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INELASTIC BEHAVIOR OF FRAMED SHEAR WALL GOVERNED BY SLIP FAILURE OF WALL PANEL

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SUMMARY

The object of this paper is to clarify the behavior of framed shear walls governed by slip failure of wall panel in connection with the restricting effect of surrounding and adjacent frame. Experiment of six frames with an isolated shear wall is performed. To evaluate the behavior of shear wall filled in frame, an analytical method is proposed. Comparing tested results with analytical ones, analytical method proposed by the author is thought to be applicable for predicting the inelastic behavior of frame with shear walls.

INTRODUCTION

Since Tokachi-Oki Earthquake in 1968, not only the strength of building but its ductility has been required and avoidance of shear failure has been needed in earthquake resistant shear walls. Consequently, slip failure type design has come to be adopted as desirable failure pattern of earthquake resistant walls, in which not surrounding frame but wall panel alone is failed in shear. Under these background, there are many studies (Ref.1 and 2) about slip failure of an isolated shear wall, but few ones about slip failure of shear walls filled in frame. Considering from the standpoint that the slip failure is effected by the restraint not only of surrounding frame but also of adjacent one, it is important to evaluate the characteristic of shear walls in connection with the adjacent frame in plane. Therefore, this paper is concerned with the relationship between the shear wall and frames in case of shear failure of wall, especially slip failure of wall panel, from experiments and analysis.

EXPERIMENTS

Outline of Experiments Experiments are devided into series I and II. Specimens of series I are intended to be failed in slip of wall panel, and specimens of series II, in shear of surrounding frame. Every specimen is three-stories, three-spans reinforced mortar frames with an isolated shear wall (hereafter referred to as " frames with a wall "). The shape and bar arrangement of the specimen (taken the case of 1W-1 as prototype) are shown in Fig.1. Parameters of each specimens are shown in Table 1.

Materials Table 2 gives properties of mortar and wire used in the test.

Method of Experiments Loading equipment is shown in Fig.2. Specimens are subjected to constant axial forces of columns (σ_0=40kg/cm^2) and equal compressive and tensile lateral forces applied simultaneously. Lateral loads at each floors are distributed in inversed triangle type. Loading is the cyclic reverse one controlled by rotation angle at the second story(=$\pm$1,2,4,6,8,10x10^{-3}rad) and afterward, monotonous increasing one till the mechanism of collapse. Hereafter,"load" means the overall shear force at the first story, and "rotation angle", the rotation angle at the second story having a wall.

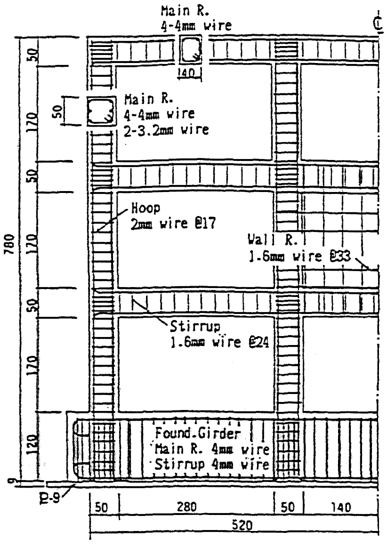


Fig.1 Typical Bar Arrangement (Specimen 1W-1)

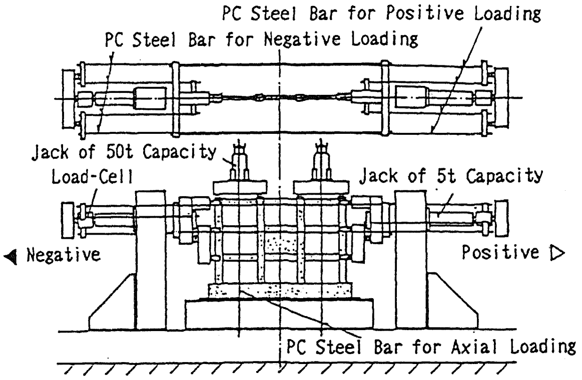


Fig.2 Loading Equipment

Table 1 Parameters of Specimens

Specimen	Column and Boundary Column			Girder			Boundary Girder		Wall Panel	
	Section	Main Rein. Ratio	Shear Rein. Ratio	Section	Main Rein. Ratio	Shear Rein. Ratio	Main Rein. Ratio	Shear Rein. Ratio	Thickness	Wall Rein. Ratio
1W-1	50x50mm^2	2.7% (2-4.0mm) (1-3.2mm)	0.7% (2mm@17)	50x40mm^2	2.6% (2-4.0mm)	0.4% (1.6mm@24)	2.6% (2-4.0mm)	0.4% (1.6mm@24)	6mm	1.0% (1.6mm@33)
1W-2								1.2% (1.6mm@8)		
1W-3							3.8% (3-4.0mm)	0.4% (1.6mm@24)		
1W-4								1.2% (1.6mm@8)		
2W-1							same to girder		10mm	0.6% (1.6mm@33)
2W-2				50x30mm^2	3.4% (4-4.0mm)	0.5% (1.6mm@24)			6mm	1.0% (1.6mm@33)

Table 2 Properties of Materials (unit:kg/cm^2)

	Mortar			Reinforcement							
	Compressive Strength	Tensile Strength	Young's Modulas (x10^5)	4.0mm		3.2mm		2.0mm		1.6mm	
				Yield Point	Tensile Strength	Yield Point	Tensile Strength	Yield Point	Tensile Strength	Yield Point	Tensile Strength
Series I	278	25.2	1.69	1,782	2,985	2,370	3,131	2,910	3,480	2,270	3,280
Series II	266	19.7	1.95	1,700	2,970	2,600	3,510	1,600	3,153	2,030	3,150

TEST RESULTS

Strength and Failure Process Table 3 gives shear cracking load of wall panels and maximum strength, ultimate strength, and failure pattern of frame with a wall. As examples of failure condition, crack pattern of 1W-4 and 2W-1 at ultimate are shown in Fig.3. They are typical examples of slip failure of wall panel and shear failure of surrounding giredrs, respectively. Strength and failure process are mentioned below.

Table 3 Strengths and Failure Pattern

Specimen	Compressive Strength(kg/cm²)	Cracking Load (t)	Maximum Load (t) and Rotation Angle at Maximum ($\times10^{-3}$rad)						Ultimate Load ‡1 (t)		Failure Pattern ‡2	
	σc	ePcr	ePmax	cPmax	Ratio‡3	eRmax	cRmax	Ratio‡4	ePult	Ratio‡5	Experiment	Analysis
1W-1	268	0.54	1.95	1.89	1.03	6.06	6.88	0.88	1.53	0.21	WS,BF	WS,BF
1W-2	273	0.58	2.00	1.89	1.05	6.11	7.07	0.86	1.70	0.15	WS,BF	WS,BF
1W-3	287	0.52	2.28	2.00	1.14	10.09	8.14	1.24	1.72	0.25	WS,BF	WS,BF
1W-4	282	0.50	2.17	2.00	1.09	10.08	8.19	1.23	1.80	0.17	WS,BF	WS,BF
2W-1	265	0.90	2.13	2.10	1.01	5.95	5.04	1.18	1.60	0.25	BS,BF	BS,BF
2W-2	266	0.75	1.89	1.79	1.06	8.00	6.44	1.24	1.51	0.20	BS,WS,BF	BS,WS,BF

Notation σc=cylinder compression strength of mortar, ePcr=cracking load of wall panel, ‡1: ultimate load means the load at mechanism. ‡2: WS=Slip Failure of Wall Panel, BF=flexural yielding at the end of girder, bottom of column at the first story, and top of continuous column at the first story, BS=shear failure of boundary girder. ‡3: Ratio=ePmax/cPmax, ‡4: Ratio=eRmax/cRmax, ‡5: Ratio=(ePmax-ePult)/ePmax.

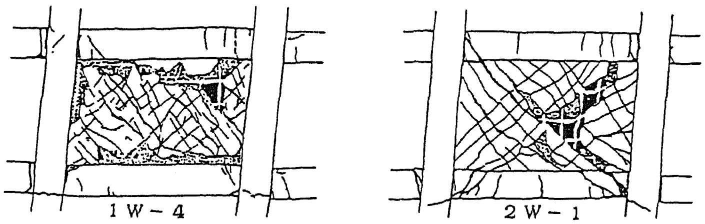

1 W − 4 2 W − 1

Fig.3 Typical Crack Patterns

Each specimen of series I approached the ultimate generally following the next cracking pattern. 1)shear crack of wall panel, 2)flexural crack at the end of surrounding girders, 3)flexural crack at the center of surrounding girders, 4)flexural crack at the bottom of the first story columns, 5)flexural crack at the top of the first story columns, 6)flexural crack at the end of the second story continuous girders, 7)shear crack at surrounding girders, 8)slip failure of wall panel (maximum load here), and 9)hinge mechanism at at the end of girders, the bottom of the first story columns and the top of the first story continuous columns (ultimate load here). No flexural or shear crack of columns was observed except flexural cracks at the bottom of the first story columns and the top of the first story continuous columns. And so, it is said that each specimen approached the ultimate in rather stable mechanism governed by the yielding of girders when the rotation angle was 15×10^{-3}rad. The contribution of the specific parameter, such as shear and main reinforcement ratio of surrounding girders to maximum or ultimate strength is evaluated by examination between each strength shown in Table 3 of two specimens of which parameters are same all except for the specific parameter. From the comparison mentioned above, it may be concluded that when the wall panel fails in slip the shear reinforcement of surrounding girders is not very effective for increase of the maximum strength but effective for prevention of decrease of the ultimate strength and extension of shear crack of surrounding girders. On the other hand, the main reinforcement of surrounding girders is said to be effective for increase of the maximum strength. The effect of shear and main reinforcement of surrounding girders may be explained from the mechanism that surrounding frame plays a part of tension ring for expansion of cracked wall panel.

Crack pattern of series II was similar to one of series I, but it was different that while specimens of series I reached the maximum load at slip failure, 2W-1 reached the one at shear failure of surrounding girders and so did 2W-2 at shear failure of surrounding girders and simultaneous slip failure of wall panel. After maximum load, specimens of series II reached the ultimate for the hinge mechanism at ends of girders, base of the first story columns and top of the first story continuous columns. In 2W-1 with thicker wall than others, surrounding girders failed in shear failure brittly when rotation angle was about 6.0×10^{-3}rad.

In 2W-2 with narrower width of girders than others, wall panel came off a bit just before rotation angle was 8.0×10^{-3}rad. And finally it failed in slip failure of wall panel with shear failure of surrounding girders. Comparing their strength in Table 3, maximum load of 2W-1(2.13t) is greater than one of 2W-2(1.89t), for wall panel of 2W-1 is thicker than one of 2W-2. But the decrease ratio of the ultimate strength to the maximum one of 2W-1(25%) is greater than one of 2W-2(20%).

Displacement and Strain Fig.4 shows envelope curves of load-displacement at each story. All specimens of series I failed in slip failure, and so they show ductile deformation. But, comparing the envelope curve of 1W-4 with one of 1W-1, 1W-2 and 1W-3 in Fig.4 as to the strength just after the maximum load, while the former hardly shows decrease of strength, the latter show it. Rotation angle at maximum load is about 6.0×10^{-3}rad for 1W-1 and 1W-2, where main reinforcement ratio of surrounding girders is comparatively less, and about 10.0×10^{-3}rad for 1W-3 and 1W-4, where one is more.

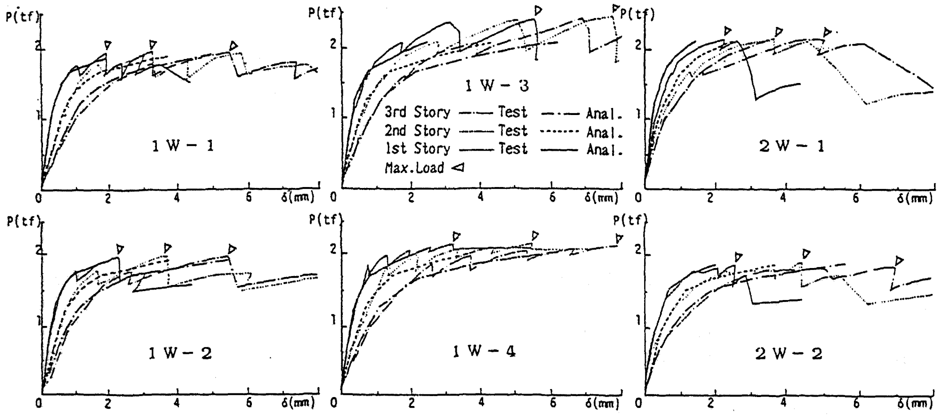


Fig.4 Envelope Curves of Load-Displacement at Each Story

From above point, 1W-4 has most ideal retoring force characteristic. In other words, it can be said that sufficient reinforcement of surrounding girders for shear and flexure(tension) is needed to get satisfactory restoring force characteristic at slip failure of wall panel. In 2W-1 and 2W-2, especially in 2W-1, decrease of strength just after maximum load is observed.

Fig.5 shows load-strain relationship measured by strain gauge sticked on the surface of wall panel of 2W-2. Slope of curve of W2 is gentler than one of W1. And W3 is gentler than W2. The same trend is observed for W1',W2'and W3'.

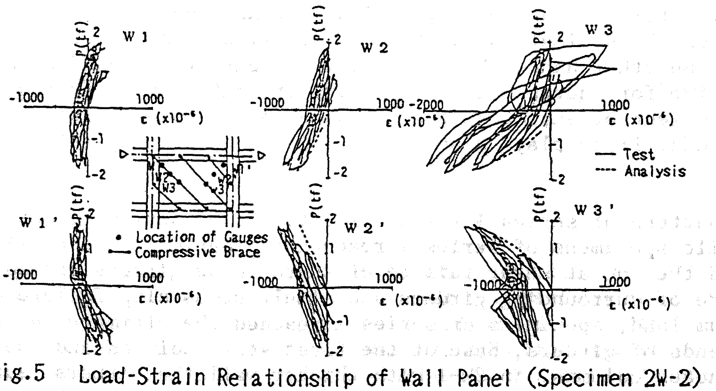


Fig.5 Load-Strain Relationship of Wall Panel (Specimen 2W-2)

Therefore, stress of compressive brace located in the middle of wall panel is concluded to be more than one located near the corner.

ANALYSIS

Outline Load incremental method is adopted to analyse three-stories, three-spans reinforced mortar frame with an isolated wall in elastic and plastic region. Fig.6 shows the analytical model. Conditions used in the analysis such as strength and restoring force characteristic of members are represented below.

Before cracking, a wall panel is substituted for diagonal elastic braces of which the shear stiffness is equivalent to the one of the wall panel. After cracking, a wall panel is replaced with tensile reinforcement brace and compressive mortar brace inclined at 45 degrees to vertical and horizontal direction. Stress-strain curves of tensile and compressive brace are shown in Fig.7(a) and Fig.7 (b), respectively. When the average stress of compressive braces in central 40% of diagonal length of wall panel reaches the slip strength (Ref.3), slip failure is taken to occur.

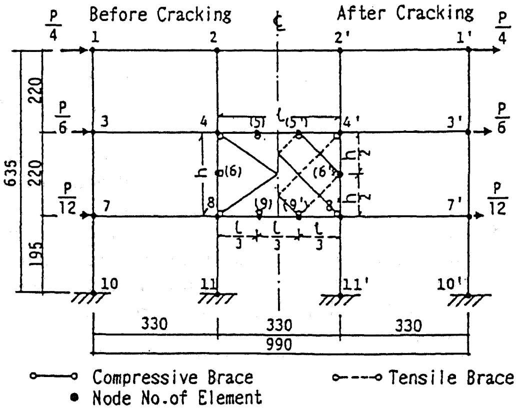
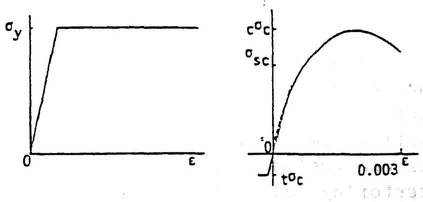


Fig.6 Analytical Model



(a)Reinforcement (b)Mortar

Notation:

σy =yield stress in reinforcement

σsc=stress in compressive brace at slip failure

$c\sigma c$ =compressive strength of mortar

$t\sigma c$ =tensile strength of mortar

Fig.7 Stress-Strain Curves of Reinforcement and Mortar

Considered deformation of frame are ones by bending moment, shear force and axial force for the column and ones by bending moment and shear force for the girder. Restoring force characteristics are tri-linear type for bending moment, perfect elastic for shear force, bi-linear type for tension and perfect elastic for compression.

Analytical Results The strength and rotation angle at the maximum and failure pattern are shown in Table 3. Thick lines in Fig.4 represent load-displacement relationship in each story by analysis in case of positive loading. In Fig.5, continuous lines represent tested results got by strain gauges sticked on wall panel, and dashed lines derived from analysis of the compressive braces corresponded to locations of strain gauges.

As mentioned in above tables and figures, analysed values are found to be very close to the corresponding ones in the test in respect of strength, load-rotation angle relationship, strain, failure patterns. Hence, analytical method presented by the author can be said to be applicable as a method of elasto-plastic analysis for frames with a wall regarding all aspects such as strengths, failure patterns, deformations and strains.

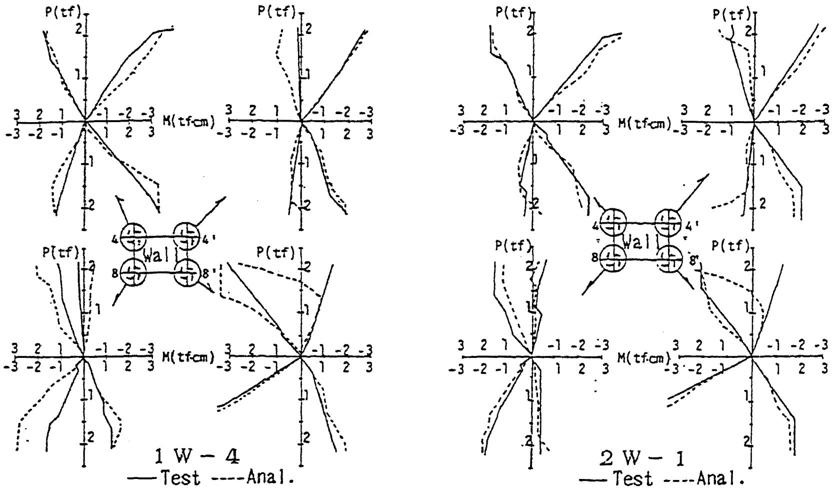


Fig.8 Load-End Moment Relationship

Analytical values of end moment of surrounding frame and continuous girders and columns are compared with tested ones of specimen 1W-4 and 2W-1 relating with load in Fig.8. Analytical values agree well with tested ones except for the bottom moment $M_{8'4'}$ of surrounding column. The deffernce between analytical values and tested ones of the surrounding column is due to the unestablishment of restoring force characteristic during the decrease of strength in case of calculation of the moment from data measured in the test. The more importance is that not only moments of the surrounding frame but also ones of continuous girders and columns are effected by the development of failure of wall. Paradoxically speaking, the restraint due to the adjacent frame is found to play an important role upon the slip failure of wall panel.

CONCLUSIONS

From above, following cocnclusions are obtained.

(1) To expect ductile restoring characteristic by slip failure of wall panel, sufficient reinforcement for shear and tensile forces of surrounding frame are needed.

(2) The analytical method replacing wall panel after cracking with tensile and compressive braces can be said to be reasonable for frames with a wall governed by shear failure evaluating strength, displacement, strain, and failure mode.

(3) It is necessary to study not isolated shear wall but shear wall filled in frame for more accurate study of slip failure.

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