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Experimental Study for Developing a Seismic Confined Brick Masonry Walls
Part 2: Experimental results on three-dimensional specimens.

AIJ members Koji Yoshimura[*1], Kenji Kikuchi[*2], Masayuki Kuroki[*3], Hideko Nonaka[*3],
○ Tania Croston[*4], Shunji Koga[*4] and Kyong Tae Kim[*4].

1. INTRODUCTION


Figure 1. Damage to URM walls, 1999 Quindio Earthquake in Colombia. [Ref.1]

Every time when developing countries were attacked by a big earthquake, a large number of severe structural damage occurred in unreinforced masonry (URM) wall building structures. Figure 1 shows one of the typical examples of the extensive structural damage to the URM walls caused by the 1999 Quindio Earthquake in the Republic of Colombia, where URM walls failed not only in their own plane but also many walls separated each other along their vertical wall-to-wall connections and turned over in their out-of-plane directions occurred. Similar structural damage to the URM walls was widely observed during the 1976 Tanshang Earthquake in the People's Republic (P.R.) of China, where more than 240,000 people were killed by this earthquake.

In order to prevent this kind of wall separation damage during big earthquakes, confined masonry (CM) wall system was developed and has been constructed in many earthquake countries. Although this CM wall system has been widely accepted into the low- and medium-rise masonry buildings as an effective seismic structural wall system, extensive structural damage occurred in some of the newly constructed CM walls, where adjacent URM walls were separated from the R/C confining columns.

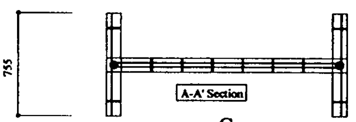
Main objective of the present study is to investigate the effective seismic strengthening methods for masonry walls in the developing earthquake countries. Experimental results on three-dimensional specimens with different parameters are reported in the present paper.

2. SPECIMENS

A total of four confined and unconfined masonry wall specimens with different connection details, listed in Table 1 and Figure 2, were designed and constructed. Thickness of all the masonry walls is 10.5cm, and except for 3D-L0-H0V0-LC specimen, other three masonry walls are confined by R/C columns with 10.5cm x 10.5cm cross-section in the extreme edges of each main wall.

The effective length of intersecting walls, constructed at the extreme edges of the main wall, was determined based on the recommendation presented in Reference [2].

Each of the specimens is designated by five-symbol code, such as 3D-L1-H42V0, with exception of 3D-L0-H0V0-CB specimen, which has six-symbol code. The first symbol "3D" represents three-dimensional specimen. The second letter "L" represents the location of the applied lateral forces (or height of the inflection point of the wall) is "low". The third numeral "1" after the letter L represents that only one longitudinal Re-bar with bar-size of D19 (#6) is provided in each of the confining R/C column-section, which is transversely reinforced by circular spiral hoops of D6 (#2) as shown in Figure 2. The fourth symbol "H42" indicates that the horizontal Re-bars are provided in the spacing of 42cm and "H0" means that there is no horizontal Re-bars provided, and also the fifth symbol "V0" indicates that vertical Re-bars are not used. The sixth symbol "CB" indicates that U-shaped connecting steel Re-bars with bar-size of D6 (#2) are placed every 21cm between masonry wall-edges and attached R/C column sec-



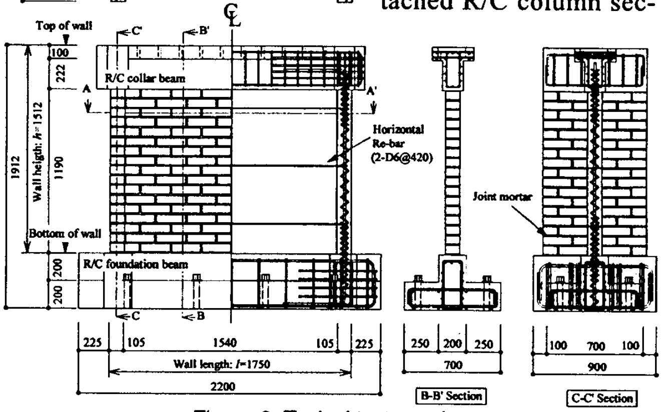


Figure 2. Typical test specimen.

*1 Professor, Department of Architectural Engineering, Oita University, Japan, Dr. Eng.
*2 Associate Professor, Department of Architectural Engineering, Oita University, Japan, Dr. Eng.
*3 Research Associate, Department of Architectural Engineering, Oita University, Japan.
*4 Graduate Student, Department of Architectural Engineering, Oita University, Japan.

tions, where these connecting bars are recommended by the Standards of P.R. of China. In case when the specimen's name does not have this symbol, there is no connecting bars provided in the masonry wall panel. Mechanical properties of materials used for specimens are shown in Tables 2 and 3.

3. TEST SETUP

The test setup adopted in the present study is shown in Figure 3, where height of the longitudinal axis of the lateral forces applied to the specimens (or height of the inflection point induced in the wall) is approximately 0.67 times of the wall height. A hydraulic jack applied corresponding constant vertical axial load with a capacity of 490 kN (50tf), and another double-acting hydraulic jack applied alternately repeated lateral forces with 980kN (100tf) capacity. An auxiliary jack installed between loading- and reaction- frame is for counterbalancing and setting the test specimens. Displacement transducers and strain gages measured important displacement and strains in reinforcing bars, and all the measured information were processed simultaneously by a personal computer.

4. RESULTS AND DISCUSSIONS

Complete hysteresis loops between applied lateral force (Q) versus story drift (R) relations obtains from the present test are shown in Figure 4, where story drift (R) is defined as an interstory displacement divided by the story-height of the specimen. In all the Q-R curves, crack and strain information are also presented by using five different symbols shown in Table 4. Dashed lines in the figures represent the theoretical values determined by the ultimate flexural moment capacity at the bottom of each wall, while dotted lines are the ultimate lateral strengths determined in shear failure mode of the masonry wall. In addition, final crack patterns observed on the West surface of all the specimens are shown in Figure 5.

For all the specimens, theoretical ultimate lateral strengths determined by the existing equations to predict the ultimate flexural and shear strengths of the masonry walls, are shown in Table 5, together with the expected failure modes and observed test results.

By summarizing the test results obtained:

3D-L0-H0V0 Specimen: Initial flexural crack in the brick masonry wall occurred at R=+0.038%, when R=-0.035% the specimen started to failure by shear and the ultimate strength occurred at R=+0.038% and R=-0.035%.

3D-L1-H0V0 Specimen: Initial shear crack in the brick masonry wall occurred at R=+0.039%. Ultimate strength occurred at R=+0.039% and R=-0.043%. Longitudinal Re-bars in the bottom part of the north and south columns yielded at R=-0.471% and R=+0.385%, respectively.

Table 1. List of test specimens.

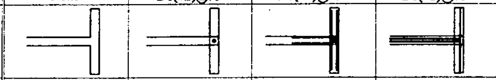
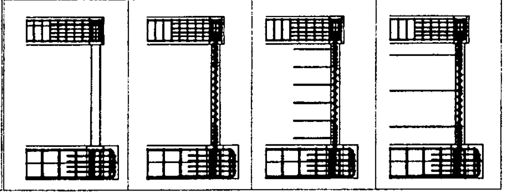
Specimen	3D-specimens			
	3D-L0-H0V0	3D-L1-H0V0	3D-L1-H0V0-CB	3D-L1-H42V0
Heigth of applied lateral force	0.67x*h* (*h*:Wall height)			
Axial stress σ_0 (MPa)	0.84 (Per horizontal wall cross-section in main (or web) wall)			
Horizontal Wall Re-bars	None	None	None	2-D6(#2)@420
Vertical Wall Re-bars	None	None	None	None
Connection Re-bars	None	None	D6(#2)@210	None
Longitudinal Column Re-bars	None	1-D19(#6)	1-D19(#6)	1-D19(#6)
Column Hoop	None	D6(#2)@75	D6(#2)@75	D6(#2)@75
Horizontal Cross-section				
Details of Reinforcement				

Table 2. Mechanical properties of reinforcing bars.

Bar size	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
D6 (#2)	448	565	10
D19 (#6)	341	483	24

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

Specimen	Concrete (MPa)		Prism (MPa)	Joint Mortar (MPa)
	Column	Beam		
3D-L0-H0V0	none	28.8	24.7	34.7
3D-L1-H0V0	26.4	24.2	22.0	33.6
3D-L1-H0V0-CB	27.0	30.7	22.6	34.6
3D-L1-H42V0	28.2	30.8	19.9	33.4

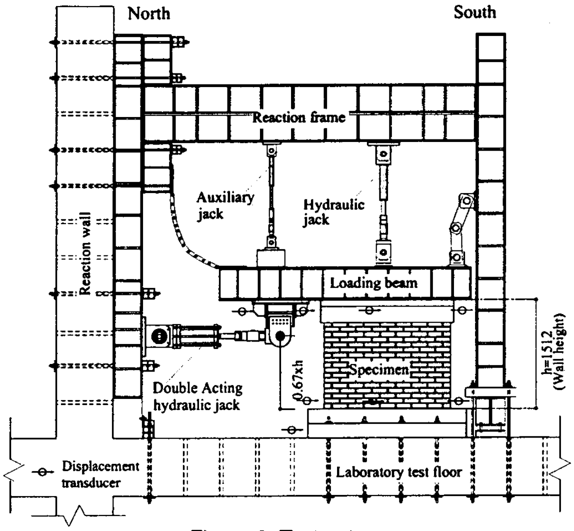


Figure 3. Test setup.

Table 4. Symbols used in Figure 4.

□ :	Initial flexural crack in masonry wall
△ :	Initial shear crack in masonry wall
● :	Initial yield* in longitudinal Re-bar in south
■ :	Initial yield* in longitudinal Re-bar in north
▲ :	Initial yield* in horizontal Re-bar in masonry

* Yield in tension

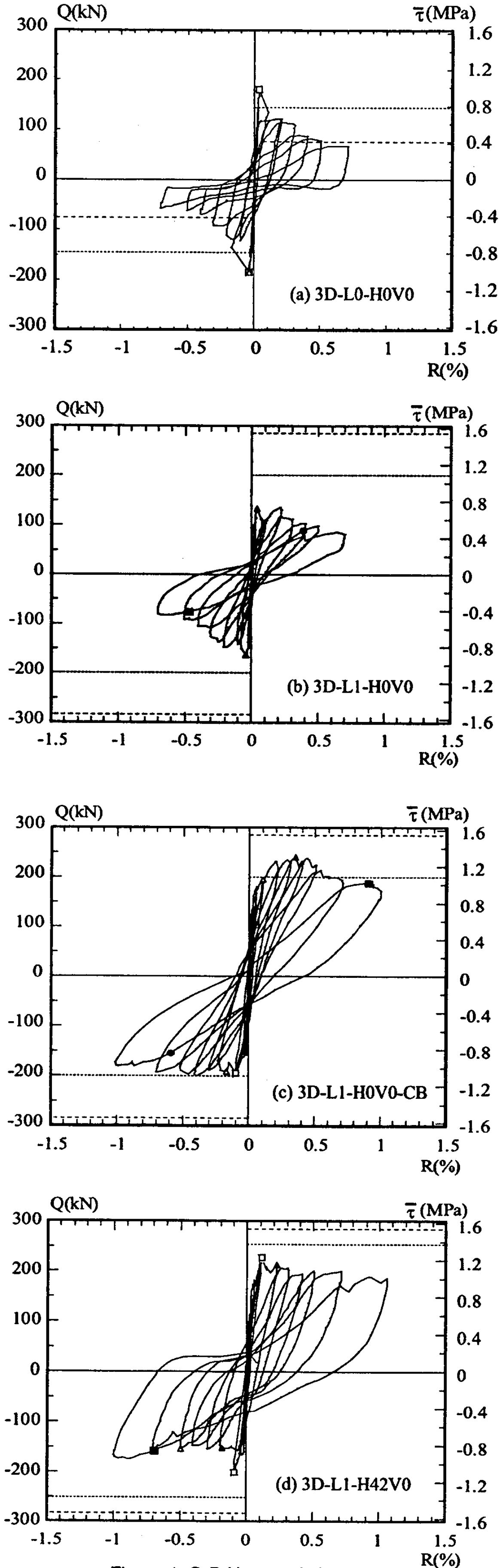


Figure 4. Q-R Hysteresis loops.

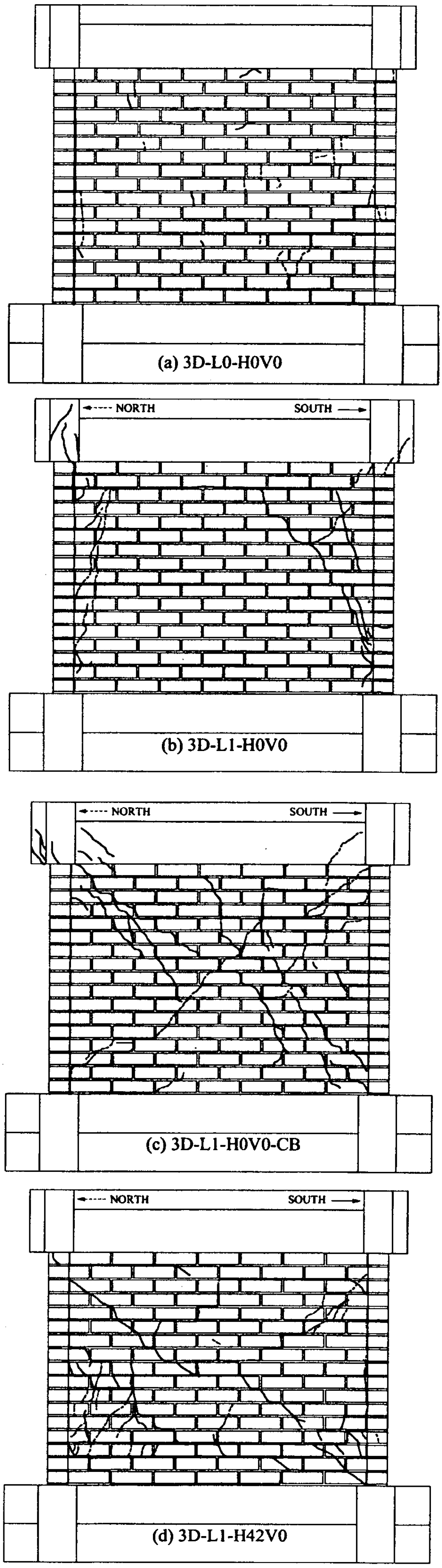


Figure 5. Final crack patterns.

Table 5. Predicted and observed ultimate lateral strengths and failure modes.

Specimen	Observed Initial Stiffness K(kN/rad) x10^6	Theoretical Prediction				Test Results	
		Evaluation	Ultimate lateral strength: Flexural Mode Q_u(kN)	Ultimate lateral strength: Shear Mode Q_u(kN)	Predicted Failure Mode*	Ultimate Lateral Strength Q(kN)	Observed Failure Modes*
3D-L0-H0V0	0.56	Refs. 3 and 4	77	145	F	184	F, S
3D-L1-H0V0	0.51	Ref. 5	285	200	S	164	S
3D-L1-H0V0-CB	1.17	Ref. 5		200		241	
3D-L1-H42V0	0.77	Ref. 5		252		227	

* F=Flexural Failure Mode, S=Shear Failure Mode

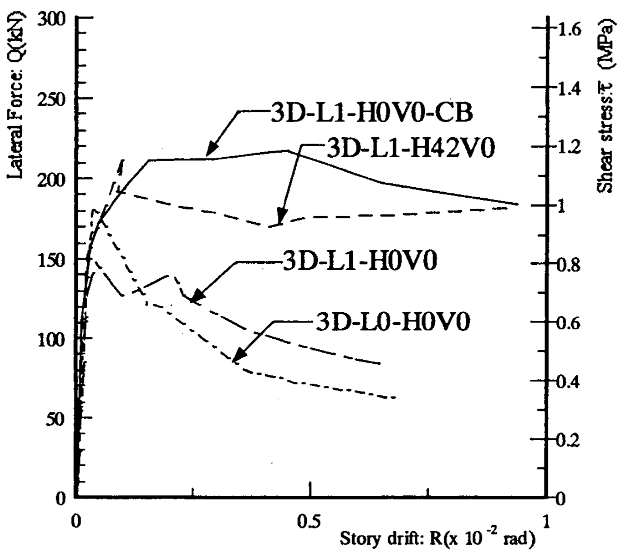


Figure 6. Q-R Envelope curves.

3D-L1-H0V0-CB Specimen: This specimens developed the best seismic behavior. Initial shear crack occurred at R=+0.101% and diagonal cracks occurred in the brick masonry wall from the bottom of both columns up to the top of each column. Ultimate strengths occurred at R=+0.322% and R=-0.403%. Longitudinal Re-bar in the bottom part of the south column yielded at R=-0.597% and in the top part of the north column at R=+0.900%.

3D-L1-H42V0 Specimen: Initial flexural crack occurred at R=+0.105% and R=-0.095% between the bottom of the masonry wall and the top surface of the foundation-beam. When R=+0.219%, the specimen started to fail by shear mode and the ultimate strengths occurred at R=+0.105% and R=-0.095%. Longitudinal Re-bar in the middle part of the north column yielded at R=-0.703% and the horizontal re-bar in the bottom north side yielded at R=-0.183.

Figure 6 represents all the envelope curves obtained from the Q-R hysteresis loops shown in Figure 4. Clear difference in the ultimate strengths and deformation capacity can be observed between wall specimens with and without horizontal reinforcement and connecting bars. In case of the CM walls with horizontal reinforcement (L1-H42V0) and connecting bars (L1-H0V0-CB), their ultimate strengths and deformation capacity are improved extremely better than the ordinary CM (L1-H0V0) and URM (L0-H0V0) walls. In addition, separation between masonry wall-edges and R/C columns did not occur in those two types of wall specimens with horizontal reinforcement or connecting bars. This fact means that the horizontal wall reinforcement and connecting bars provided between masonry walls and R/C columns play an important role to improve the seismic performance in the ordinary CM walls.

5. CONCLUSION

Connection details adopted in China and the horizontal wall reinforcement are very effective for improving a structural behavior of the CM walls against big earthquakes.

ACKNOWLEDGMENTS

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