Experimental Study on Reinforcing Methods Using Extra RC Elements for Confined Masonry Walls with Openings

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SUMMARY:
This paper aims to investigate effects of openings on the seismic performance of confined masonry, CM, walls and to investigate reinforcing methods using reinforced concrete, RC, elements for the openings. Cyclic lateral loading tests were carried out using ten CM wall specimens, in which five specimens are with window opening and four specimens are with door opening. The following conclusions can be drawn. Most of the CM walls with openings accompanied by the extra RC elements could develop higher lateral load carrying capacity than the walls without any openings as well as the walls without any extra RC elements around the opening. Theoretical ultimate shear strength was calculated based on a shear force transfer model with masonry strut. However, close agreements between the calculations and the test results were not obtained.

Keywords: Confined masonry, Openings, Cyclic lateral loading tests

1. OBJECTIVE

The confined masonry, CM, walls are composed of masonry wall and cast-in-place reinforced concrete, RC, small columns and beams and/or floor slabs along the perimeter of the masonry wall. Concrete of the small columns, which are called as confining columns, and beams are cast after the masonry wall is constructed.

From the lessons of quite severe earthquake damage to unreinforced masonry buildings, the CM wall system has been adopting widely as a load bearing wall in the developing countries prone to high seismic activity. However, it is noted that understanding on the seismic performance of the CM walls is not sufficient because academic investigations started in 1980s (Kikuchi (1994)).

The effect of openings on the shear strength of the CM walls is one of the important items affecting the seismic performance of the CM buildings. Kobayashi et al. (2009) reported that experimental shear strength of the CM walls with window openings agrees approximately with sum of the theoretical shear cracking strength of masonry and the ultimate shear strength of RC confining columns, where an inflection point of the RC confining column is required to be determined from the experimental data. Also, Toge et al. (2008) reported that arrangement of extra window frame made of steel pipes or timber gives some effect to reduce the loss of shear strength caused by the window opening.

This paper aims to investigate effects of openings on the seismic performance of CM walls and to investigate reinforcing methods using RC elements for the openings.

2. TEST SPECIMENS

Tables 2.1 and 2.2 are list of ten test specimens used in the present study. Fig. 2.1 shows dimensions and reinforcing details for Specimen CMWO-06, which is one of the test specimens with opening accompanied by extra RC elements. The test specimens are approximately one-half scale models of one-bay-one-story CM walls with and without opening. Clay bricks with dimensions of 210x100x60 in mm are used as the masonry unit, and thickness of the joint mortar is 10 mm. A D19 or #6 bar is arranged in the vertical extra elements as the longitudinal reinforcement, which is same as the confining column. On the contrary, four D10 or #3 bars are arranged in the horizontal extra elements, where those steel bars are anchored to the confining columns with 90 degree hook.

Specimen CMWO-07 is CM wall without any openings. Specimen CMWO-05 is a model with central window opening, in which any extra RC elements are not arranged around the opening. Specimens CMWO-08 and CMWO-06 are models with central window opening accompanied by vertical and horizontal RC extra elements, where there are two types of horizontal extra elements with different length. Specimen CMWO-09 is a model with eccentric window opening. Specimen CMWO-10 is a model with eccentric window opening accompanied by the extra RC elements.

Specimens CMWO-11 and CMWO-12 are models with central door opening, and Specimens CMWO-13 and CMWO-14 are models with eccentric door opening. The vertical extra RC elements are arranged around the opening in Specimens CMWO-12 and CMWO-14.

Table 2.3 gives compressive strengths of the concrete, joint mortar and masonry prism. Compressive strengths of the masonry prism are from 10.4 MPa to 18.1 MPa. Compressive strengths of the concrete casted in RC confining columns and extra elements are from 21.1 MPa to 27.2 MPa. Mechanical properties of the steel bars are given in Table 2.4.

Table 2.1. List of test specimens with and without window opening

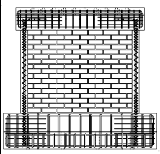
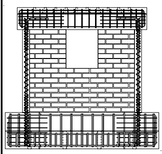
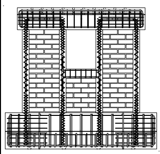
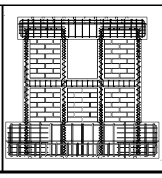
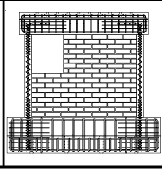
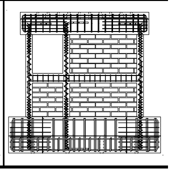
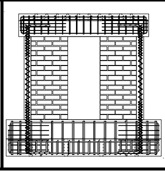
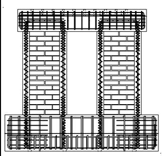
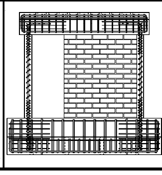
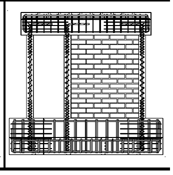
Specimen		CMWO-07	CMWO-05	CMWO-08	CMWO-06	CMWO-09	CMWO-10
Vertical extra RC element	Section	Without any openings	None	100x100 (mm)		None	100x100 (mm)
	Longitudinal steel bar			1-D19			1-D19
Horizontal extra RC element	Section		None	100x140 (mm)		None	100x140 (mm)
	Longitudinal steel bar			4-D10			4-D10
Illustration							

Table 2.2. List of test specimens with door opening

Specimen		CMWO-11	CMWO-12	CMWO-13	CMWO-14
Vertical extra RC element	Section	None	100x100 (mm)	None	100x100 (mm)
	Longitudinal steel bar		1-D19		1-D19
Horizontal extra RC element	Section	None	None	None	None
	Longitudinal steel bar				
Illustration					

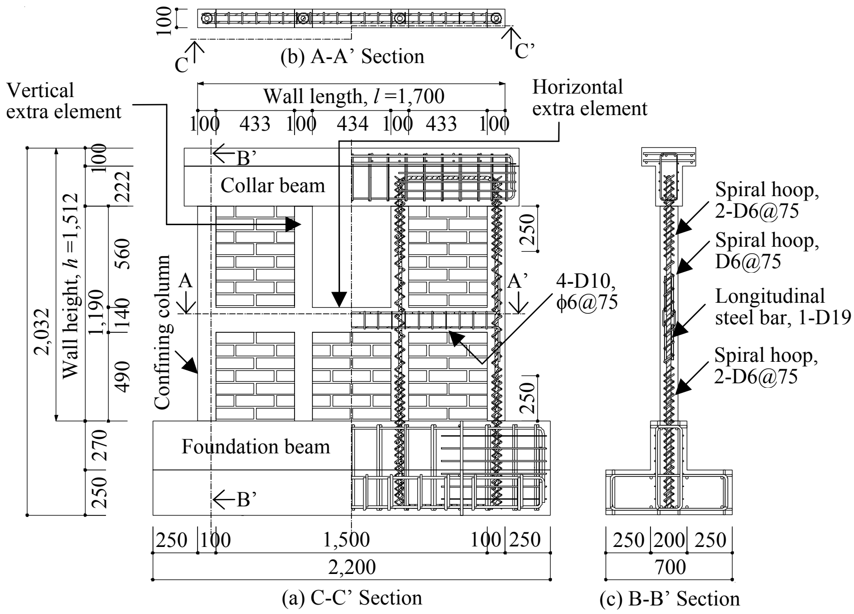


Figure 2.1. Dimensions and reinforcing details for Specimen CMWO-06

Table 2.3. Compressive strengths of concrete, joint mortar and masonry prism

Specimen	Concrete (MPa)		Masonry prism F_m (MPa)	Joint mortar F_z (MPa)
	Confining column, Extra element	Collar beam		
CMWO-05	27.2	28.1	12.7	19.2
CMWO-06	26.8	28.1	11.0	19.2
CMWO-07	21.1	22.5	10.4	19.5
CMWO-08	22.0	22.5	11.1	19.5
CMWO-09	26.8	24.1	14.4	23.7
CMWO-10	25.1	24.1	13.6	23.3
CMWO-11	21.4	20.6	10.8	19.9
CMWO-12	22.7	21.8	11.3	19.9
CMWO-13	23.6	21.7	17.1	23.2
CMWO-14	23.4	22.5	18.1	22.8

Table 2.4. Mechanical properties of steel bars

Specimen	Designation	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Remarks
CMWO-05 CMWO-06 CMWO-07 CMWO-08	ϕ6	428 *	521	11	* 0.2% offset strength
	D6	411 *	508	15	
	D10	361	512	19	
	D19	395	614	15	
CMWO-09 CMWO-10	ϕ6	545 *	620	Not measured	
	D6	437 *	523	20	
	D10	361	512	19	
	D19	401	626	18	
CMWO-11 CMWO-12	D6	406 *	506	18	
	D19	378	575	20	
CMWO-13 CMWO-14	D6	378 *	492	16	
	D19	385	580	19	

3. TEST PROCEDURE

Fig. 3.1 shows loading apparatus used in the experiments of the present study. A constant vertical axial load was applied by a hydraulic jack, and alternate repeated lateral forces were applied by the other double acting hydraulic jack. For all test specimens, magnitude of the constant vertical axial load is 81.6 kN in compression. This is corresponding to the axial stress, σ_0, of 0.48 MPa for Specimen CMWO-07 without any openings. Height of the application point of lateral forces measured from the top of bottom RC foundation beam is 0.67 times the wall height, h.

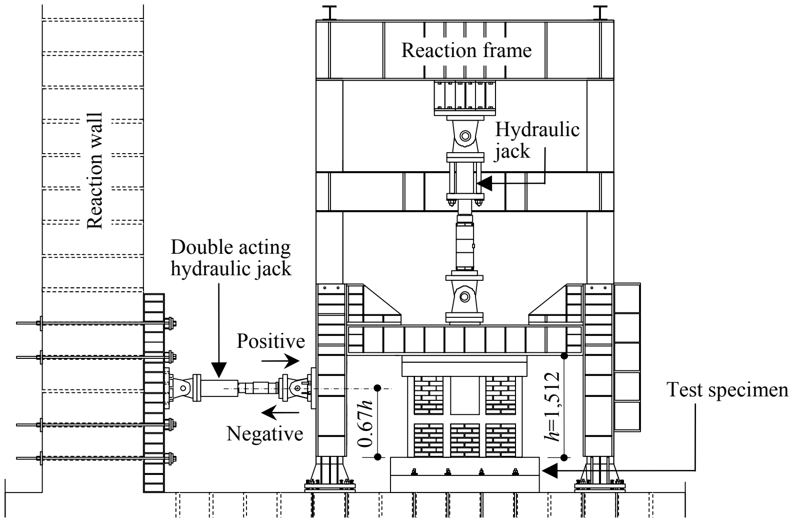


Figure 3.1. Loading apparatus

4. TEST RESULTS AND DISCUSSIONS

4.1. Complete Hysteresis Loops and Crack Patterns

Fig. 4.1 shows relation between lateral force, Q, and story drift angle, R, obtained from the experiment, in which R is defined as the lateral displacement of RC collar beam divided by the wall height, h. Right vertical axis represents mean shearing stress, $\bar{\tau}$, which is defined as the lateral force, Q, divided by the horizontal cross-sectional area of the wall. Open circles indicate occurrence of the initial shear crack. Solid circles indicate that the RC confining columns and vertical extra RC elements start to yield in tension. Dotted lines parallel to the horizontal axis represent theoretical shear cracking strength, Q_{sc}, calculated by Eqn. 4.1. Solid lines represent ultimate shear strength, Q_{su}, to be described in Section 4.4.

$$Q_{sc} = \sqrt{\sigma_t(\sigma_t + \sigma_0)}\, tD/\kappa \tag{4.1}$$

in which, σ_t is tensile strength of masonry defined as $0.125\sqrt{F_z}$ (National Standards of P.R. of China (1989)), F_z is compressive strength of joint mortar in MPa, σ_0 is axial compressive stress of the wall, t is thickness of the wall, D is length of the wall excluding the openings, and κ is a factor of stress concentration of 1.5.

Fig. 4.2 shows crack patterns. Solid and dotted curves represent cracks observed in the positive and negative loadings, respectively.

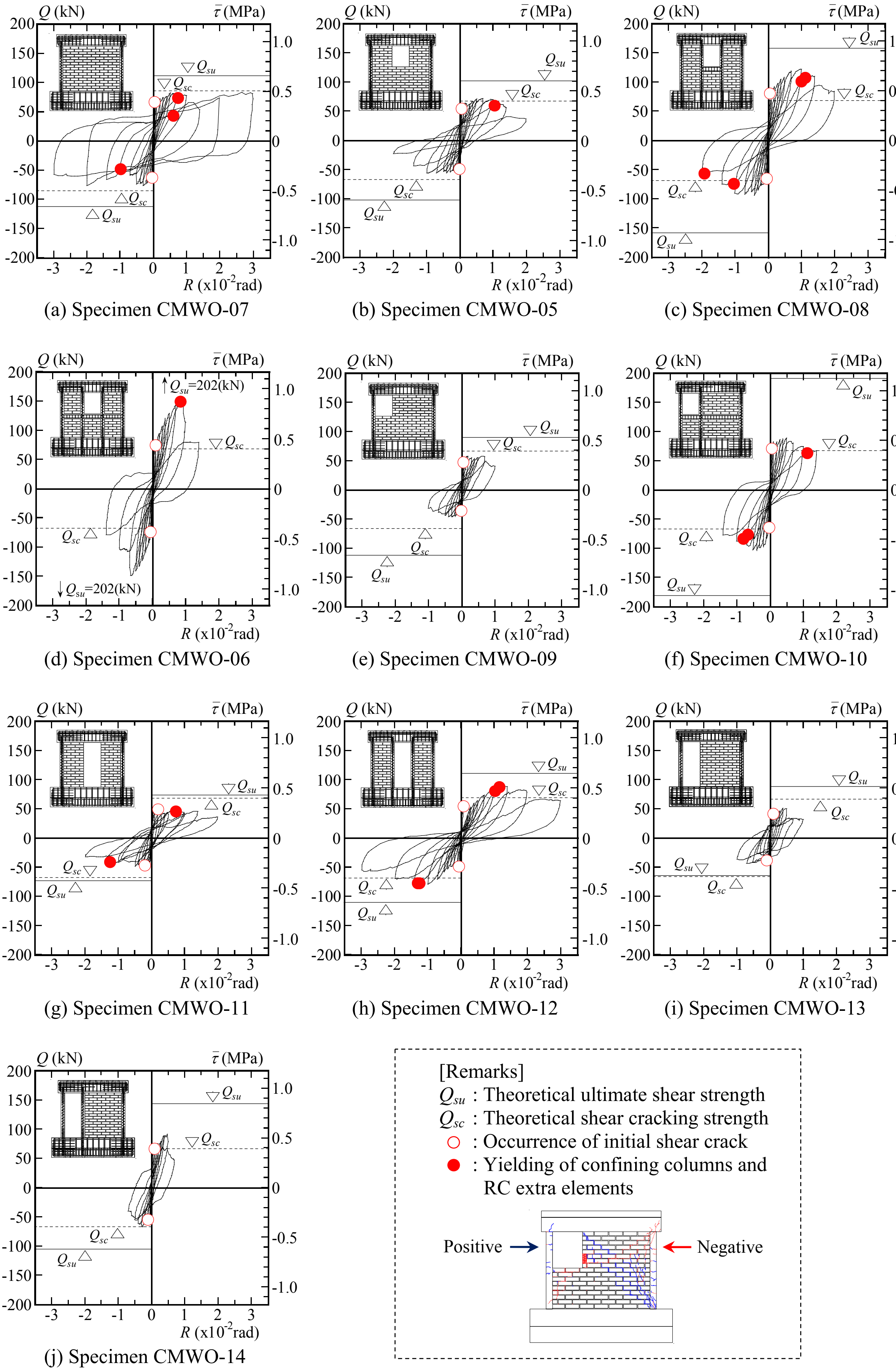


Figure 4.1. Relations between lateral force, Q, and story drift angle, R

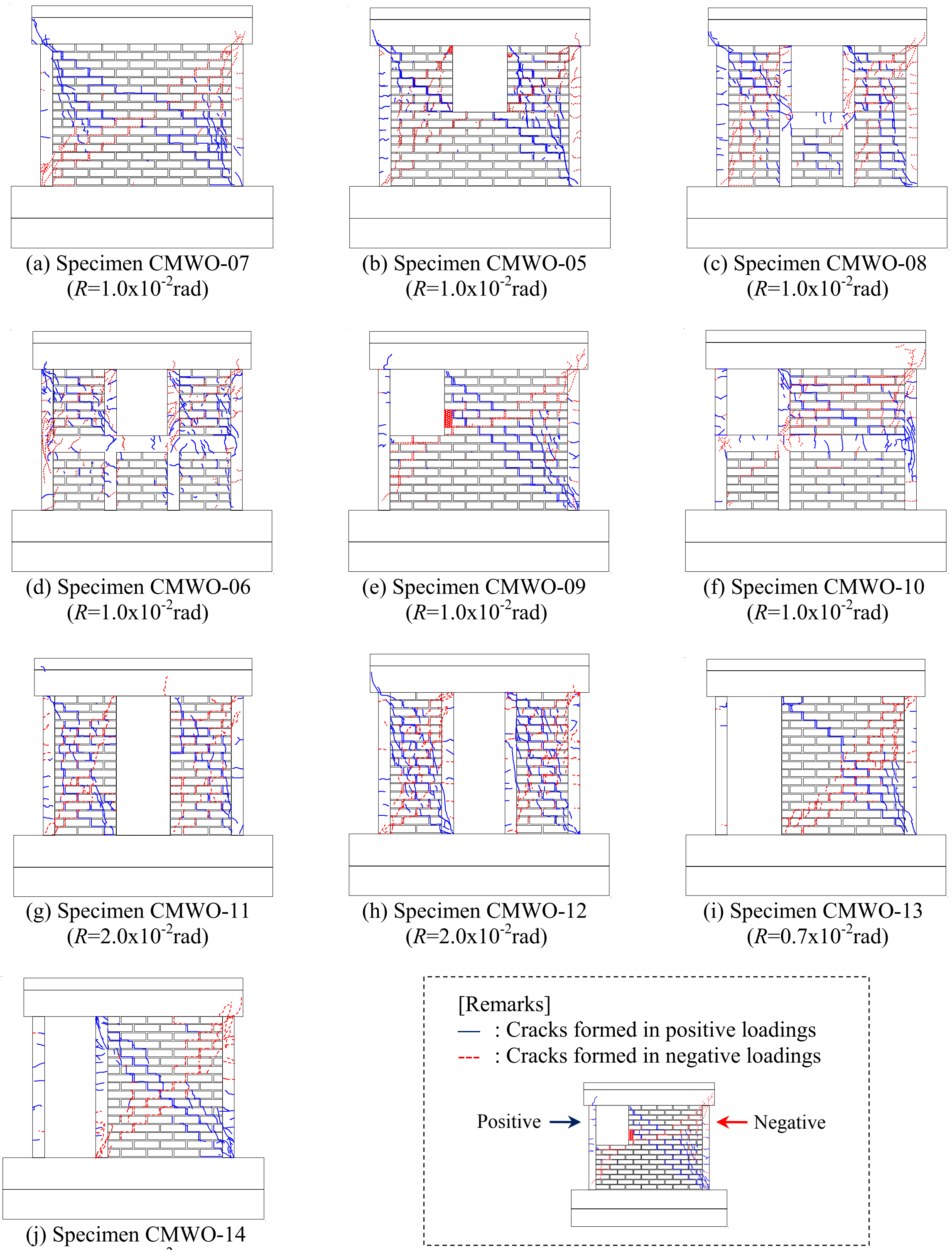


Figure 4.2. Crack patterns

4.2. Loss of Shear Capacity Caused by Openings

Specimen CMWO-07 without any openings failed in shear mode, in which very little increase in lateral load carrying capacity was observed in a stage following the occurrence of initial shear crack as shown in Fig. 4.1 (a). Similar failure characteristic was observed in Specimens CMWO-05 and CMWO-09 with window opening and in Specimens CMWO-11 and CMWO-13 with door opening. Maximum lateral forces of Specimens CMWO-05 and CMWO-09 divided by that of Specimen

CMWO-07 are 0.87 and 0.70 in positive loading, and are 0.77 and 0.61 in negative loading, respectively. Thus, the loss of ultimate shear strength caused by the eccentric window opening is larger than that by the central window opening.

4.3. Effect of Extra RC Elements Arranged Around Openings

The test specimens with opening accompanied by the extra RC elements, Specimens CMWO-06, CMWO-08, CMWO-10, CMWO-12 and CMWO-14, exhibit relatively clear increase in lateral load carrying capacity even after occurrence of initial shear crack, and failed in shear mode finally.

Specimens CMWO-06, CMWO-08 and CMWO-10, which have central or eccentric window opening, could develop higher maximum lateral forces than Specimen CMWO-07 without any openings as well as the specimens without any extra RC elements around the openings. This indicates that arrangement of the extra RC elements is effective enough to recover the loss of ultimate shear strength caused by the window openings.

Specimen CMWO-12 with central door opening could develop higher maximum lateral force than Specimen CMWO-07. Specimen CMWO-14 with eccentric door opening could not develop higher maximum lateral force than Specimen CMWO-07 in negative loading.

In the specimens with central window opening, Specimens CMWO-06 and CMWO-08 are different each other in the arrangement of the horizontal extra RC element. In Specimen CMWO-06, since the horizontal extra element tied up two parts of the wall located at right and left of the opening, the two parts of the wall developed their ultimate shear strengths at close deformation range. This results in high maximum lateral force and rapid deterioration in lateral load carrying capacity after developing the maximum lateral force.

4.4. Prediction of Ultimate Shear Strength

The ultimate shear strength, Q_{su}, is determined in accordance with the upper bound theorem, where four types of failure conditions given in Table 4.2 were taken into account. The failure conditions are based on the shear force transfer mechanism composed of compression force of masonry strut and tension forces of extra elements as well as confining columns. Shear strengths determined by the four types of failure conditions can be calculated by Eqns. 4.2a through 4.2d, respectively.

$$Q_{sua} = \nu F_m \frac{tD}{2} \tan\theta_1 \tag{4.2a}$$

$$Q_{sub} = q \tan\theta_1 \tag{4.2b}$$

$$Q_{suc} = a_h \sigma_{hy} + \left(\nu F_m - \frac{2 a_h \sigma_{hy}}{tD \tan\theta_1} \right) \frac{tD}{2} \tan\theta_2 \tag{4.2c}$$

$$Q_{sud} = a_h \sigma_{hy} + \left(\frac{2q}{tD} - \frac{2 a_h \sigma_{hy}}{tD \tan\theta_1} \right) \frac{tD}{2} \tan\theta_2 \tag{4.2d}$$

in which, ν is strength reduction factor of cracked strut, where a factor for concrete given by Eqn. 4.3 (Nielsen (1984)) is employed in the present study, F_m is compressive strength of masonry prism, t is thickness of wall, $\tan\theta$ is given by Eqn. 4.4, q is given by Eqn. 4.5, a_h and σ_{hy} are cross-sectional area and yield strength of the longitudinal steel bars in horizontal extra RC elements.

$$\nu = 0.7 - F_m / 200 \tag{4.3}$$

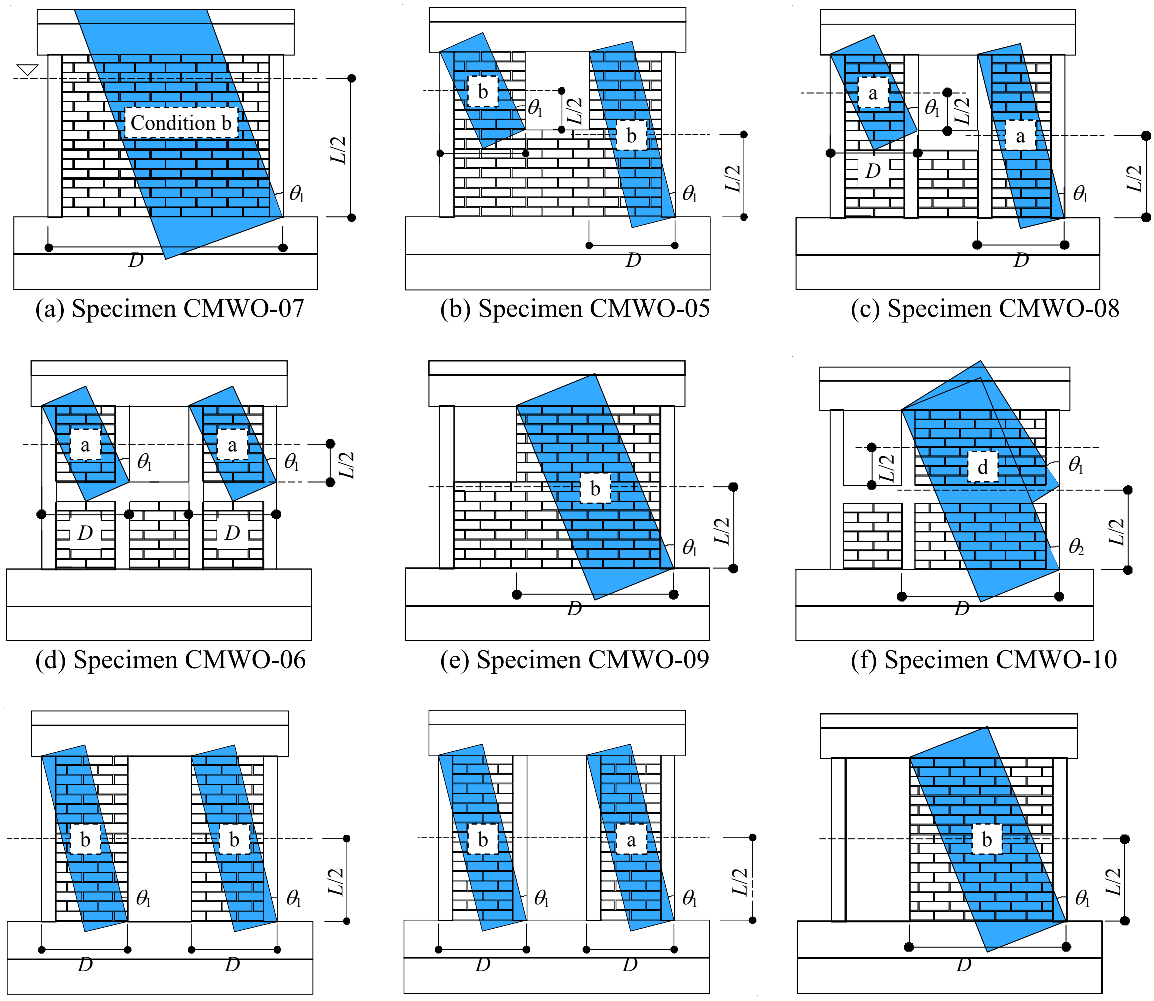
$$\tan\theta = \left(\sqrt{D^2 + L^2} - L\right)\Big/D \tag{4.4}$$

$$q = N + T_u \tag{4.5}$$

in which, D and L are depth and twice the height of inflection point for each part of the wall under consideration, N is axial force taking into account the variation due to lateral force, T_u is tension capacity of the longitudinal steel bars provided in confining columns and vertical extra RC elements. Fig. 4.3 represents size and shape of the strut for the ultimate shear strength, Q_{su} in positive loading.

Table 4.2. Failure conditions for shear strength

Condition	Compression yield corresponding νF_m of masonry strut	Tension yield of confining columns and vertical extra elements	Tension yield of horizontal extra elements	Equation
a	Yes	No	No	4.2a
b	No	Yes	No	4.2b
c	Yes	No	Yes	4.2c
d	No	Yes	Yes	4.2d

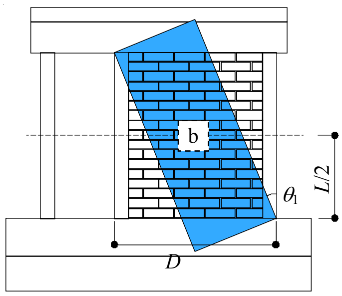


(a) Specimen CMWO-07 (b) Specimen CMWO-05 (c) Specimen CMWO-08

(d) Specimen CMWO-06 (e) Specimen CMWO-09 (f) Specimen CMWO-10

(g) Specimen CMWO-11 (h) Specimen CMWO-12 (i) Specimen CMWO-13

Figure 4.3. Size and shape of masonry strut for ultimate shear strength, Q_{su}



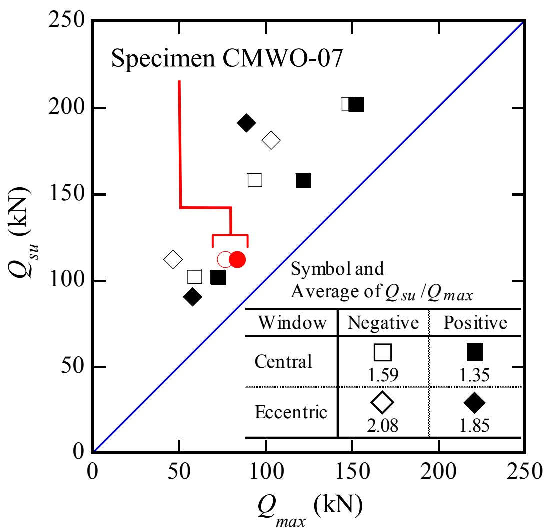
(j) Specimen CMWO-14

Figure 4.3. Size and shape of masonry strut for ultimate shear strength, Q_{su} (continued)

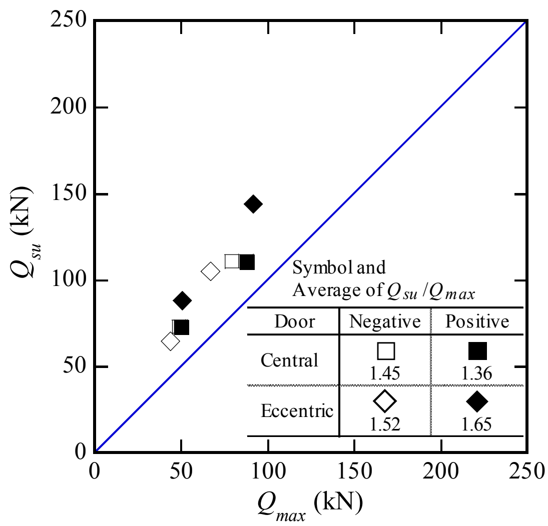
Fig. 4.4 shows relation between theoretical ultimate shear strength, Q_{su}, and experimental maximum lateral force, Q_{max}. Data of Specimen CMWO-07 without any opening is plotted in Fig. 4.4a together with those of test specimens with window openings. It can be seen that Q_{su} is higher than Q_{max} in all test specimens. Averages of the ratio of Q_{su} to Q_{max} for positive and negative loadings are given in the Figure. For the positive loading, the averages are 1.35 and 1.85 in the test specimens with central and eccentric window openings, respectively. Similar results are obtained in the test specimens with door opening. Thus, difference between Q_{su} and Q_{max} for the test specimens with eccentric opening is larger than that for the test specimens with central opening.

It was observed in the experiment that only a few cracks with staircase formation are widened remarkably when the test specimens develop their shear capacity, which is different from the crack pattern of the reinforced concrete. This may cause severe deterioration in compression capacity of the masonry, which is lower than the estimation by Eqn. 4.3.

From the above, modification of Eqns. 4.2 through 4.5 or new idea is required to predict the ultimate shear strength of the CM walls with opening.



(a) Test specimens with window opening



(b) Test specimens with door opening

Figure 4.4. Relations between theoretical ultimate shear strength, Q_{su}, and experimental maximum force, Q_{max}

5. CONCLUSIONS

To investigate effect of the arrangement of extra RC elements on the shear strength of CM walls with openings, an experimental investigation was carried out using ten test specimens with and without opening. Conclusions are summarized as follows.

(1) Most of the test specimens with openings accompanied by the extra RC elements could develop higher lateral load carrying capacity than the specimen without any openings as well as the specimen without any extra RC elements around the opening.

(2) Theoretical ultimate shear strength was calculated based on a shear force transfer model with masonry strut. However, close agreements between the calculations and the test results were not obtained. Modification of the present model or new idea is required to predict the ultimate shear strength of the CM walls with opening.

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