Earthquake Resistance of Reinforced Masonry Wall with Lap Joints

Toshiyuki Kubota
Akio Baba
(Japan)

1. PREFACE

Since non-reinforced masonry buildings were greatly damaged by the great Kanto Earthquake Disaster, the regulation for masonry buildings in Japan has been so strict that reinforced concrete beams were required for reinforced masonry buildings and the use of lap joints for vertical reinforcing bars in the masonry wall was not allowed. These severe regulations are disturbing smooth and effective construction of brick masonry.
Against these strict Standards, this paper reports the results of horizontal load tests in plane to clarify the earthquake resistance of masonry walls with lap joints in the vertical reinforcements and anchored directly to the reinforced concrete slab on the top.

2. EXPERIMENTAL METHOD

2. 1. Materials and Specimens

The kind, the size and the strength of masonry units used in this experiments are shown in Table 1.
Table 2. shows the mix proportion and the strength of joint mortar, grout mortar and grout concrete. Table 3. shows the size and the properties of reinforcements.
Specimens were 1800 x 1800 x 150 or 200 mm, with reinforced concrete beam at the bottom for anchoring on an experimental reaction floor and with reinforced concrete a slab or a beam on the top. All vertical reinforcements were lapped at the length of 40 times of their diameter. For masonry units of concrete blocks with comparatively low strength - nos. 5,6,7 & 8 (Table 4) lap parts of bending reinforcements were reinforced with spiral hoops, but no spiral reinforcements in the other specimens.

2. 2. Loading and Measuring Method

There are various methods of loading masonry walls, with merits and demerits for each ones.

To test the cyclic behaviours of masonry walls with lap joints in the vertical reinforcements under lateral load, the Centilever Method to repeat lateral loading on the top which is considered the most destructive method to these specimens, was adopted.
The deformation of walls under lateral load was measured by the displacement gauge of 1/100 or 1/200 mm precision, and lateral displacement and vertical displacement on top, vertical displacement of lap part of bending reinforcement at the edge, lateral displacement of border of masonry wall and reinforced concrete beam at the bottom, and twisting displacement of specimens under lateral load were measured.
The displacement gauges to measure these displacements were set on the stable frame fixed on the reinforced concrete beam at the bottom of a specimen. Therefore the experimental results of lateral displacement on the top are shown as the total of the bending and shearing deformation of masonry wall and border between wall and reinforced concrete beam at the bottom, and the slipping deformation of the same border part. Based on the allowable stress design method, 1 cycle of load equal to average shearing stress of 2.2 kg/ch^2 was given first, and 3 cycles of lateral load to occur lateral displacement of 1/800, 1/400, 1/200 on top followed, in order to gain the results of the strength decline by repeated loads.

3. EXPERIMENTAL RESULTS

3. 1. Load and Deformation Behaviour

The summary of the experimental results are shown in Table 5. The experimental results are reported mainly on the relations between load and deformation, and the fracture mechanism in this paper.
As shown in Fig. 2 and Fig. 3, the relation between load and deformation showed elastic movement under the design load, but non-elastic movement after 1/800 cycle. Besides, as the general tendency, their movements were different in case of plus load and minus load. The ultimate strength under plus load was observed when rotation angle of member was 1/200 (the type with a large quantity of bending reinforcement) or 1/100 (the type with small quantity of bending reinforcement). Under plus loading the specimens showed property of comparatively larger ductility which meant smaller strength decline against large deformation. On the other hand, the ultimate strength under minus loading was observed at the point of smaller deformation than plus loading, as shown in Fig.2.
The strength decline by repeated load was observed in the all walls.
It is considered that there is no strength decline in the elastic range,

but, in the cycle of larger rotation angle of member than 1/800, non-elastic movement was observed, and the strength decline was recognized. Generally, the decline of 90 - 70% against the first cycle at the same deformation was observed.

There was no remarkable tendency of deformation by increasing rotation angle of member, but in case of the rotation angle of member having shearing crack or bond splitting crack in the first cycle, the great strength reduction was observed. On the contrary, in case of no shearing crack or bond splitting crack, the strength reduction was smaller.

The specimen no.3 showed remarkable strength decline after repeated loading compared with other specimens(Fig. 3).

This specimen is composed of two brick wall connected by wall ties and reinforced horizontally and vertically, and grouted in the cavity part. It is distinctive that the bricks and the reinforcements are not connected directly. Grout concrete or mortar was cast at a time after laying masonry units for height of 1800 mm.

If reinforcements slipped out when measuring the vertical displacement of lap part of bending reinforcement at the edge (Fig. 1), it would be measured directly. But such a phenomenon was not observed in any case of loading cycles and wall types.

During loading, bond splitting cracks were observed in some walls, but no discontinuous phenomenon in the vertical displacement was observed before or after the crack, and the ductile relationships of lateral load - lateral displacement on top even after bond splitting crack were gained.

3. 2. Fracture Mechanism

The fracture of walls is characterized by bending cracks in horizontal joints, shearing cracks, bond splitting cracks along vertical reinforcements, or yield of bending reinforcements and shearing reinforcements. The order of damages was different in the kind of specimens, but these damages occured generally by the following order:

(1) Occurence of bending cracks (BC)

(2) Yield of bending reinforcements (BY)

(3) Occurence of shearing cracks (SC)

(4) Yield of shearing reinforcements (SY)

(3) or (4) did not occur in some specimens.

Bond splitting cracks (BSC) along bending reinforcements did not occur in the specimens with spiral reinforcements, but occured in the other specimens. The time of their occurence was between (BC) and (BY), or (BY) and (SC), or after (SC). To examine the efficiency of lap joints, it is important whether they occured after yield of bending reinforcements or before.

Based on the above consideration, specimens were classified as Table 6 according to the order of damages.

As mentioned before, it is considered that brittleness at the deformation curve under minus load is mainly caused by slipping deformation in horizontal joints at the bottom due to incline of the neutral axis toward the compressed side by too little bending reinforcements, making the compressed edge stress from bending moment at the bottom of masonry wall small, and then making friction from the compressed edge stress smaller than shearing force - not related with use of lap joints.

That is to say, also in the wall with spiral reinforcements, the rotation angle of wall to show the largest strength is smaller compared with cases of plus loading as shown in Table 6.

Therefore, as to the general influence of lap joints on the wall damage, it is most important to examine the order of damages under plus load.

As shown in Table 6, the rotation angle at the ultimate strength under plus load is 1/100 in 5. and 7. with little bending reinforcements, and 1/200 in the other specimens, and influence of fracture mechanism on strength feature is small.

Besides, all of the bond splitting cracks occured after yield of bending reinforcements. But, examining the occurence of bond splitting cracks in relation to shearing cracks, it occured after shearing cracks in 2. and 9., and it occured before shearing cracks in 1. and 3. In 4., bond splitting cracks and shearing cracks occured at the same time. 2. and 4. had joint reinforcements, and it was proved that joint reinforcements were more effective than usual horizontal reinforcements to prevent brick from splitting.

9. had a large hollow to arrange vertical reinforcements, and was easy to cast grout concrete, and was considered hardly influenced by lap joints alike usual reinforced concrete.

The minus load caused slipping fracture at the bottom and showed the general tendency that the final rotation angle of member was small, and their tendency of decline is the essential and inevitable problem for the fracture mechanism of masonry walls which combine different materials.

First, specimens with spiral reinforcements showed the tendency to show the ultimate strength at larger rotation angle of member compared with ones without spiral reinforcements, and ones without spiral reinforcements occured bond splitting cracks in the early stage except 9., and it is characterized that bond splitting cracks occured before yield of bending reinforcements. That means 9. is effective to make the damage by lap joints small, as mentioned before.

The point to be noticed is that bond splitting cracks under minus load is caused by the direct splitting action by large slip at the bottom besides influence of pull-out strength, and different from usual push and pull. This is explained qualitatively by the measuring result of slide at the bottom that bending and shearing deformation of wall under minus cycles are very small, and cracks occured before yield of bending reinforcements. It is considered possible to realize early occurence of bond splitting cracks if slipping fracture under minus load is prevented by means of reinforcement or execution to reduce slide at the bottom, consequently to delay or not to occur bond splitting cracks.

On the other hand, as the masonry wall shows sufficiently ductile behaviour under plus load, it is possible to make more ductile the load - deformation relation under minus loading by various means to prevent slip at the bottom.

4. CONCLUSIONS AND OUTSTANDING PROBLEMS

The following points are concluded from the above experimental results and their consideration.

(1) Some specimens showed largely different P - δ relation under plus load and minus load. It is considered not because of lap joints, but due to slip after spreading of bending cracks through the whole section.

(2) The strength reduction by repeated loads was remarkable in the cycle occuring shearing cracks and bond splitting cracks, and the general strength reduction ratio was 70 - 90% of the first cycle. This tendency was also remarkable in the double wall with horizontal reinforcements in the grouted cavity part.

(3) No harmful non-elastic movements which are considreed due to the use of lap joints were observed.

(4) Some of the lap parts of bending reinforcements occured bond splitting cracks. The wall with spiral reinforcements did not occur these damages, and the wall with joint reinforcements or with sufficiently large cavity for reinforcements showed the tendency to delay the occurence of these damages.

The following points are proposed from the above considerations.

(1) The border of different materials such as masonry and reinforced concrete is apt to occur slide phenomena. It is important to devise suitable increase of bending reinforcements, arrangement of slide-preventing reinforcements, improved grouting or improved design of the details of the wall bottom to prevent slide phenomena.

(2) Spiral reinforcements are effective to effectuate lap joints. It is also important to devise joint reinforcements and cavity parts.

The above mentioned conclusions were gained qualitatively, and more detailed results will be gained from minute theoretical examination in future.

Table 1 Masonry Units Used in Experiments

Notation	Kind of Unit	Size L x T x H (mm)	Compressive Strength* (kg/cm^2)
A	Hollow Clay Brick	290 x 150 x 90	465
B	Perforated Clay Brick	215 x 75 x 65	613
C	Hollow Concrete Block 1	390 x 150 x 190	186
D	Hollow Concrete Block 2	390 x 150 x 190	202

(Note) Based on actual net area

Table 2 Joint Mortar and Grout Used in Experiments

Notation	Mortar	Mix Proportion C : W : S : G (by weight)	Compressive Strength (kg/cm^2)
JM	Joint Mortar	1 : 0.50 : 2.50 : 0	402
GM	Grout Mortar	1 : 0.45 : 2.25 : 0 ∿25	490
CC	Grout Concrete	1 : 0.65 : 2.68 : 2.96	242

Table 3 Reinforcements Used in Experiments

Notation	Kind of Reinforcement	Tensil Strength (kg/cm^2)	
		Yield Point	Ultimate Point
ϕ6	Round Bar 6mm	3542	4738
D10	Deformed Bar 10mm	3856	5567
D13	Deformed Bar 13mm	3827	5622
D16	Deformed Bar 16mm	3708	5675
D19	Deformed Bar 19mm	3700	5744

Table 4 Specimens Used in Experiments

No	Type of Wall	Thickness of Wall (mm)	Kind of Masonry Unit	Grout	Reinforcement			Remarks
					Vertical		Horizontal (Shearing)	
					Bending	Shearing		
1	Solid Clay Brick Wall	150	A	GM	4 x D19	4 x D13	2 x D13	Slab Non-Spiraled
2	Solid Clay Brick Wall	150	A	GM	4 x D19	4 x D13	10 x ϕ6	Slab Non-Spiraled
3	Double Wythe Grouted Core Clay Brick Wall	200	B	GM	4 x D19	3 x D13	2 x D13	Slab Non-Spiraled
4	Double Wythe Grouted Core Clay Brick Wall	200	B	GM	4 x D19	3 x D13	10 x ϕ6	Slab Non-Spiraled
5	Solid Concrete Block Wall	150	C	GM	2 x D16	3 x D10	2 x D10	Beam Spiraled
6	Solid Concrete Block Wall	150	C	GM	4 x D19	3 x D13	2 x D13	Slab Spiraled
7	Solid Concrete Block Wall	150	C	GM	2 x D16	3 x D10	10 x ϕ6	Slab Spiraled
8	Solid Concrete Block Wall	150	C	GM	4 x D19	3 x D13	10 x ϕ6	Slab Spiraled
9	Solid Concrete Block Wall	150	D	GC	4 x D19	4 x D13	2 x D13	Slab Non-Spiraled

(Note) Joint Mortar JM in Every Case

Table 5 Experimental Results (2)

No	Loading Directions	Bending Crack		Bond Spiliting Crack		Shearing Crack		Yield Point of Bar for Bending		Yield Point of Horizontal Bar (1)		Ultimate		
		Load (ton)	Average shear stress (kg/cm^2)	Load (ton)	Average shear stress (kg/cm^2)	Load (ton)	Average shear stress (kg/cm^2)	Load (ton)	Average shear stress (kg/cm^2)	Load (ton)	Average shear stress (kg/cm^2)	Load (ton)	Average shear stress (kg/cm^2)	Lateral Drift
1	+	8.0	3.0	15.0	5.6	18.0	6.7	12.0	4.4	20.9	7.7	27.5	10.2	1/200
	−	4.0	1.5	10.0	3.7	16.0	6.0	16.0	6.0	−	−	17.6	6.5	1/400
2	+	10.0	3.7	22.0	8.2	20.0	7.4	19.6	7.3	−	−	25.4	9.4	1/200
	−	10.0	3.7	10.0	3.7	19.0	7.0	−	−	−	−	23.7	8.8	1/200
3	+	8.0	2.2	19.0	5.3	22.0	6.1	16.0	4.4	−	−	25.6	7.1	1/200
	−	8.0	2.2	18.0	5.0	−	−	18.0	5.0	−	−	19.7	5.5	1/800
4	+	10.0	2.8	21.7	6.0	21.7	6.0	12.0	3.3	24.4	6.8	25.9	7.2	1/200
	−	10.0	2.8	10.0	2.8	−	−	15.9	4.4	−	−	15.9	4.4	1/800
5	+	3.0	1.1	−	−	10.1	3.7	10.2	3.8	−	−	12.8	4.7	1/100
	−	2.0	0.7	−	−	10.0	3.7	10.0	3.7	−	−	11.0	4.1	1/100
6	+	4.0	1.5	−	−	19.0	7.0	18.0	6.7	−	−	21.3	7.9	1/200
	−	3.0	1.1	−	−	12.9	4.8	−	−	−	−	16.4	6.1	1/400
7	+	8.0	2.9	−	−	10.3	3.8	10.2	3.8	−	−	14.5	5.4	1/100
	−	2.0	0.7	−	−	9.4	3.5	9.0	3.3	−	−	10.3	3.8	1/400
8	+	6.0	2.2	−	−	11.2	4.2	20.7	7.7	−	−	24.3	9.0	1/200
	−	5.0	1.9	−	−	12.4	4.6	−	−	−	−	21.5	8.0	1/400
9	+	7.0	2.6	27.0	10.0	20.0	7.4	18.9	7.0	−	−	27.6	10.0	1/200
	−	10.0	3.7	15.0	5.6	−	−	10.0	3.7	−	−	16.9	6.3	1/800

(Note) (1) Yielding of Vertical Shearing Reinforcements not Measured.

Table 6 Classification of Fracture Mechanism of Wall Specimens

Classification			Specimen (Lateral Drift at Ultimate) Loading Direction +	Specimen (Lateral Drift at Ultimate) Loading Direction −	Remarks
Without Bond Splitting Crack		BC → BY → SC → SY	5(1/100), 6(1/200)	5(1/100), 6(1/400)	With Spirals
		BC → BY → SC	7(1/100), 8(1/200)	7(1/400), 8(1/400)	
With Bond Splitting Crack	After By	BC → BY → BSC → SC → SY	1(1/200), 4(1/200)		Without Spirals
		BC → BY → SC → BSC	2(1/200), 9(1/200)		
		BC → BY → BSC → SC	3(1/200)		
		BC → BY → BSC		9(1/800)	
	Before By	BC → BSC → BY SC		1(1/400), 2(1/200)	
		BC → BSC → BY		3(1/800), 4(1/800)	

(Note) BC; Bending Crack, SC; Shearing Crack, BSC; Bond Splitting Crack

BY; Yielding of Bar against Bending, SY; Yielding of Bar against Shearing

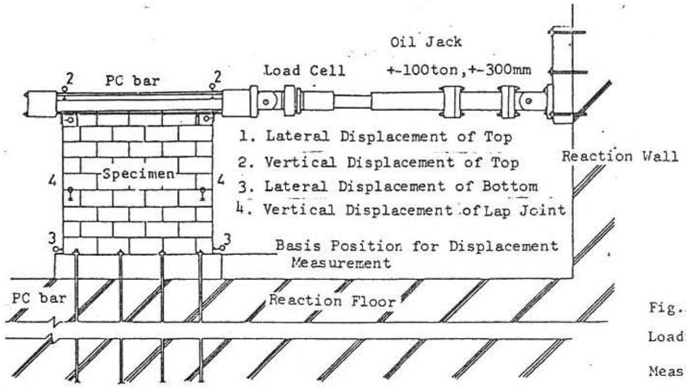

Fig.1
Loading and
Measuring Divices

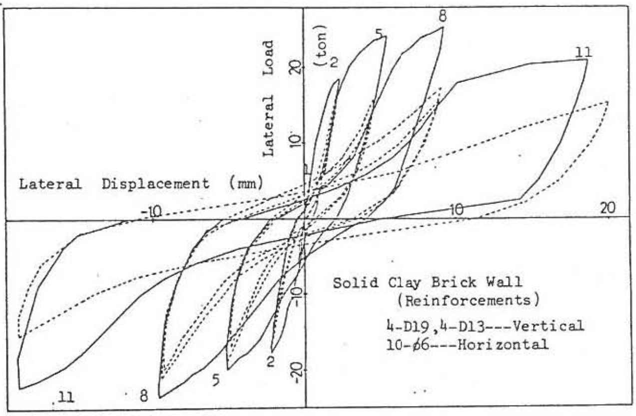

Fig.2
Typical Hysteresis
(No.2 Solid Clay
Brick Wall)

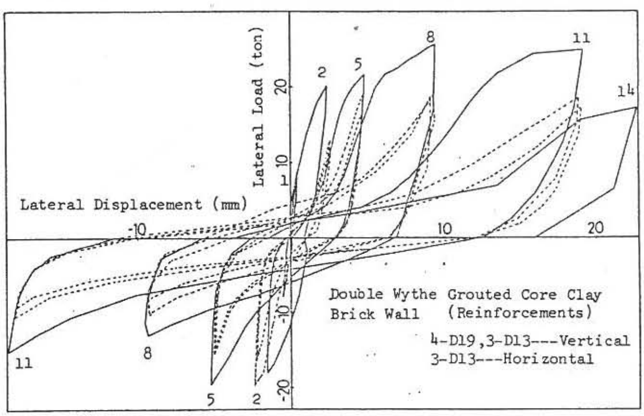

Fig.3
Typical Hysteresis
(No.3 Double Wythe
Grouted Core
Clay Brick Wall)

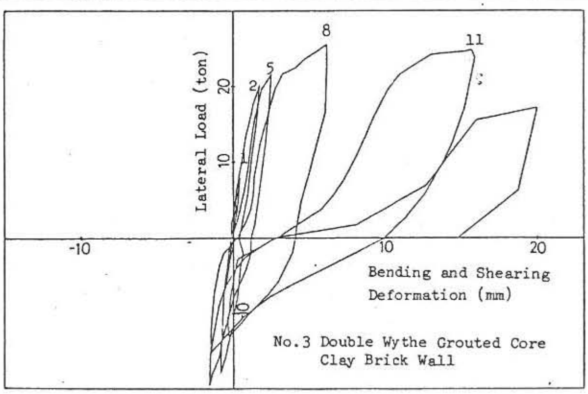

Fig.4
Bending and Shearing
Hysteresis (No.3 Double
Wythe Grouted Core
Clay Brick Wall)

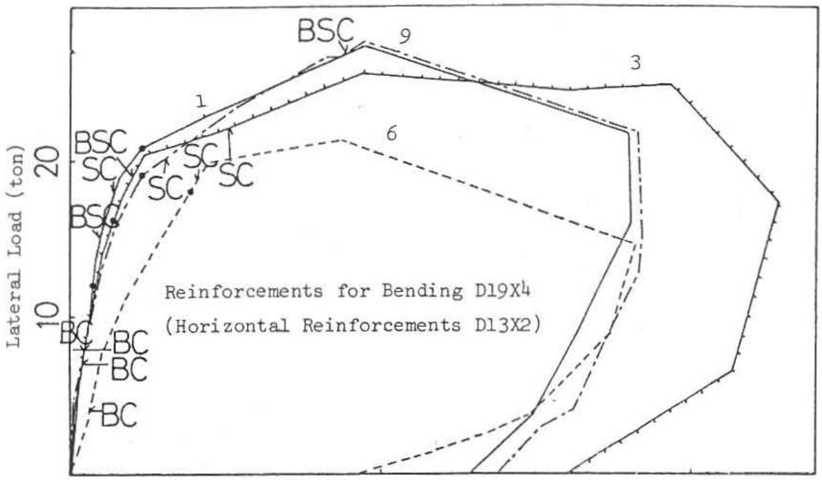

Fig.5 Hysteresis Envelope (Part. 1)

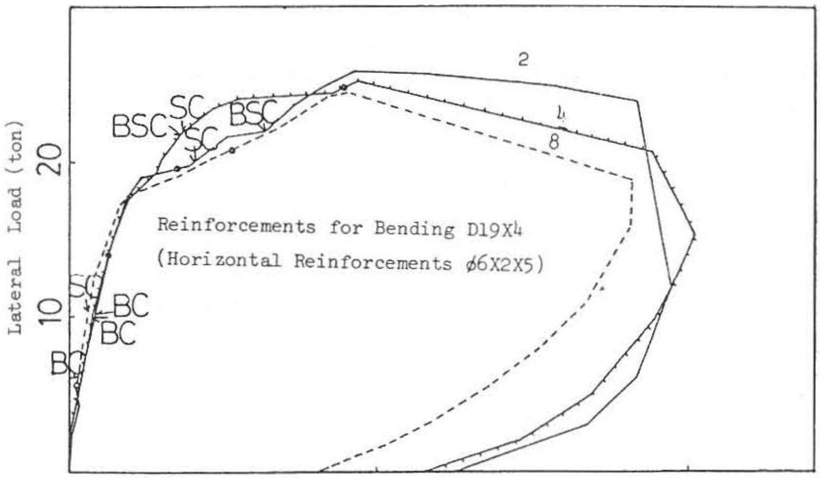

Fig.6 Hysteresis Envelope (Part. 2)

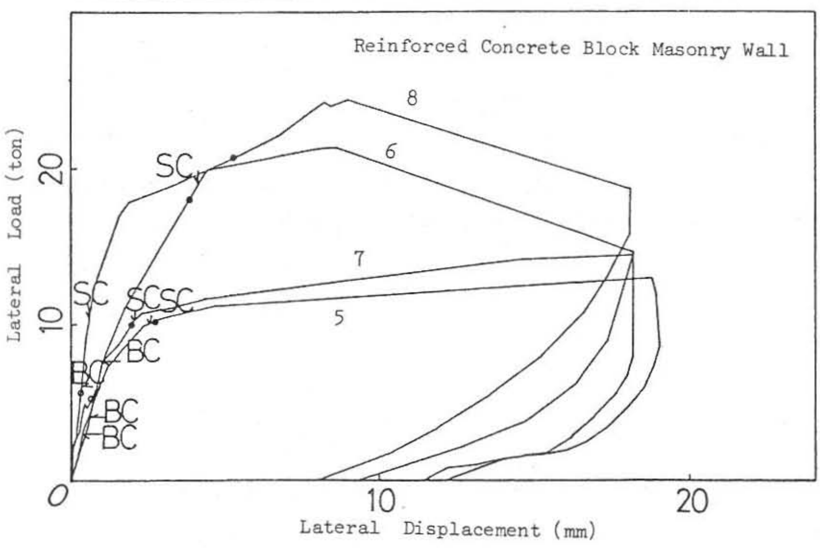

Fig.7 Hysteresis Envelope (Part. 3)