TESTS OF RC SHEAR WALLS SUBJECTED TO BI-AXIAL LOADING

by

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SUMMARY

The tests reported herein are to investigate the behavior of RC shear walls subjected to constant bending out of plane and reversals of in-plane shear and bending. Differences of initial cracks, ultimate strength and deformation, hysteretic loop, crack pattern and mode of failure were observed and examined, comparing with the case of uni-axial loading. Ultimate strength in plane was calculated by a conventional method to divide specimens into compressive and tensile parts due to out-of-plane moment, and found to match well with experimental results.

INTRODUCTION

Damage to RC structures during recent earthquakes[1][2][3] has demonstrated that theoretical and experimental research into the behavior of RC members subjected to two dimensional forces is an urgent subject. The tests of columns subjected to bi-axial bending have been extensively investigated in recent ten years[4][5] But there are few cases of bi-axial shear walls tests[6] so long as the authors know. During an earthquake motion, RC shear walls are subjected to forces in and out of plane, which vary with time. However in the present condition that there are few past experiments concerning shear walls subjected to two directional forces, it was felt desirable to simplify out-of-plane force, to comprehend the influence of this force. For this reason, specimens were tested under the condition of constant out-of-plane bending moment and in-plane load reversals.

TEST SPECIMENS

"Fig. 1" shows dimensions and reinforcement of test specimens with 15cm x 50cm rectangular cross-section. Main reinforcement ratio and shear reinforcement ratio in plane direction are 0.765% and 1.69% respectively, and 1.44% and 0.51% out of plane. Eight specimens with the same dimensions and reinforcement were made, and named as Y0/6, Y1/6, Y2/6-1, Y2/6-2, Y3/6, Y4/6-1, Y4/6-2 and Y6/6 according to the amount of constant out-of-plane moment, i.e. 0/6, 1/6, 2/6, 3/6, 4/6 and 6/6 of yielding moment.

Compressive strength of concrete were 249kg/cm^2 for Y0/6 and Y2/6-1, 327 kg/cm^2 for Y4/6-1 and Y6/6, and 242kg/cm^2 for the other specimens, while yielding strength of main and shear reinforcement were 3710kg/cm^2 for Y0/6, Y2/6-1, Y4/6-1 and Y6/6, and 4040 kg/cm^2 for the others.

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LOADING APPARATUS AND PROGRAM

"Fig. 2" shows test equipment and method of loading in both directions. Out-of-plane moment was first applied through the reacting beam and PC bars, and was kept constant to a prescribed value. The in-plane antisymmetric load was then applied in complete reversals, where loading program was in general as follows: first cycle up to the horizontal displacement angle,R, of 1/250, second cycle to find maximum strength in both directions, and third cycle up to the complete failure of specimens.

TEST RESULTS

In-plane maximum load, mPx, and specified out-of-plane load, mPy, were shown in "table 1". "Fig. 3a to 3c" show load-displacement response in both directions for specimens Y2/6-1, Y4/6-1 and Y6/6.

Specimen Y2/6-1 had many flexural cracks in tension side due to out-of-plane moment. The words 'tension side' and 'compression side' hereafter will refer to those due to out-of-plane moment. Initial shear cracks due to in-plane loading were observed at the load of 20ton in the tension side, and at 30ton in the compression side. The reason for lower shear crack load in the tension side would be the existence of tension stress caused by out-of-plane moment. The initial stiffness was almost similar to the calculated one, showing no influence of out-of-plane moment. The load of 18ton, at which load the stiffness began to decrease from the initial value, the maximum load of 64.5ton and associated displacement of about 0.4cm, observed shear mode of failure, and slip type hysteretic loop were all similar to the specimen Y0/6. Out-of-plane displacement, δy, of Y2/6-1 increased during in-plane loading reversals and incremental value of δy between load step 115 to 123 amounted to 0.25cm in the last cycle. Except for this increase of out-of-plane displacement, the behavior of Y2/6-1 was not affected by the out-of-plane moment.

Y4/6-1 showed initial shear cracks at the in-plane load of 15ton in tension side and at 40ton in compression side. The initial stiffness was a little higher than calculated one, and close to those of Y0/6 and Y2/6-1. Stiffness began to decrease from load of 5ton, considerably lower than the previous specimens. Maximum load was 56.4ton. During in-plane load reversals, specimen became unable to sustain out-of-plane moment due to the progress of crushing in the compression side, resulting in out-of-plane flexural failure. Hysteretic loop due to in-plane load did not show much pinching. Out-of-plane displacement greatly increased during in-plane loading, finally reaching the value of 1.5cm, more than twice the yielding displacement.

Initial cracks of Y6/6 occured at the load of 10ton in tension side and 29ton in compression side. Number of cracks in the compression side was small and their direction was more inclined, i.e. closer to axis of the specimen. Compared with those of Y0/6 or Y2/6-1, which occurred at an angle of 45°, it indicates the effect of strong compressive stress caused by out-of-plane moment. The initial stiffness began to fall from the load of 5ton. Maximum load was 39ton, and associated displacement was 0.25cm, both much smaller than the previous specimens. Hysteretic loop could be deemed as spindle-shaped similar to the hysteresis of shear walls under high compression. At the 45th load step crushing in the compression side was so extensive that the specimen could not sustain specified out-of-plane moment. So during the subsequent loading out-of-plane moment was lowered. Out-of-plane displacement finally reached 2.9cm, five times the yielding displacement. Above three specimens represent typical behaviors of all eight specimens.

"Table 2" shows strain condition of reinforcing steel. For specimens with comparatively low out-of-plane moment, i.e. Y0/6, Y1/6, Y2/6-1 and Y2/6-2, strain of main reinforcement in tension and compression side remained in the elastic range, while shear reinforcement were in general beyond yielding. This indicates that these specimens failed in the in-plane shear. On the other hand, other specimens with high out-of plane moment showed different strain conditions between tension and compression sides. In tension side main and longitudinal shear reinforcement yielded while no reinforcement yielded in compression side. This evidently indicated that these specimens failed in flexure out-of-plane.

Ultimate in-plane strength, cPx, calculated by "Eq. 1", and ultimate

$$cPx = cPxo \times \sqrt{Fc/Fco} \qquad (1)$$

Where cPxo : measured max. load of Y0/6
Fc : compressive strength of concrete
Fco : Fc of Y0/6

out-of-plane strength, cPy, by 'e' function method were shown in "table 1". The normarized interaction between mPx and mPy was shown in "Fig. 4", which indicates that the failure criterion was very close to a circle. It was interesting to note that the failure criterion of shear wall could be represented by a 'circle', in the same way as flexural columns in two directions.

METHOD TO CALCULATE ULTIMATE IN-PLANE STRENGTH

In-plane ultimate strength was calculated by a conventional method to divide a specimen into two parts, tension side and compression side, and to add strength of two sides which were independently obtained as the smaller of the shear and flexure strengths. To determine how the specimen would be divided, the location of neutral axis under out-of-plane moment was studied. It was found to be quite insensitive to the amount of out-of-plane moment. Distance from extreme compression to the neutral axis was between 4.0 and 5.0cm. Hence in the following analysis, divided thickness for compression side, a, was taken to be 4cm, 5cm, or 7.5cm (half the total thickness), and the influence of different value was studied. Strength of divided two sides of the wall were calculated by 'e' function for flexure and by the following

$$c\tau = \phi \cdot c\tau o + 0.1\sigma o \qquad (2)$$

Where $c\tau$: ultimate shear stress
$c\tau o$: ultimate shear stress by Arakawa's Eq.
σo: axial stress (positive in compression)

"Eq. 2" for shear.

As $_c\tau$ of Y0/6 with zero axial stress obtained by Arakawa's Eq.7) was 57.1kg/cm^2, much lower than the measured value of 71.1kg/cm^2 in "table 1", a coefficient ϕ of 1.25 was introduced to compensate for the difference. The axial stress σ_o was determined by dividing the normal force by the respective area, where the normal force was calculated as the quotient of out-of-plane moment by the lever arm. Since the lever arm varies little by the amount of out-of-plane moment, an approximate value of j = 10cm was used.

"Fig. 5" shows strength of tension and compression sides and total strength by adding the two. Strength of compression side was determined by shear and was expressed by straight lines in "Fig. 5". Noting that total strength of Y4/6-1 and Y6/6 was almost carried by compression side, it could be understood that these specimens showed similar hysteretic loops to shear walls subjected to compressive load.

As flexure strength of tension side was chiefly determined by the area of tensile main bar, it was not affected by the thickness of compression side, a. On the other hand the shear strength depends on the area of sections. So the strength of tension side tended to be dictated by shear strength, as the thickness, a, increased. "Fig. 5" shows that shear strength governed in general in range of Py ≦ 3ton for a = 7.5cm, Py ≦ 1.5ton for a = 5.0cm and Py = 0ton for a = 4 cm. From the steel strain shown in "table 2", the boundary of shear and flexure failures was between Py = 3ton and Py = 4.5ton. Further more the total strength as predicted by the above-mentioned method showed the best agreement with test values in "Fig. 5", if a is taken to be 7.5cm. Accordingly a = 7.5cm was thought to be most appropriate in this analysis.

CONCLUSIONS

Eight RC shear wall specimens subjected to bi-axial loading were tested to investigate influence of bi-axial loading. It was noted that out-of-plane moment less than half the yielding moment had no effect on the in-plane behavior of specimens. On the other hand, out-of-plane moment over half the yielding moment had remarkable effect, reducing ultimate in-plane strength and displacement and changing the failure mode to out-of-plane bending failure, and finally changing the shape of hysteretic loop to a spindle shape.

A method to evaluate ultimate in-plane strength was proposed. The wall was divided into tension and compression sides, and the ultimate strength of each side was determined considering flexural and shear strength under axial tension or compression. From the steel strain shown in "table 2", the boundary of in-plane shear failure and out-of-plane flexural failure, Y2/6 and Y3/6, also corresponds to the boundary of elastic and inelastic strain of main bars in tension side. Assuming that this boundary corresponds to that of shear and flexural failures of tension side, thickness a of 7.5cm was found to be most adequate as it gives this boundary at about Py = 3ton in "Fig. 5".

Studies were made of three cases with different thickness in dividing. It was concluded that dividing specimens into two equal thickness was the most suitable way, not only to evaluate ultimate strength, but also to comprehend the failure mode.

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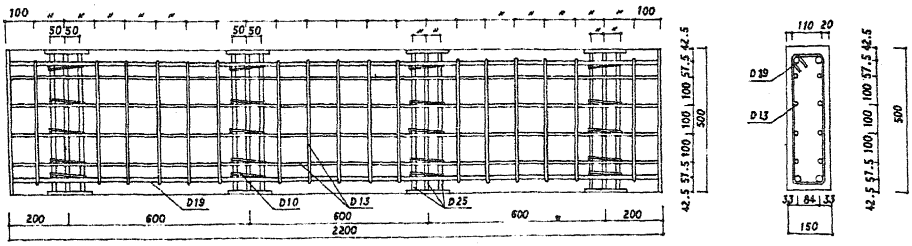


Fig.1 Test Specimen

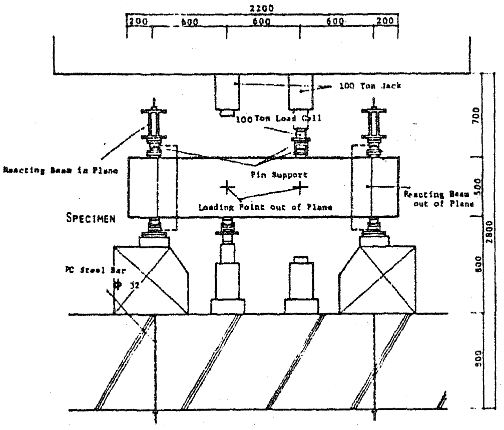


Fig.2a In-plane Loading Apparatus

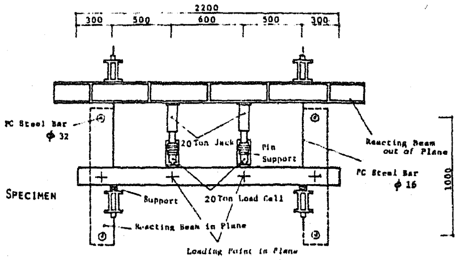


Fig.2b Out-of-Plane Loading Apparatus

Table 1 Measured and Calculated Max. Strength

In-Plane Direction					Out-of-Plane Direction		
Name	mPx (t)	τ (kg/cm²)	cPx (t)	mPx/cPx	mPy (t)	cPy (t)	mPy/cPy
Y0/6	64.0	71.0	64.0	1.00	0.0	7.77	0.00
Y1/6	62.0	68.0	63.1	0.98	1.5	8.52	0.18
Y2/6-1	64.5	71.6	64.0	1.01	3.0	7.77	0.39
Y2/6-2	60.0	66.6	63.1	0.95	3.0	8.52	0.35
Y3/6	55.0	61.1	63.1	0.87	4.5	8.52	0.53
Y4/6-1	56.4	62.6	73.3	0.77	6.0	8.15	0.74
Y4/6-2	47.0	52.2	63.1	0.75	6.0	8.52	0.70
Y6/6	39.9	43.3	73.3	0.53	8.0	8.15	0.98

Note mPy : measured ultimate in-plane strength

τ : ultimate in-plane shear stress

cPx : calculated ultimate strength subjected to only in-plane load

mPy : constant out-of-plane load

cPy : calculated ultimate strength subjected to only out-of-plane load

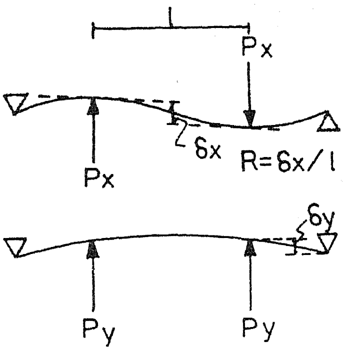
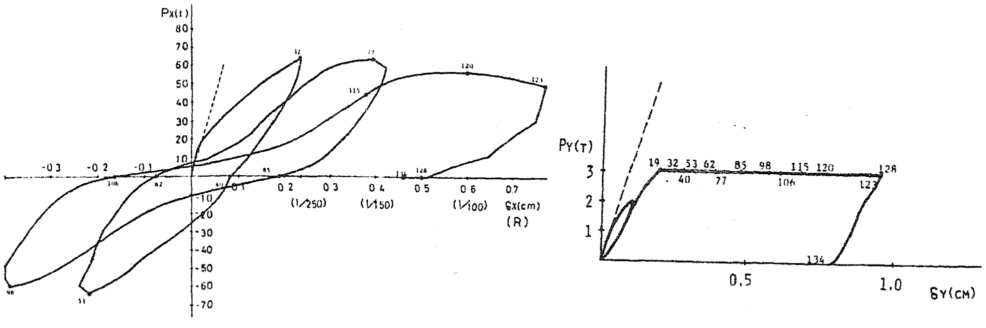


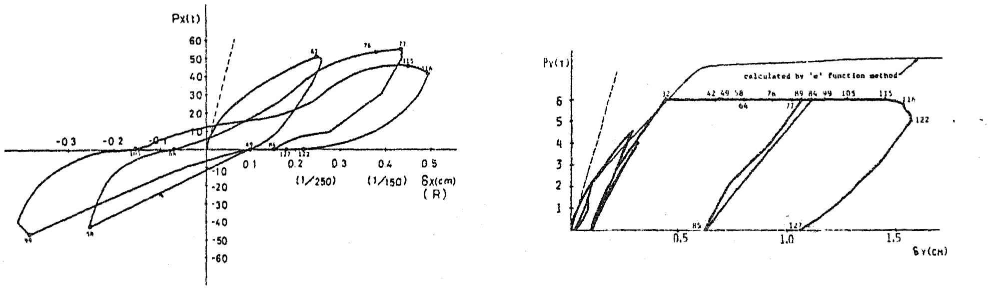
Fig.2c Measurement of Displacements



in-plane

out-of-plane

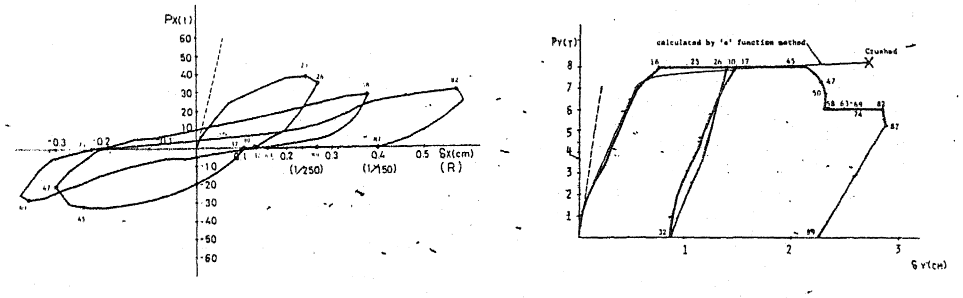
Fig.3a Hysteretic Loop of Y2/6-1



in-plane

out-of-plane

Fig.3b Hysteretic Loop of Y4/6-1



in-plane

out-of-plane

Fig.3c Hysteretic Loop of Y6/6

Table 2 Yielding Condition of Steel

Name	Tensione side			Conpression side			Failure Mode
	M.R.	T.S.R.	L.S.R.	M.R.	T.S.R.	L.S.R.	
Y0/0	X	O	/	X	O	/	Shear in Plane
Y1/6	X	X	O	X	Δ	X	Shear in Plane
Y2/6-1	X	O	/	X	O	/	Shear in Plane
Y2/6-2	X	O	O	X	Δ	X	Shear in Plane
Y3/6	O	X	O	X	X	X	Flexure out of Plane
Y4/6-1	O	X	/	X	X	/	Flexure out of Plane
Y4/6-2	O	X	O	X	X	X	Flexure out of Plane
Y6/6	O	X	/	X	X	/	Flexure out of Plane

Note

O : Almost Yielded

Δ : Partly Yielded

X : Not Yielded

/ : Not Measured

M.R. : Main Reinforcement

T.S.R. : Transverse Shear Reinforcement

L.S.R. : Longitudinal Reinforcement

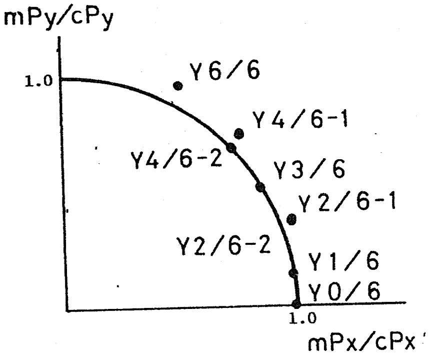


Fig.4 Interaction of Bi-axial Strength

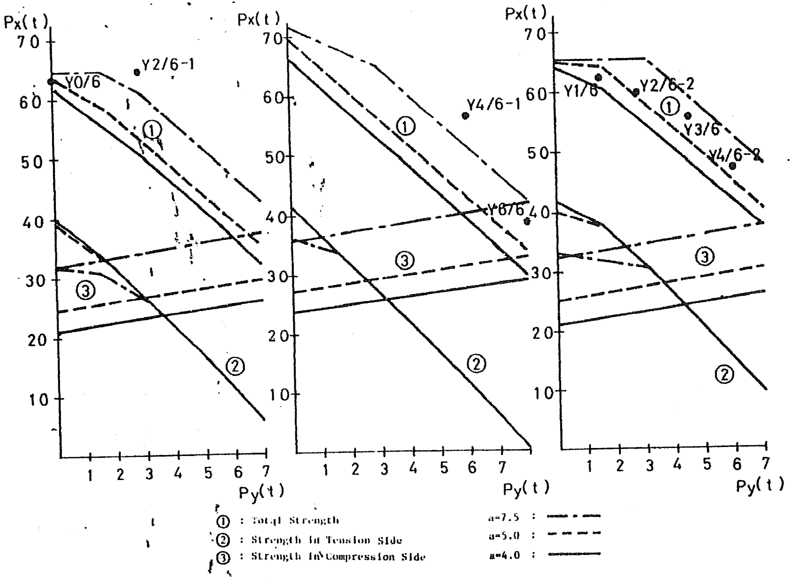


Fig.5 In-Plane Calculated Strength