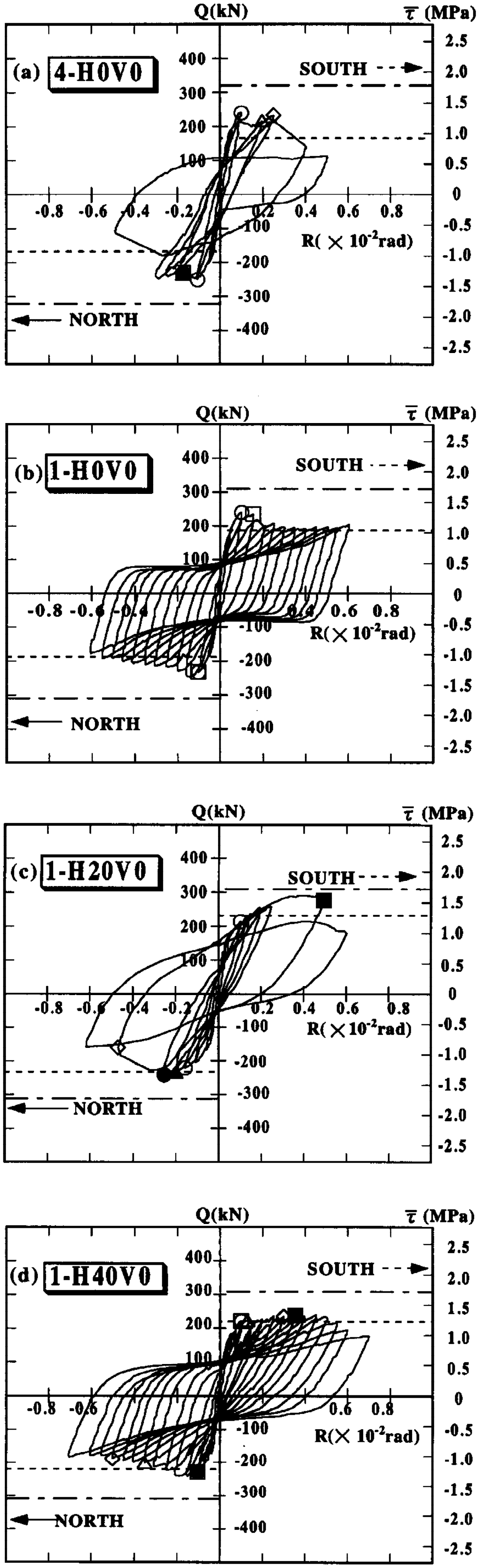
Complete hysteresis loops between applied lateral force (Q) versus story drift (R) relations obtained are shown in Figs. 4(a) through 4(h), where story drift (R) is defined as an interstory displacement divided by the story-height of the specimen. In all the Q-R curves shown in Figs. 4, crack and strain informations are also presented by using eight different symbols, which are listed in Table 4. Dotted lines in the figures represent the theoretical values determined by ultimate flexural moment capacity at the bottom of each wall, while dashed lines are ultimate lateral strengths determined in shear failure mode of the masonry wall with flexural reinforcement in its wall-edges (or R/C confining columns). In addition, final crack patterns observed on the West surface of all the specimens are shown in Figs. 5(a) through 5(h).

Summarizing the test results; in the early stage of loading up to the story drift (R) of 0.1%, hair cracks occurred along through the horizontal joint between bottom of masonry wall and top-surface of foundation beam for all the specimens. These cracks are caused by tensile stresses due to flexure of the masonry wall.

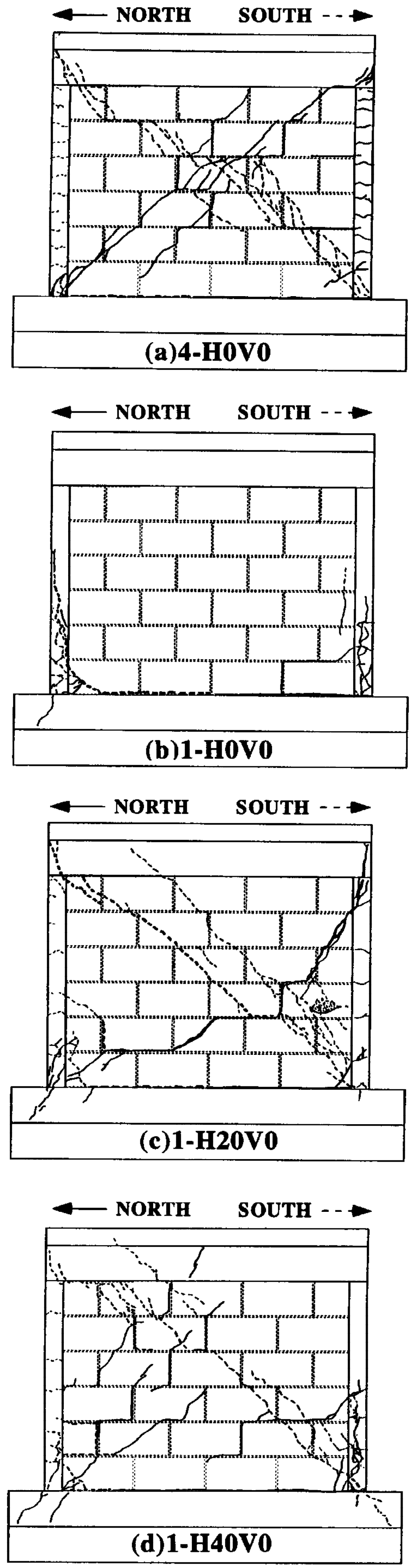
In Specimen (4-H0V0), initial yield in South-column longitudinal Re-bars occurred at R = -0.1%. When displacement was increasing from R = +0.1% to +0.15%, initial but extensive diagonal shear crack occurred in

Table 4. Symbols used in Figs. 4(a) through 4(h) for crack and strain informations.

○: Initial flexural crack in column
◇: Initial shear crack in column
□: Initial flexural crack in masonry wall
△: Initial shear crack in masonry wall
●: Initial yield* in longitudinal Re-bar in South column
■: Initial yield* in longitudinal Re-bar in North column
▲: Initial yield* in horizontal Re-bar in masonry wall
◆: Initial yield* in vertical Re-bar in masonry wall
* yield in tension



Figs. 4(a) through (d).
Lateral-shear vs. story-drift relations.



Figs. 5(a) through (d). Final crack patterns.

masonry wall surface with big sound, and story drift jumped dynamically nearly up to R = -0.2% with rapid strength deterioration. After this, similar phenomenon occurred at R =+0.2%. Rapid deterioration in lateral load-carrying capacity occurred when story drift was from R =+0.25% to+0.3%. Diagonal cracks occurred in the masonry wall propagated into top and bottom of both columns, and passed completely into bottom of the columns and beam-to-column connection at the top of each column. This specimen failed in most drastic shear failure mode among eight specimens (see final crack pattern in Fig. 5(a)).

In Specimen (1-H0V0), most of the cracks in the masonry wall concentrated along through the horizontal bottom joint of masonry wall, and any prominent diagonal shear cracking could not be observed within the masonry wall-surface. This means that most of the horizontal displacement was a relative movement between bottom of masonry wall and foundation beam. As the result, bottom-half of both columns damaged severely, and cover concrete of the North-column was spalled off finally (see Fig. 5(b)). Any yielding did not measured in the longitudinal Re-bars in both of the South and North columns.

In Specimen (1-H20V0), initial yield in horizontal wall reinforcing bars occurred nearly at R = -0.2%. On the contrary, yielding in longitudinal Re-bar initiated in South column at around R = -0.25%. After this, extensive diagonal shear crack occurred suddenly and dynamically when story drift was moving from -0.25% to -0.3%, and first rapid deterioration in lateral load carrying capacity was observed. Just before R =+0.5%, the longitudinal Re-bar in North column yielded. Up to the story drift of 0.6%, all the horizontal Re-bars located in masonry wall yielded completely. Final crack pattern observed on the West wall-surface is shown in Fig. 5(c). In this specimen, diagonal shear crack in the masonry wall passed completely through the beam-to-column connection at the top of the North column. This specimen failed in brittle shear failure mode in both North- and South-side directions.

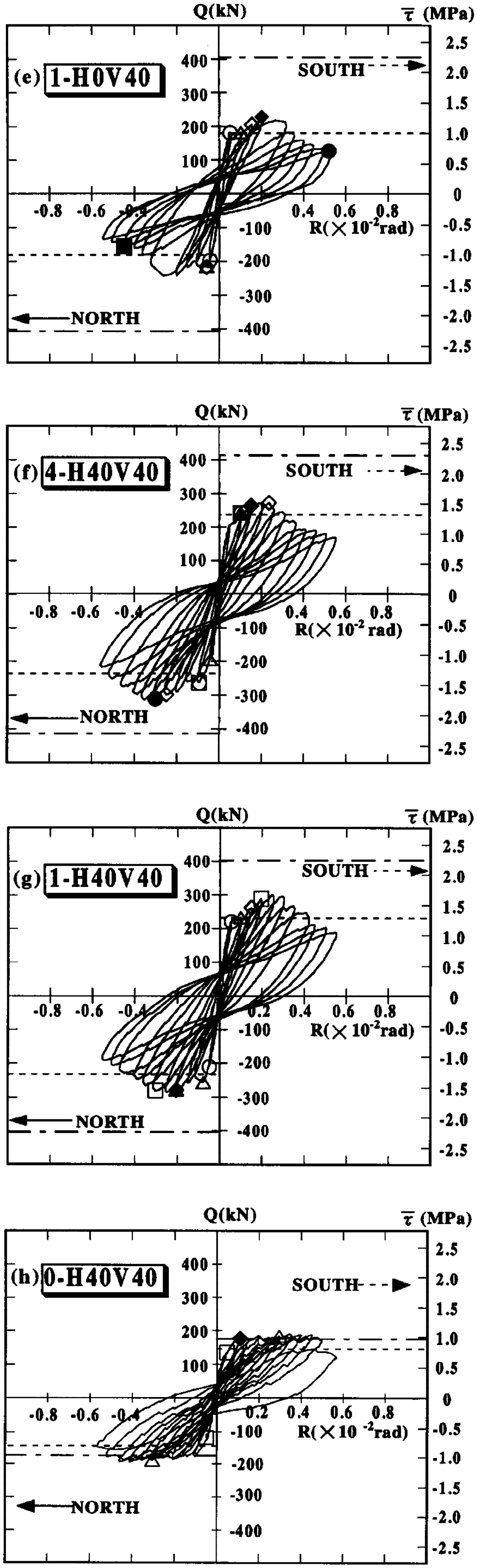
In Specimen (1-H40V0), initial yield of the longitudinal Re-bars in South and North columns occurred at R = -0.1% and R = +0.35%, respectively. Relative displacement between bottom of the masonry wall and top-surface of foundation beam became prominent after story drift was more than 0.25%. Although any deterioration in lateral load-carrying capacity did not occur during the North-side loading, strength deterioration initiated from R =+0.45% when South-side loading was being conducted. In this specimen, any yielding did not measured in all the horizontal wall Re-bars.

In Specimen (1-H0V40), initial shear cracks observed on the central portion of the masonry wall at about R=+0.1 and -0.1%. Vertical wall Re-bars yielded in tension at R=+0.20% when ultimate lateral strength in South-side loading was observed. In North-side loading, the ultimate lateral strength appeared at R=-0.3%, and all the vertical wall Re-bars yielded at R=+0.3%. Yielding of the longitudinal Re-bars in R/C columns occurred at larger displacements (see Fig. 4(e)). This specimen failed in typical shear failure mode.

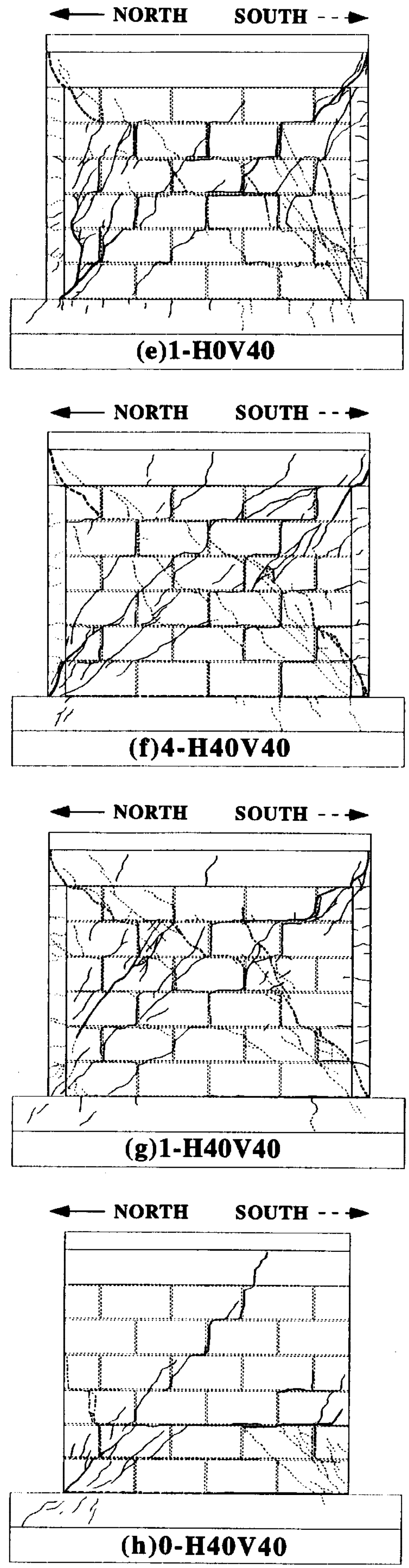
In Specimen (4-H40V40), initial yielding in horizontal wall Re-bars was observed at R=+0.10%. When R=-0.15%, extensive shear cracks occurred on central part of masonry wall. Vertical wall Re-bars yielded initially at R=+0.15%, and ultimate lateral strength in South-side loading was observed at R=+0.25% when all the vertical wall bars yielded in tension. After occurrence of yielding in South-column main bar at R=-0.3%, ultimate strength in North-side loading appeared at R=-0.35%. A large number of shear cracks occurred in masonry wall surface (see Fig. 5(f)), which failed in shear.

In Specimen (1-H40V40), initial shear cracks appeared on wall surface at R=-0.10% and R=+0.10%. Initial yielding in horizontal and vertical wall Re-bars were observed at R=-0.20%. Ultimate lateral strengths appeared at R=0.25% in both-side loading, and all the vertical wall bars yielded up to these ultimate stages. Although any yielding did not take place in longitudinal Re-bars in R/C confining columns, this specimen failed in shear failure mode. Final crack pattern shown in Fig. 5(g) is quite similar to the former specimen (4-H40V40).

In Specimen (0-H40V40) whose masonry wall was not confined by any R/C columns, initial yielding in wall Re-bars was observed in bottom of the North-vertical Re-bar at R=+0.10%, and shear cracks appeared at bottom part of the wall when R=+0.30% and R=-0.30%. Ultimate strengths in North- and South-side loading appeared at R=-0.40% and R=+0.35% respectively. After reaching these ultimate strengths, slight sliding displacements appeared between horizontal joints in bottom part of the masonry wall. Rapid deterioration in lateral load-carrying capacity took place when R were larger than ±0.55 percent radians.



Figs. 4(e) through (h).
Lateral-shear vs. story-drift relations.



Figs. 5(e) through (h). Final crack patterns.

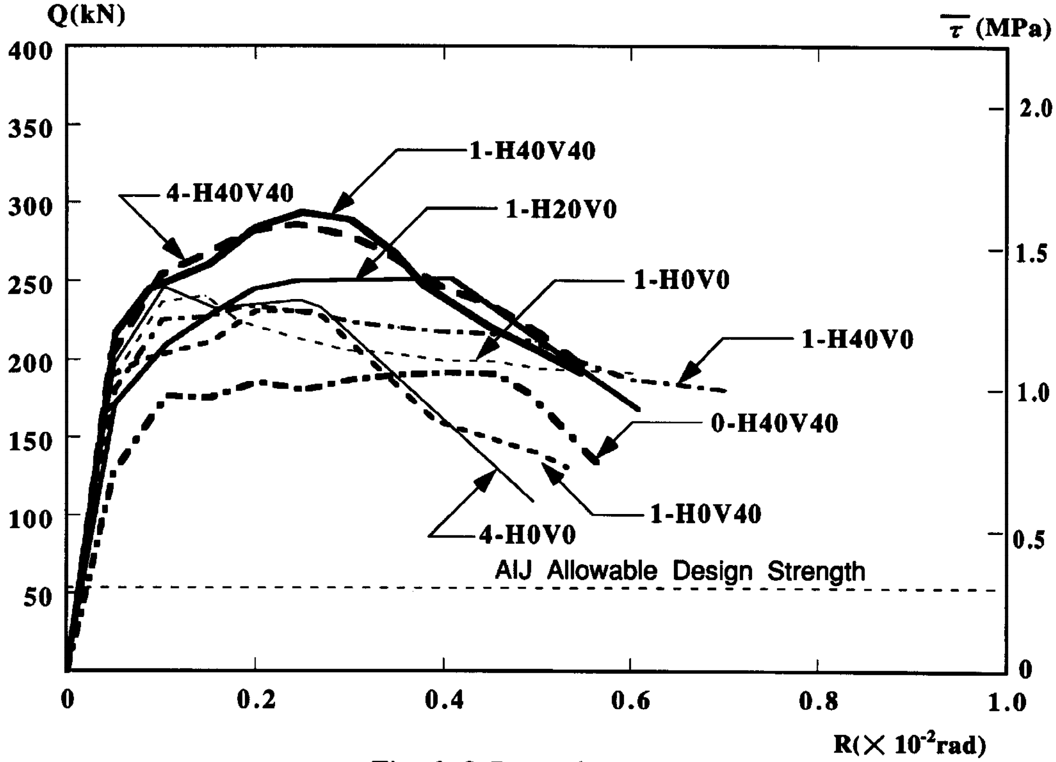


Fig. 6. Q-R envelope curves.

Envelope curves obtained from all the Q-R hysteresis loops in Figs. 4(a) through 4(h) are shown in Fig. 6, where lateral forces (Q) are given by simple average calculated from the North- and South-side loading curves. Dashed line parallel to the horizontal axis represent the maximum (or allowable) lateral shear force permitted in the current AIJ Design Standard for Hollow Concrete-block Masonry Structures. Ultimate lateral strengths obtained from the seven confined masonry wall specimens are more than 450 percent of the AIJ design strength. In case of confined masonry walls having both vertical and horizontal wall Re-bars such as 4-H40V40 and 1-H40V40 specimens, ultimate lateral strengths become higher than other specimens without any wall Re-bars or with wall Re-bars provided only in one direction. In case of specimens without any vertical wall reinforcement such as 1-H0V0 and 1-H40V0, sliding failure occurred between bottom of masonry wall and R/C foundation beam. Other specimens failed in shear failure mode. In addition, Q-R envelope curve in Specimen (4-H40V40) showed quite similar behavior observed in 1-H40V40. This fact suggests that there are some possibilities to be able to improve the complex R/C column reinforcing details with four longitudinal Re-bars adopted in Latin American countries to the simpler cross-sectional reinforcing method with only one main Re-bar.

CONCLUSIONS

In case of the confined concrete masonry wall system, both of the vertical and horizontal reinforcement in masonry walls play an important role for expecting higher ultimate lateral strength and better ductility. This is because high shear stresses are induced in confined masonry wall panels especially when the masonry walls are subjected to lateral forces and expected to fail in brittle shear failure mode.

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