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EXPERIMENTAL STUDY ON SEISMIC PERFORMANCE OF REINFORCED MASONRY WALLS

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SUMMARY

It is important to estimate the strength and the deformation capacity of walls in design of reinforced masonry (RM) buildings against earthquake motions. Twenty-two RM wall specimens were tested under a double curvature deformation with constant axial stress. Factors which is considered to be effective on the strength and deformation capacity of the RM walls, such as axial stress, reinforcement detail, and etc., is verified. And it is clarified that the diagonal compressive strain of the wall has a strong relationships with the deformation capacity of the wall.

INTRODUCTION

Research on RM building structures is being carried out under U.S.-Japan Coordinated Earthquake Research Program. The final objective of Japanese side research is to construct RM buildings up to five stories. In design of RM buildings, it is important to estimate the strength and the deformation capacity of the walls which are one of the most important elements of RM building structure against earthquake motions. Twenty-two wall specimens were tested under a double curvature deformation to represent the stress condition due to earthquake motions. Main objective of this test is to evaluate the effect of axial stress, shear span ratio, amount of shear reinforcement, joint method of reinforcing bar, spiral reinforcement at the compressive toe of the wall, and transverse wall on the seismic behavior of the walls. In this paper, the effects of the factors, mentioned above, on the seismic performance of the walls are described and the deformation capacity is discussed with focusing on the diagonal compressive strain of the wall.

SPECIMEN AND TESTING METHOD

Twenty-two specimens were fourteen concrete block walls, five clay block walls, and three reinforced concrete walls, and those were eighteen "I" shaped walls, three "T" shaped walls, and one "+" shaped wall. Figure 1 shows the specimen WSR1. Outline, dimensions, and material properties of the specimens are listed in Table 1. The lateral loading method producing a double curvature deformation mode under the constant axial stress was selected for this test in order to obtain basic informations on the seismic behaviors of the walls. The setup of loading system and the specimen are shown in Fig.2. The shapes of the concrete block unit and clay block unit are illustrated in Fig.3.

TEST RESULTS

Shear stresses (τ) and drift angles (R) of each specimen at the occurrence of the flexural crack and the shear crack and at the maximum strength, etc. are tabulated in Table 2. The effect of each factor on the strength and the deformation capacity are summarized as follows;

Axial Stress (WF1,WS4,WSN1,WSN2) WF1(axial stress was 5kg/cm^2) yielded in flexure at R=0.002radian, reached the maximum strength at R=0.004radian, and the deterioration of strength was small until R=0.01radian. WF4, WSN1, and WSN2 (axial stress was 20kg/cm^2 and over) failed in shear, reached the maximum strength at R=0.002radian, and the strength decreased to 80 % of the maximum strength at R=0.004radian. The maximum shear stress increased with increase of the axial stress.

Shear Span Ratio (WS1,WS4,WS7,WSR1,WSR4,WSR7) The specimens which shear span ratios were less than 0.8 (WS1,WS4,WSR1,WSR4) reached the maximum strength at R=0.002 radian, and after that the deterioration of strength was large. These specimens failed in shear. The specimens which shear span ratios were 1.139 (WS7,WSR7) had been expected to fail in shear. However, These specimens showed the similar deformation characteristics as that of the specimens failed in flexure, and reached the maximum strength at R=0.0075radian, and the deterioration of strength of WS7 was small until R=0.014radian.

Amount of Shear Reinforcement, Spiral Reinforcement, Joint method of Reinforcing bar (WF1,WF2,WFL1,WFLM,WFJ1,WFJ2,WFR1,WFR2) These specimens were designed to fail in flexure. These factors had little effect on the flexural strength of the specimen. However, increase of the amount of shear reinforcement and the spiral reinforcement around the flexural reinforcing bars at the compressive toe of the wall gave better deformation capacity to the specimens.

Transverse Wall (WS4,WF1,WTT1,WTT2,WTC1) The specimens with the transverse wall showed the larger maximum strength and better deformation capacity than those of the specimens which had the same dimensions and details without the transverse wall.

Ratio of Calculated Shear Strength to Calculated Flexural Strength Figure 4 shows the relationships between τsucal/τmucal and τmax/τsucal or τmax/τmucal of the specimens. Figure 5 shows the relationships between the ratio of τsucal/τmucal and the drift angle at τmax and the 80% of τmax.

τmax: maximum shear stress

$$\tau_{mucal} = 2\left\{0.9\, a_t\, \sigma_y\, d + 0.4\, a_w\, \sigma_{wy} D + 0.5\, ND\left(1 - \frac{N}{BDFm}\right)\right\} h/(B\,D)$$

$$\tau_{sucal} = \left[\left\{\frac{0.053\, Pt^{0.23}\,(Fm+180)}{M/(QD)+0.12} + 2.7\sqrt{\sigma_{wh}\, Pw} + 0.1\,\sigma_o\right\} Bj\right]/(B\,D)$$

$$\text{where: } 1.0 \leq M/(QD) \leq 3.0$$

The specimens which τsucal/τmucal was over 1.0 failed in flexure and τmax/τmucal was approximately 1.0. These specimens reached their maximum strength around R=0.005radian and kept 80% of their maximum strength beyond R=0.01radian. The specimens which τsucal/τmucal was less than 0.7 failed in shear and τmax/τsucal was larger than 1.0 (the maximum value was 1.8 of WS1). These specimens reached their maximum strength around 0.002radian and the strength decreased to 80% of the maximum strength around R=0.004radian.

FAILURE MODE AND DIAGONAL STRAIN

Figure 6 shows the envelope curves of the shear stress vs. drift angle.

Specimens which failed in shear reached maximum strength around R=0.002radian, at the same time the occurrence of diagonal tension crack was observed. After that rapid strength deterioration was observed. In specimens which failed in flexure, flexural yield was observed around R=0.004 - 0.005 radian, diagonal tension crack occurred around R=0.004 - 0.01 radian. and the strength deterioration started at R=0.01radian. Specimens WF2 and WFJ2, which were reinforced with heavy horizontal shear reinforcement (Pw=0.667%: a value of cross sectional area of one set of the shear reinforcement divided by the thickness of wall and the spacing of the shear reinforcements), did not experience the diagonal tension crack, and no strength deterioration occurred in spite of large deformation (more than R=0.02radian). Stable limit deformations for RM walls of flexural failure type were around R=0.01radian, and for RM walls of shear failure type were around R=0.0025radian. The diagonal tension crack is a fatal phenomenon for stable limit deformation. Thus, the relationships between the diagonal strain, the diagonal tension crack, and the stable limit of deformation has to be discussed.

DISCUSSION ON DIAGONAL COMPRESSIVE STRAIN

Figure 7 shows the envelope curve of the relationships between shear stress and diagonal compressive strain (εd). εd represents the nominal compressive strain along the diagonal direction of the wall. The white circle represents the point of diagonal crack initiation, and the black circle shows the stable limit point. Diagonal crack of both shear and flexural type specimens occurred in the region of 500 micro strain of εd. The strength deterioration of the specimens which failed in shear started in the region of 700 - 1000 micro strain of εd. While, the specimens which failed in flexure showed the strength deterioration in the εd region of 2000 - 2500 micro strain.

It is presumed based on the characteristics of εd that the failure processes of RM wall were as follows;

1) Specimens of Shear Failure Type
   a)The strength increased up to εd=500 micro strain.
   b)In the εd region of 700 - 1000 micro strain, the diagonal crack width became large and the strength deteriorated.
2) Specimens of Flexural Failure Type
   a)After flexural yielding, diagonal crack occurred in the εd region of 500 micro strain.
   b)There were two types of failure modes. One lost its strength in the εd region of 700 - 1000 micro strain, and the other kept its strength up to εd region of 2000 - 2500 micro strain. The former one is considered as a type of shear failure (diagonal tension failure) and the latter one is diagonal compression failure.

Figure 8 (Ref.4) shows a result of the prism compression tests. In this figure, the relationships between the compressive strength, compressive strain, and the volumetric strain are depicted. Maximum strength was provided at the compressive strain from 2000 to 2500 micro strain. Volumetric strain, however, became larger at the compressive strain of 1000 micro strain. It was also reported in reference 4 that some cracks occurred in the prism specimens around 500 micro strain. It is believed that these prism compression test results can explain every point of the diagonal compressive strain vs. deformation curves.

CONCLUSIONS

Conclusions obtained from the test and discussions are as follows;

1) For the specimens failed in shear, the maximum shear strength increased and the deformation capacity decreased with increase of axial stress and also with decrease of shear span ratio.

2) For the specimens failed in flexure, the deformation capacity increased with increase of the amount of shear reinforcement and also by the confinement of the compression toe by the spiral reinforcement.
3) The deformation capacity was not affected by the joint of reinforcing bars.
4) Transverse wall made the strength and the deformation capacity increase.
5) The specimens, which $\tau_{sucal}/\tau_{mucal}$ was 1.0 and more, failed in flexure. These specimens reached τ_{max} around R=0.005radian and kept 80% of their maximum strength until the drift angle was more than 0.01radian. The equation for the flexural strength could estimate the flexural strength of the specimens accurately.
6) The specimens, which $\tau_{sucal}/\tau_{mucal}$ was 0.7 and less, failed in **shear.** These specimens reached τ_{max} around R≈0.002 radian and kept 80% of their τ_{max} until the drift angle was more than 0.004radian. the equation for the shear strength could estimate the shear strength of the specimens conservatively.
7) Strength deterioration occurred in the diagonal compressive strain from 700 to 1000 micro strain for the specimens of shear failure type, and from 2000 to 2500 micro strain for the specimens of flexural failure type, respectively. These strains correspond to the starting strain of volumetric expansion and the strain at maximum prism strength, respectively.

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Table 1 Outline, Dimensions, and Material Properties of Specimens

Name of Specimen	Type of Masonry Unit	Height of Wall h (cm)	Length of Wall l (cm)	Thickness of Wall t (cm)	Shear Span Ratio M/QD	Axial Stress σ_0 (kg/cm^2)	Horizontal Reinf.Bar Pwh (%)	Vertical Reinf.Bar Pwv (%)	Flexural Reinf.Bar At (cm^2)	Note	Prism Compressive Strength Fm' (kg/cm^2)	Yield Stress of Reinf.Bar σ_y (kg/cm^2) D-19	D-16
WS1	Concrete Block	180	199	19	0.452	20	D13@400 (0.167)	D16@400 (0.262)	2D-19 (5.74)	Shear Failure	183	3948	3791
WS4			119		0.756								
WS7			79		1.139						233		
WSN1			119		0.756	40					183		
WSN2						60					233		
WF1						5				Flexural Failure		3542	3289
WF2							2D13@200						
WFL1							D13@400 (0.167)				219		
WFLM												3438	
WFJ1												3542	
WFJ2							2D13@200						
WSR1	Clay Brick		199		0.452	20	D13@400 (0.167)	D16@400 (0.349)		Shear Failure	273	3948	3708
WSR4		170	109		0.780						257		3791
WSR7		180	79		1.139						218		
WFR1		170	109		0.780	5				Flexural Failure	268	3542	3289
WFR2							2D13@200						
WTT1	Concrete Block	180	119		0.756	20	D13@400	D16@400 (0.262)		Trans. Wall	251	3948	3791
WTT2							2D13@200						
WTC1						5	D16@400 (0.167)					3542	3289
WSRC	Reinf. Concrete					20				Reinf. Concrete	273	3948	3791
WFRC						5					254	3542	3289
WTRC						20					252	3948	3791

note: WFL1 has lap joints of reinforcing bar at the bottom of wall.
WFLM has mechanical joints of reinforcing bar at the bottom of wall.
WFJ1 and WFJ2 have spiral reinforcing bars at top and bottom of wall.

Table 2 Shear Stress, Drift Angle, and Failure Type obtained from Tests

Name of Specimen	Flexural Crack		Shear Crack		Ultimate Strength		0.8×Ultimate Strength	Type of Failure	$\tau_{su\,cal}/\tau_{mu\,cal}$
	Shear (kg/cm^2)	Drift Angle (10^{-3}radian)	Shear (kg/cm^2)	Drift Angle (10^{-3}radian)	Shear (kg/cm^2)	Drift Angle (10^{-3}radian)	Drift Angle (10^{-3}radian)		
WS1	6.6	0.12	25.1	1.13	30.7	1.72	2.22	S	0.44
WS4	7.1	0.19	17.7	1.06	20.8	1.91	3.78	S	0.70
WS7	5.2	0.21	15.4	2.28	20.2	9.36	13.50	F	0.81
WSN1	9.6	0.19	17.6	0.52	26.0	2.11	4.78	S	0.56
WSN2	-	-	19.8	0.75	26.3	2.41	4.56	S	0.50
WF1	5.0	0.15	12.6	1.40	16.3	4.14	12.63	F	1.08
WF2	2.5	0.07	10.9	1.04	16.9	10.38	over 20.5	F	1.39
WFL1	3.6	0.12	10.2	1.10	16.2	5.09	16.00	F	1.06
WFLM	5.2	0.30	12.3	1.57	16.9	5.04	18.56	F	1.06
WFJ1	5.9	0.24	14.0	1.47	16.0	5.07	over 20.0	F	1.06
WFJ2	5.0	0.20	11.8	1.94	15.1	19.61	over 19.6	F	1.39
WSR1	4.9	0.09	30.3	1.89	31.3	2.01	3.75	S	0.44
WSR4	9.4	0.22	20.2	1.13	23.6	2.51	6.63	S	0.72
WSR7	7.3	0.26	17.7	4.55	19.6	6.81	7.00	S	0.86
WFR1	3.0	0.06	15.1	1.78	17.0	4.93	7.68	F+S	1.09
WFR2	3.6	0.12	13.5	1.19	17.3	4.96	10.94	F	1.41
WTT1	4.4	0.12	18.4	0.98	26.1	3.46	6.63	F+S	0.61
WTT2	5.4	0.15	12.0	0.44	37.3	7.74	over 9.3	S	0.76
WTC1	2.1	0.05	18.8	1.46	23.1	4.12	11.75	S+F	0.87
WSRC	12.7	0.44	17.4	0.93	23.3	1.99	5.28	S	0.74
WFRC	4.4	0.12	14.5	1.52	17.7	9.48	17.75	F	1.12
WTRC	5.0	0.17	23.7	2.07	24.5	4.49	23.06	F	0.61

Failure Type F: Flexural Failure S: Shear Failure

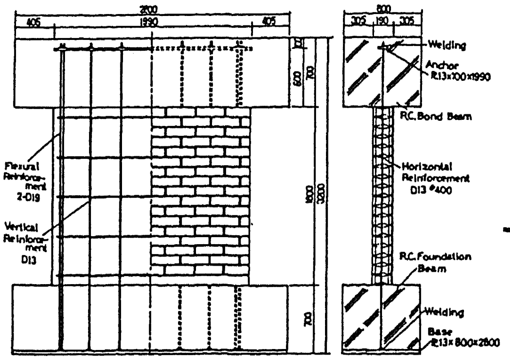

Fig.1 Outline of Specimen (WSR1)

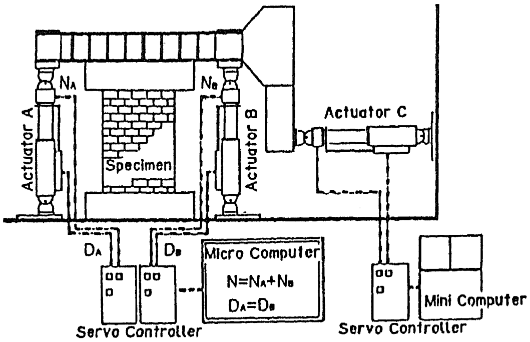

Fig.2 Loading System

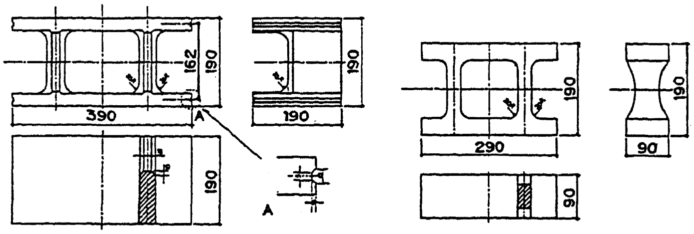

Fig.3 Concrete BLock Unit and Clay Block Unit

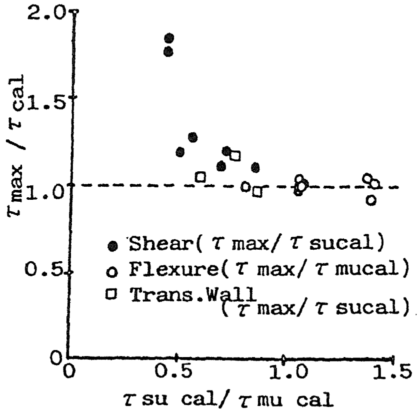

Fig.4 Relationships of τmax/τcal vs. τsucal/τmucal

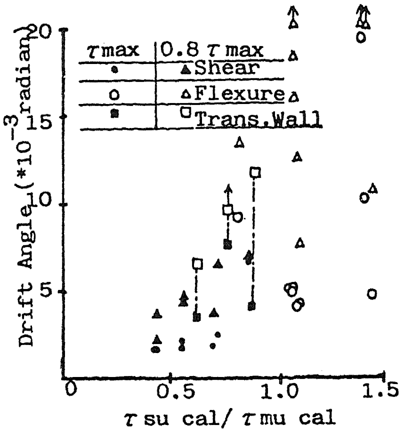

Fig.5 Relationships of Drift Angle vs. τsucal/τmucal

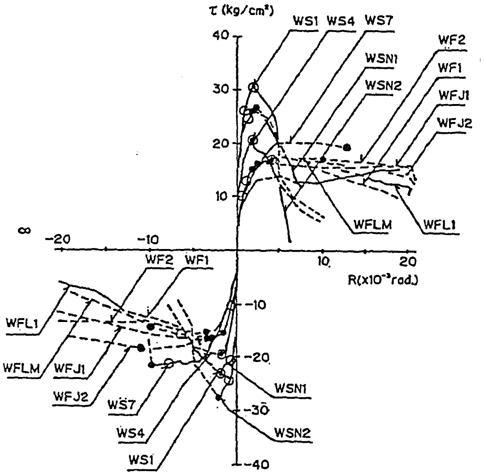

Fig.6 Relationships of Horizontal Load vs. Drift Angle

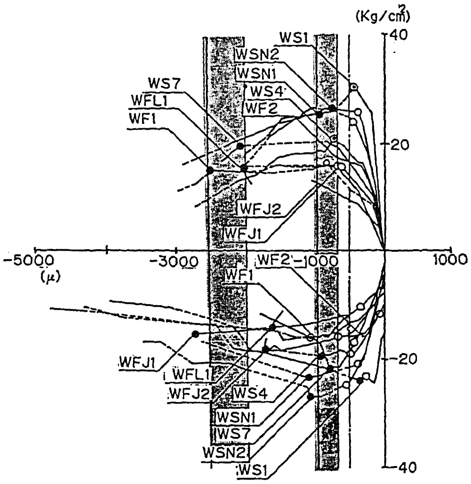

Fig.7 Relationships of Horizontal Load vs. Diagonal Strains

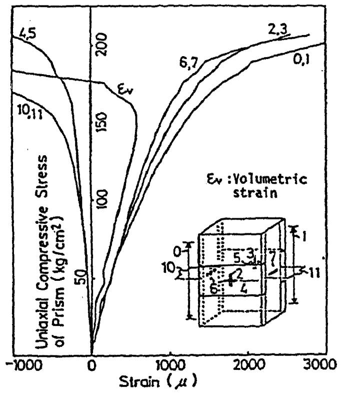

Fig.8 Prism Compression Test Results (Ref.4)