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SHAKING TABLE TEST ON SEISMIC PERFORMANCE OF CONFINED MASONRY WALL

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ABSTRACT

In order to investigate earthquake-resistance performance of confined masonry structure, shaking table test of confined masonry wall was carried out. Specimens are consist of bricks and mortar in walls and two columns of reinforced concrete. Parameters of the specimens are kinds of bricks, reinforcement in walls and columns. In the specimen without reinforcement of walls, shear cracks occur in walls, and the walls are not able to support the weight and collapse. In the specimens with reinforcement in walls, the walls are able to support the overburden pressures without collapse. The reinforcement in walls improves the seismic performance of CM structures. The hysteresis loops in the shaking table test are corresponding to the envelop curves of the relationship between horizontal load and horizontal displacement in the static test. It is demonstrated that the results in the static tests can be utilized in the evaluation of seismic capacity of the confined masonry structures.

KEYWORDS

confined masonry, wall, shaking table test, earthquake resistance, failure mechanism, reinforcement

INTRODUCTION

There are many research activities on investigation seismic behavior of confined masonry structures(Ishibashi *et al.*, 1992). The authors have conducted a series of research activities on an earthquake resistance of confined masonry(CM) structure through a structural testing on CM walls to clarify failure patterns of walls, effects of reinforcements in columns and walls on ultimate capacities(Mizuno *et al.*, 1990, Kato *et al.*, 1992 and Mizuno *et al.*, 1994). It is pointed out that the reinforcements improve the seismic performance of the CM walls. With ductile elements seismic performance of CM structure becomes high. In the paper seismic performance of CM walls is investigated by shaking table test, focussed on failure mechanism and effects of reinforcements in walls on strength and ductility of CM walls.

SPECIMEN AND EXPERIMENTAL PROCEDURE

An apartment building suffered from an earthquake of 1985 in Chile was selected as a prototype of CM structures(Cruz *et al.*, 1988). A wall in the CM house was modelled through a similitude law. Typical similitude ratios are shown in Table 1. The CM wall models are made of the same materials as the prototype(replica model). The ratio of length is set to be 1/2.

Specimens of CM walls are consist of a inner wall and two columns. The inner wall is made of bricks and mortar. The columns are made of reinforced concrete. Figure 1 illustrates a CM wall specimen with Japanese bricks. A width of columns is the same as that of the wall. The ratios of height to width in CM walls with Japanese and Mexican bricks are about 1.24 and 1.12. Steel bar arrangement in columns and wall and brick arrangement with Mexican bricks are drawn in Fig. 2. The concrete columns are reinforced by four longitudinal bars and a number of hoops. The numbers of piled bricks are 19 and 22 according to the height of bricks. The mortar is used in joints between bricks by 10mm in width.

The condition of specimens is shown in Table 2. Three specimens with Japanese bricks and two specimens with Mexican ones were tested. Each specimen is denoted by three characters; that is, IDJ, HDJ, MDJ with Japanese bricks and IDM, KDM with Mexican ones. Parameters considered in the experiments are as follows.

i)Two kinds of bricks: One is a brick which was produced in Japan and the other is in Mexico. The dimensions of Japanese and Mexican bricks are 210x100x60, 230x115x50mm, respectively. The average compressive strength of prism specimens, which were consist of piled five bricks and joint mortar, is 364 and 54 kgf/cm ^{2}, respectively. The mortar is consist of cement and sand with 1:2.5 in volume ratio.

ii)Reinforcement in wall: The reinforcement of steel bars is considered as one of the parameters, in order to investigate the effects of the reinforcement on seismic bearing capacity and failure mechanism of the CM structures. The steel bars were arranged in the horizontal joints. In the case of CM wall with Japanese bricks, two columns are fully connected by steel bars in each joint(MDJ). In the case of CM wall with Mexican bricks, the column and walls are partially connected at corners of the wall(KDM).

iii)Reinforcement in column: The different reinforcement in columns is considered, in order to investigate the effects of the confinement on seismic bearing capacity of the CM structures. The cross-sectional ratio of longitudinal steel bars to columns are set to be 2 and 0.5%(HDJ). The shear reinforcement corresponds to the longitudinal one.

The CM wall specimens and supporting facility shown as in Fig. 3 were installed on the shaking table which is in National Research Institute for Earth Science and Disaster Prevention, Science and Technology Agency. The shaking direction of table is a horizontal one. Two CM walls support a concrete mass and an abutment. The total weight of the concrete and abutment is 28.44 tonf. Through preliminary studies the weight was necessary to collapse the specimens. Overburden pressures to the CM walls with Japanese and Mexican bricks are 13.29 and 10.48 kgf/cm ^{2}, respectively. As the test specimens were installed in center of the abutments, the abutments on and beneath specimens were connected by turnbuckles to prevent the rotation of the concrete mass.

The earthquake waveform(EW component) observed at the Hachinohe harbor in 1968 Tokachi-oki earthquake was adopted as an input motion from the shaking table. The waveform was modified in time interval and amplitude. Considering the similitude ratio of time as shown in Table 1, the time interval is 0.7 times of observed record. And the waveform was filtered by high-pass of 1 Hz. The maximum amplitude of input acceleration was 30 and 1100 cm/s2 for fundamental characteristics of the specimens and for collapse mechanism, respectively.

Measured items are mainly acceleration, displacement and strain. The accelerometers were arranged at the table, upper abutment and top of the concrete mass in vibrating direction. On the upper abutment, the accelerometers were installed for measuring data of the vertical direction and the perpendicular one to the excitation. Horizontal displacement of the CM walls and longitudinal displacement of columns were measured. Strain gauges were attached on the reinforcing bars in columns and walls.

FUNDAMENTAL CHARACTERISTICS OF WALL

Dynamic characteristics of CM walls are discussed by utilizing the response of walls subjected to small earthquake motion excitation. Figure 4 illustrates time histories of acceleration response for the IDJ specimen. The accelerations at the concrete mass, the abutment and the shaking table in the exciting direction and the transverse and vertical ones at the abutment are included in the Figure. Maximum horizontal acceleration at the top of the concrete mass is 1.8 times of that of input motion. The responses of transverse and vertical direction have high frequency component, and maximum acceleration of both directions are 1/3 to 1/4 of that of the exciting direction. The transfer function in frequency domain of the acceleration response at the top of the concrete mass to that of the input motion are drawn in Fig. 5. The transfer function shows resonance at frequency of 8.5 Hz. The average resonant frequencies of CM walls with Japanese and Mexican bricks are 8.37 and 7.16 Hz, respectively. Spring constants derived from the resonant frequency and the weight are 80.3 and 58.7 tonf/cm. Otherwise, horizontal stiffness of CM walls at small displacement in static loading tests is about 230 and 200 tonf/cm.

FAILURE MECHANISM DURING EARTHQUAKE

Dynamic behavior of CM walls during severe earthquakes is discussed with focussing failure mechanism. Table 3 summarizes damage features for occurrence of collapse, cracks in walls and maximum shear strength of walls. The CM walls without any reinforcements in walls collapsed(IDJ, HDJ, IDM). The reinforcements in walls prevent from the collapse(MDJ, KDM). The reinforcements keep the walls from excess displacement and enable the walls to maintain the resistance against overburden pressure.

The time histories of response for the IDJ specimen are drawn in Fig. 6. There are the inertia force of the concrete mass for each wall, the horizontal displacement of the wall and the axial displacement of the column, as well as the input acceleration. When 8 seconds passed, the CM wall collapsed. According to the failure time, there is little difference between the strength of bricks and between the amount of reinforcement in columns. Just before the collapse, the horizontal displacement increased suddenly. With increasing the horizontal displacement, the vertical displacement increased due to damage of columns. The final situation of the wall(IDJ specimen) are shown in Photo. 1. The shear cracks occurred in the wall and then the cracks extended in the ends of columns. At ends of columns, the longitudinal reinforcements were bended by the shear force. The response and the final situation of the wall are drawn in Fig. 7 and Photo. 2 in case of the IDM specimen. The process to collapse of the wall with Mexican bricks is similar to that with Japanese bricks.

In case of little reinforcements in columns(HDJ specimen), it is found after excitation that steel bars at bottom end of column broke. Due to overturning moment of the concrete mass, repeated compressive and tensile forces exerted the columns. The tensile break of bars resulted in the uplifing phenomena of walls.

The time histories of response for the MDJ specimen are shown in Fig. 8. In the Figure, the inertia force of the concrete mass the horizontal displacement of the wall and the axial displacement of the column, etc. are drawn. There is a little residual horizontal displacement in the wall. The residual drift angle is about 1/500. The axial displacement of the column is very small in compression side. The displacement in tensile side is remarkably large. Figure 9 shows the final crack situation of the MDJ specimen. The cracks occur lower part of the wall. There are diagonal cracks in the wall and bending cracks of the columns. As the MDJ specimen has much reinforcement in the wall, it seems that the shear capacity is increased and the bending failure is remarkable. Figure 10 illustrates the final crack of the KDM specimen. There are diagonal cracks in the wall. Unfortunately there occurred a slip between specimen and abutment occurred during the excitation in case of the KDM specimen.

SHEAR CAPACITY OF WALL

Relationship between horizontal loads and horizontal displacements of all specimens is shown in Fig. 11. The horizontal loads is calculated from inertia force, conditioned that the inertial force of the concrete mass acts on two walls equally. These hysteretic loops drawn are records until 8 to 10 seconds from beginning regardless collapse or not. In case of the MDJ specimen with the reinforcement in the wall, it can be seen that the hysteretic loop is remarkably stable after maximum shear capacity. Energy dissipation due to hysteretic loop is working well. In case of the KDM specimen with the partial reinforcement in the wall, it can be seen that the stiffness of the wall decreases with increasing cracks in the wall.

In the IDJ specimen without any reinforcement in wall, the hysteresis loop is similar to that in the MDJ specimen when the horizontal displacement is not so much. But with increasing the horizontal displacement the energy dissipation suddenly reduces. In the IDM specimen, the shear capacity and stiffness become less with displacement after maximum shear capacity.

Maximum shear stress for each walls is shown in Table 3. The shear stress is dependent on the strength of bricks and the reinforcement in walls. With increasing the strength of bricks and increasing the amount of reinforcement, the shear stress is large. In case of bricks which have a higher strength(IDJ, MDJ), there are little difference with the reinforcement in walls.

Figure 12 compares the dynamic hysteresis loop with the relationship between horizontal load and horizontal displacement in the static tests, in case of Mexican bricks. The hysteresis loop during earthquake is quite similar to the envelop curve in the static test. Also the comparison have done in case of Japanese bricks with reinforcement in walls, as shown in Fig. 13. Although the horizontal displacement in the shaking table test is less than that in the static test. These results are corresponding to each other. It is demonstrated that the results in the static tests can be utilized in the evaluation of seismic capacity of the CM structures.

CONCLUSIONS

The specimens without the reinforcement in walls collapse by shear cracks extending to ends of columns. The specimens with the reinforcement express stable hysteretic characteristics and are able to support the overburden pressures during earthquake. The reinforcement in walls improves the seismic performance of CM structures. Maximum shear stress depends on the strength of bricks and confined elements. The use of bricks with high compressive strength and the reinforcement of confined elements increase the seismic resistance of the confined masonry structures. The results in the static test can be utilized in the evaluation of seismic capacity of the CM structures.

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Table 1 Similitude Ratios

Item	Dimension	Ratio
Length	L	1/2
Mass	M	1/4
Time	T	$1/\sqrt{2}$
Velocity	LT^{-1}	$1/\sqrt{2}$
Acceleration	LT^{-2}	1
Stress	$ML^{-1}T^{-2}$	1
Stiffness	MT^{-2}	1/2

Table 2 Conditions of Test Specimens

Kinds of bricks Dimension (mm)	Name of Specimen	Inner Brick Wall		Columns of Reinforced Concrete		
		Layer Dimension(mm)	Reinforcement (Horiz. Dir.)	Longitudinal (ratio,Pg:%)	Shear (Ratio,Pw:%)	Comp. Strength
Mexican L:230 W:115 H:50	IDM	22 layers W:950 H:1,320 T:115 Strength of Pile Specimen 53.5kgf/cm2	No	4D10 (2.16)	D4-@40 (0.63)	276 (kgf/cm2)
	KDM		Corner 6 Layers D4, L:40cm	4D10 (2.16)	D4-@40 (0.63)	
Japanese L:210 W:100 H:60 (brick for MDJ have dips)	IDJ	19 layers W:870 H:1,330 T:100 Strength of Pile Specimen 364.3kgf/cm2	No	4D8 (1.98)	D4-@40 (0.63)	267 (kgf/cm2)
	HDJ		No	4D4 (0.50)	D3-@45 (0.31)	
	MDJ		Full,19 layers D4,L:100cm	4D8 (1.98)	D4-@40 (0.63)	

Table 3 Summary of Damage Features against Earthquake

Brick	Specimen	Collapse or not	Crack Situation	Max. Shear Stress (kgf/cm2)	Remarks
Mexican	IDM	Collapse after 8 sec.	Diagonal cracks. Cracks extended to columns.	9.27	Buckling at center of column
	KDM	No collapse	Diagonal cracks. Cracks extended to columns. Separation of columns to walls.	11.41	Damage of lower part of columns is slight. Slippage between abut- and CM walls.
Japanese	IDJ	Collapse after 8 sec.	Just before collapse diagonal cracks oc- cured. Cracks ex- tended to columns.	14.34	Horizontal displacement of walls increased sud- dunly and immediately collapsed.
	HDJ	Collapse af- ter 9.5 sec.	Diagonal cracks. Cracks extended to columns. Separation between columns and wall.	12.45	Break of longitudinal bars in columns. Uplift of wall form lower abut- ment
	MDJ	No Collapse	Diagonal-bending cracks in lower part of walls.	14.32	Damage of lower part of column was remarkable.

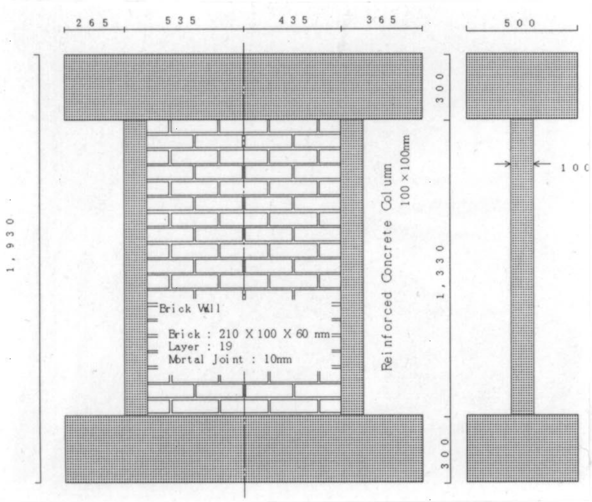
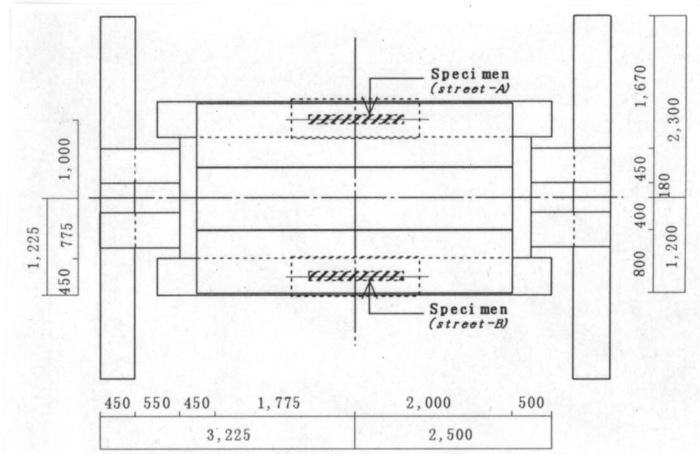


Fig.1 Confined masonry specimen(IDJ)



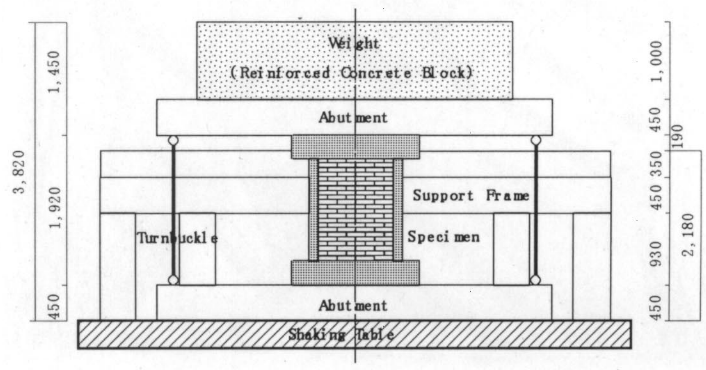


Fig.3 Set up of CM specimen and experiment apparatus

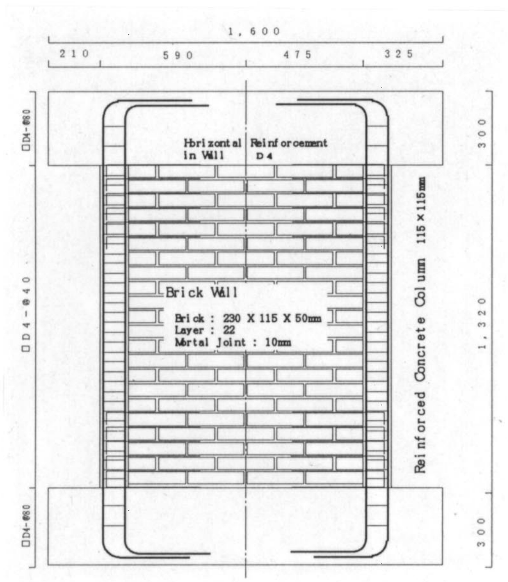


Fig.2 Reinforcement in columns and wall(KDM)

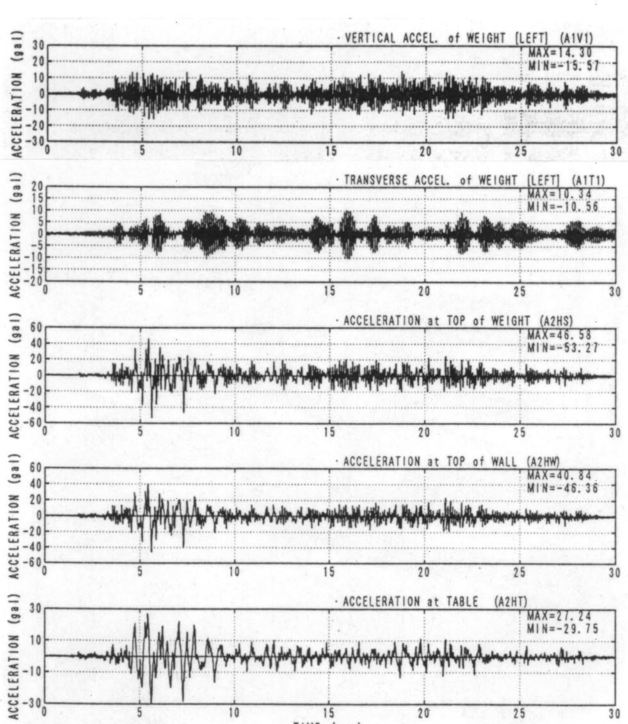


Fig.4 Acceleration response of CM wall subjected to small excitation(IDJ)

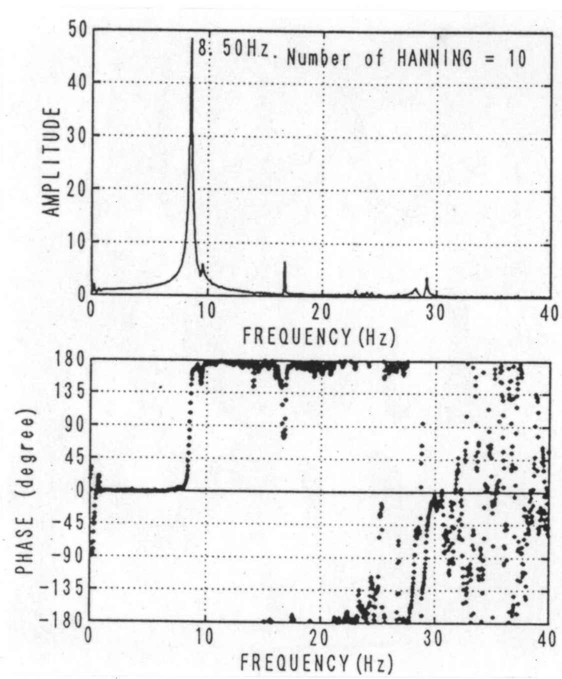


Fig.5 Transfer function of CM wall(IDJ)

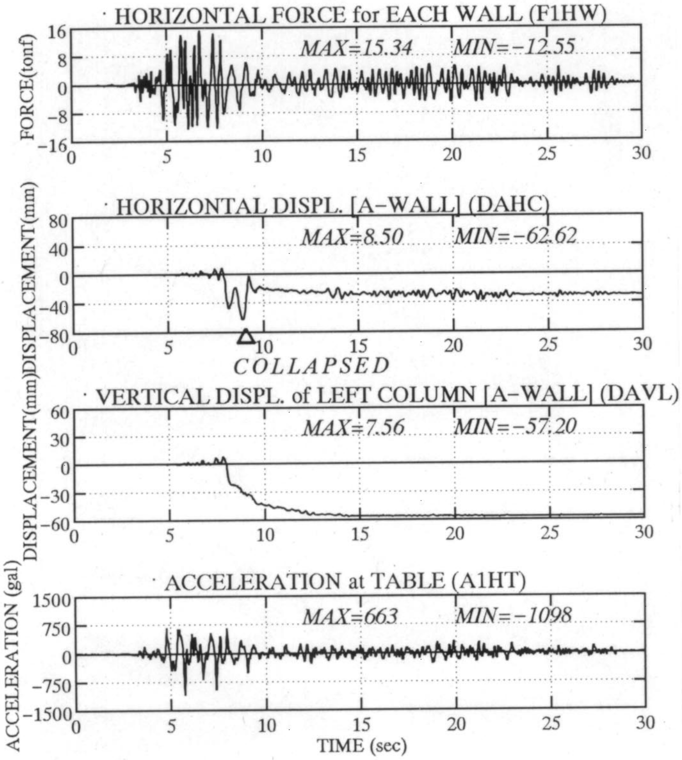


Fig.6 Response of CM wall with Japanese bricks during severe earthquake(IDJ)

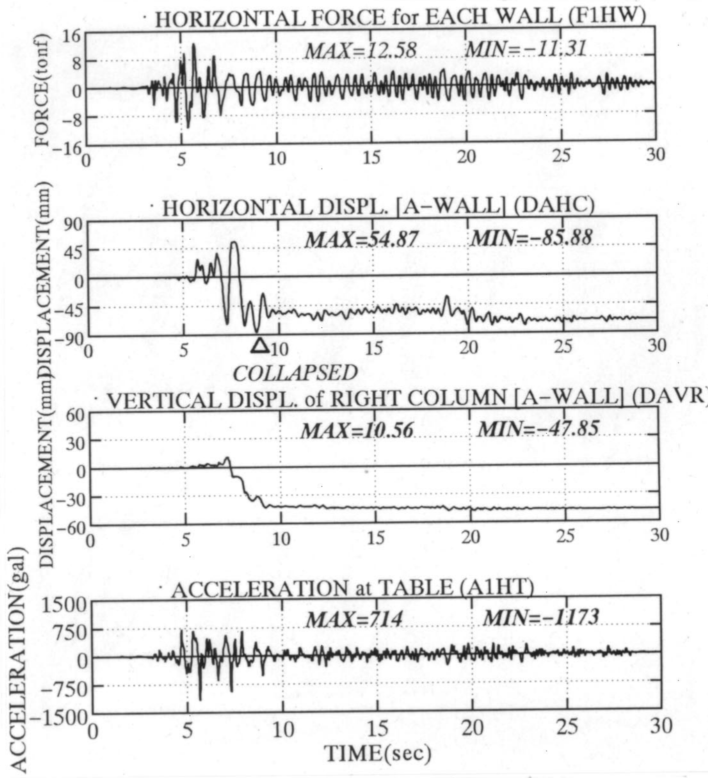


Fig.7 Response of CM wall with Mexican bricks during severe earthquake(IDM)

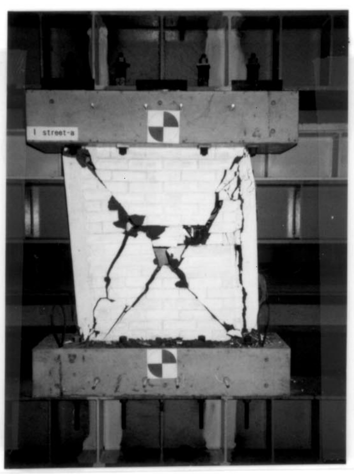


Photo.1 Final Damage of Wall with Japanese Bricks(IDJ)

Photo.2 Final Damage of Wall with Mexican Bricks(IDM)

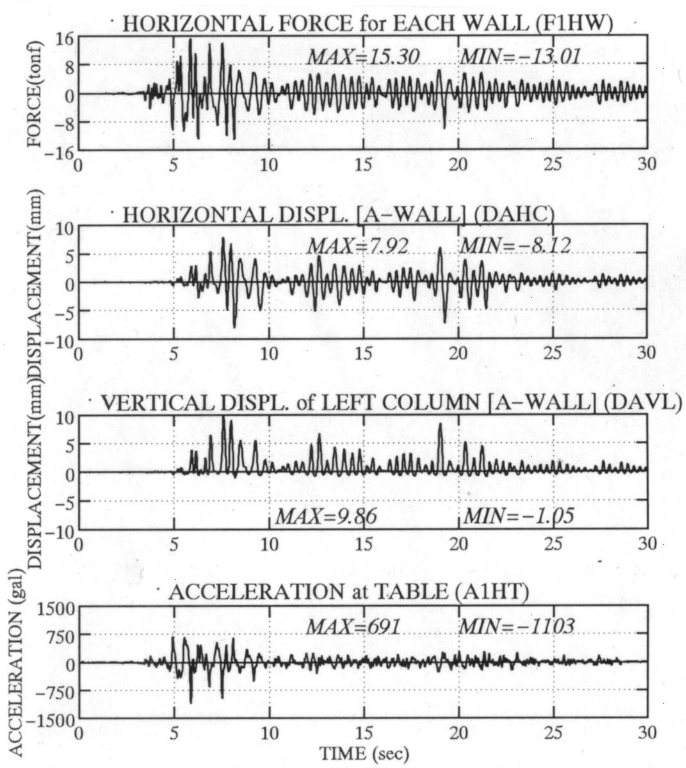


Fig.8 Response of CM wall with wall reinforcement during severe earthquake(MDJ)

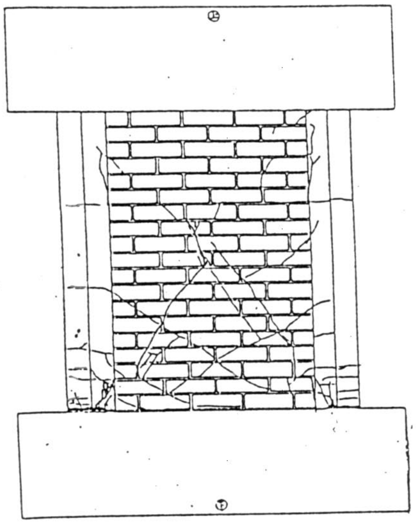


Fig.9 Final cracks of wall with Japanese bricks and reinforcement(MDJ)

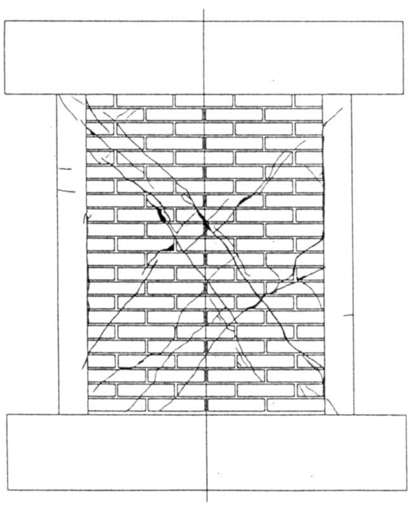
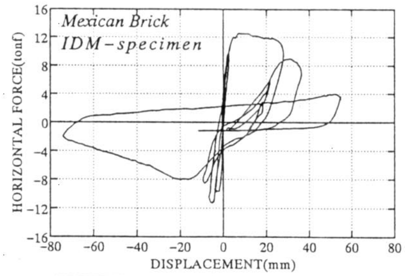
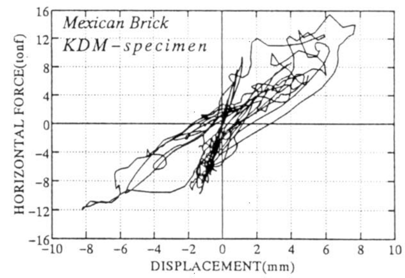
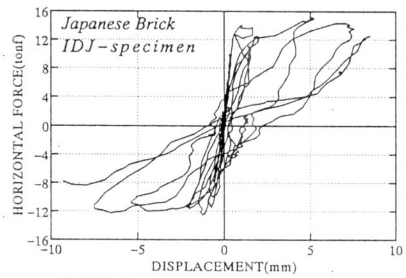
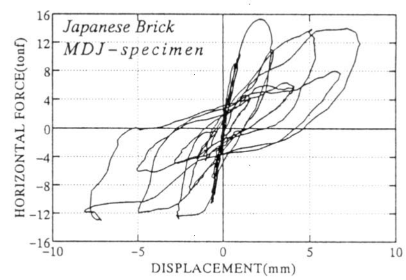


Fig.10 Final cracks of wall with Mexican bricks and reinforcement(KDM)









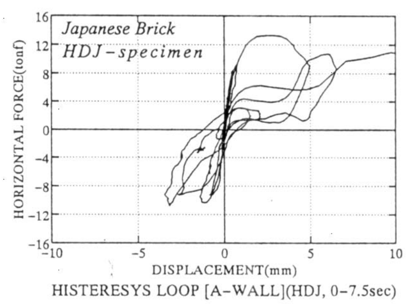


Fig.11 Hysteresis loop of CM walls during severe earthquake

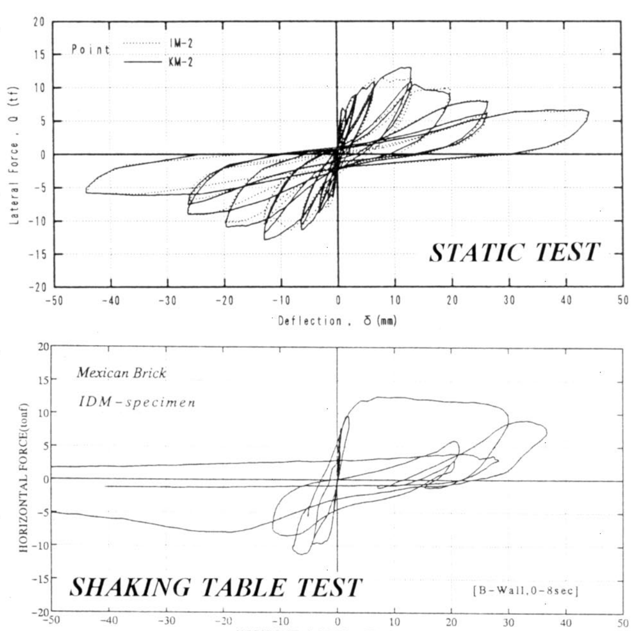


Fig.12 Comparison of load vs. displacement between in shaking table and static tests(KDM)

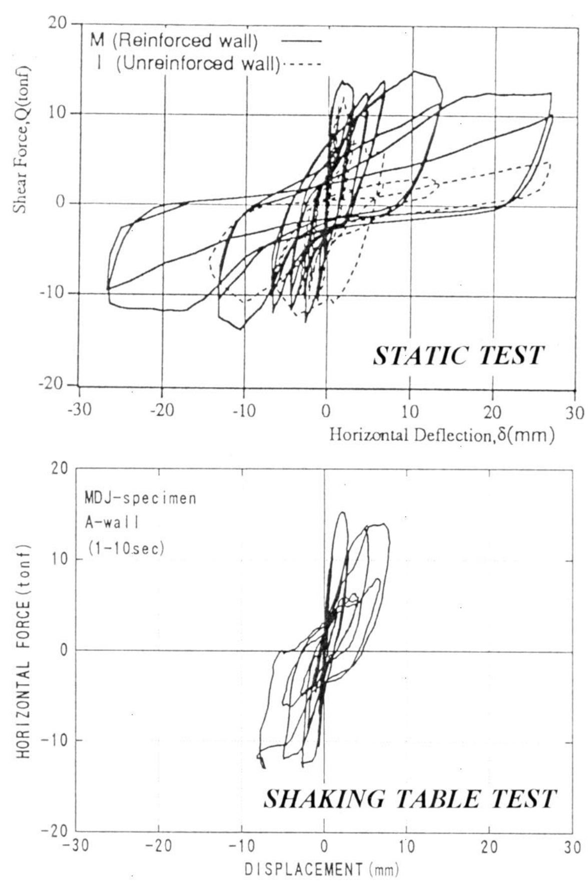


Fig.13 Comparison of load vs. displacement between in shaking table and static tests(MDJ)