RESTORING FORCE CHARACTERISTICS OF RC WALLS WITH OPENINGS AND REINFORCING METHODS

by

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SYNOPSIS

A series of tests were reported to investigate the effect of opening on the restoring force characteristics of RC box-type shear walls, and the method of reinforcing the opening. It was shown that the overall effect of opening on the behavior of box-type wall could be reduced if the reinforcement around the opening was arranged effectively, especially against shear failure of short vertical members on both sides of opening.

INTRODUCTION

Nuclear reactor structures utilizing box-type reinforced concrete wall as the major seismic unit inevitably posess openings in the walls. These openings are usually located on one side of the box, thus creating not only the problem of loss of strength and stiffness, but also the problem of torsional effect. In order to investigate the overall influence of opening on the seismic behavior of heavily reinforced box-type shear walls, a series of lateral load tests were conducted at the University of Tokyo. They are reported in this paper in four sections; namely, box-type walls without opening as prototype structures, I-type walls with opening to represent the in-plane behavior, box-type walls with openings on one side of box to represent the out-of-plane behavior, and plate-type walls with opening under simple shear to study the effective method of peripheral reinforcement.

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BOX-TYPE WALLS WITHOUT OPENING

This is the test of box-type RC wall specimens, idealizing nuclear reactor structures, however without openings, in order to serve as the prototype to compare with other specimens with openings. Specimens consisted of B-series of about one-fiftieth scale.$^{1)}$ (83cm x 83cm in plan, 80cm in height, see Fig.1a), and BL-series approximatetly twice as large (Fig.1b).

Major variable was the wall reinforcement ratio. Table 1 summarizes the design outline of each specimen. B-6, B-10, B-16 had vertical and horizontal wall reinforcement of 0.6%, 1.0% and 1.6%, respectively. B-10R had additional vertical reinforcement at corners. BL-10, and BL-16

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correspond to B-10 and B-16, respectively.

Arrows in Fig.1 indicate points of alternate load application by means of hydraulic jacks. The shear span ratio ($M/Q\ell$) was 0.96 for B-series and 0.76 for BL-series. No vertical load was applied.

Fig.2 shows envelope curves of load-deformation relation, and Table 2 shows mode of failure and ultimate strength. Flexural yielding of vertical steel occurred in the flanges of all B-series specimens. B-6 and B-10 subsequently failed in flexure by enlarging crack width in the tension side. B-16 and B-10R failed by simultaneous concrete crushing of compressive flange and slip shear in the web walls. BL-10 and BL-16 failed in the concrete crushing of compression flange and both webs before the flexural yielding of vertical bars in tension flange prevailed over the entire width (Fig.3).

Table 2 also shows the computed flexural and shear strength. Flexural strength was derived from the perfectly plastic moment where entire flange width was taken to be effective. Shear strength was based on the modified PCA equation.[2)3)] Tested strength favorably compares with computed ones for B-6, B-10, BL-10 and BL-16 considering mode of failure. In case of B-16 and B-10R which failed in shear under large deformation after flexural yielding, it appears that the modified PCA equation overestimates the shear strength.

I-TYPE WALLS WITH OPENING

Tests of these specimens were meant to represent the in-plane behavior of web walls with opening. They consisted of I-series and IL-series, shown in Fig.4. They represent one web wall and part of flange walls of box-type, the latter being attached to the web symmetrically with respect to the plane of loading in order to avoid eccentricity. The height of I-series was same as B-series, but the height of IL-type, to be tested under one-point loading, was determined so that the shear span ratio was same as that in the lower story of BL-series specimens.

Four specimens were tested in each series, as shown in Table 3. Wall reinforcement ratio was kept constant to 1.0% for all specimens. Major variable was the location and shape of opening in the web wall. I-series specimens were loaded alternately like box-type specimens, while IL-series were loaded under one-side cyclic loads.

Figs.5 and 6 show envelope curves of load-deflection relation. All specimens followed similar cracking process. Final mode of failure of I-1 and IL-1 without opening was flexural, that is, similar to B-10 and BL-10, except that I-1 failed in flexural compression, possibly due to slightly reduced flange area. All specimens with openings failed in shear at the height of opening, where the horizontal cross-section had minimal area (Figs.7 and 8). I-2 with opening at the lowest position showed more rapid loss of strength after maximum load than I-3 and I-4. IL-4 with scattered openings showed much slower loss of strength than IL-2 and IL-3.

Table 4 compares the tested and computed ultimate strength. Frexural strength was obtained by the same method as box-type, while shear strength was determined as the total of those of short vertical members at both sides of opening, using the same equation as before. They compare quite favorably for both I- and IL-series.

The A.I.J. code provides an equation to evaluate the loss of shear strength due to opening from the peripheral ratio. For specimens tested, predicted ratio of opening vs. non-opening walls was between 0.68 and 0.71 excluding IL-4. Observed ratio was between 0.72 and 0.80, that is slightly higher than the predicted ratio.

BOX-TYPE WALLS WITH OPENING

Two box-type walls, having opening on one side of webs only, were tested to evaluate the out-of-plane effect of opening. Two specimens, shown in Fig.9, were identical to B-10, and location and size of opening was identical to I-2. Specimens were marked as BO-1 and BO-2. Different loading methods were adopted. BO-1 was loaded by different force ($P_1 \neq P_2$) so that deflection was equal ($\delta_1 = \delta_2$), while BO-2 was loaded by the same force ($P_1 = P_2$), leading to torsional deformation ($\delta_1 \neq \delta_2$).

Both had initial shear failure at the web with opening. Then BO-1 ended by the shear failure of the other web at much higher total load. BO-2 finally failed at the flanges due to torsion.

Table 5 shows tested and calculated ultimate strength. Shear strength of each web of BO-1 compares very well with calculated shear strength, although flexural strength was overshooted. Ultimate strength of BO-2 corresponds to flexural strength, but this is incidental, because BO-2 actually failed in torsion. Figs.10 and 11 show load-deflection curves under reversal. Both show fairly ductile behavior regardless of brittle shear failure of the opening side. This is probably due to the fact that two webs did not fail simultaneously.

The effect of eccentricity was studied comparing with the theoretical prediction from FEM analysis. From this test it was inferred that, although openings did reduce the strength of that side of the web, its effect on the overall behavior might not be serious if the shear failure of the opening side was relatively ductile.

REINFORCING METHODS OF OPENING

This is the test to study the methods to reinforce the periphery of opening in the shear walls having relatively heavy reinforcement as is usual in case of box-type shear walls of nuclear reactor structures. Plate type shear walls with circular opening at the center, with a variety of peripheral reinforcement, were subjected to reversal of shear force.

Fig.12 shows the variety of nine specimens, and Fig.13 shows the detail of a typical specimen. Wall reinforcement ratio was kept constant to 1.0% for all specimens. Major variables were peripheral ratio p (0, 0.15 and 0.25) and arrangement of peripheral reinforcement. All specimens were subjected to horizontal load having point of contraflexure at the center of wall where the opening was provided, in order to minimize the effect of flexure on the behavior of opening. This loading method was selected, concidering that the openings in the prototype nuclear reactor structures would be located in such a way that openings are not subjected to predominant flexure but rather to the stress state closer to pure shear.

Fig.14 shows envelope curves of load-deflection relation, and Table 6 shows test results with calculated strength. All specimens failed in shear. Specimens IO-1, ISO-10 without peripheral reinforcement and IO-5 with diagonal reinforcement only (see Fig.12) failed along the main diagonal of the wall. All other specimens failed in shear at the height of opening where the horizontal cross-sectional area was minimal. For these specimens with peripheral reinforcement as shown in Fig.12 , the ultimate shear strength corresponding to diagonal tension or compression failure was higher than the shear strength of short vertical members on both sides of the opening. Specimens having reinforcement as specified in A.I.J. code or similar arrangement showed shear strength closer to that without opening multiplied by reduction factor of A.I.J. code due to opening (peripheral ratio). Shear strength of short vertical members evaluated by modified PCA equation was also adequate.

Different arrangement of peripheral reinforcement influenced not only the ultimate load but also the deformation capacity. IP-10 and IX-10, specimens having particular reinforcement in the short vertical members at opening sides, showed larger deformation capacity. IX-10 also showed increased strength. Fig.15 compares energy absorption capacity of specimens. Here the energy absorption was defined as the area under load-deflection envelope up to the point of 5% loss of load beyond maximum. It can be seen that IO-2 and IO-3 had inferior capacity, while IO-5, IP-10 and IX-10 had superior capacity in terms of energy absorption thus defined.

CONCLUSION

Strength reduction could be predicted by AIJ equation based on the reduction factor from the opening peripheral ratio, but a better result would be obtained by use of modified PCA equation. Effective reinforcement around opening would increase not only the shear strength but also the deformation capacity of web walls with opening. Such reinforcement also aids in improving the overall behavior of box-type shear walls having openings on one side of web only.

REFERENCE

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2) Felix Barda, John M.Hanson, and W.Gene Corley, "Shear Strength of Low-Rise Walls with Boundary Elements", Reinforced Concrete Structures in Seismic Zones, ACI SP-53, 1977, pp.149-202.

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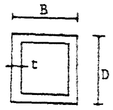
Table-1 Details of Specimen

Name of Specimen	Band D (cm)	t (cm)	ρg (%)
B - 6	83	8	0.6
B -10	83	8	1.0
B -16	83	8	1.6
B -10R	83	8	1.0
BL-10	158	8	1.0
BL-16	158	8	1.6



as:Bar Area
ρg=as/tx t:thickness wall
x;Bar space

B-10R had additional vertical reinforcement 4-D13 at corners

Table-2 Test Results and Failure mode

Name of Specimen	Fc (kg/cm²)	Ultimate Strength				Test/Cal.		Failure mode
		Test		Calculate				
		Q_u	${}_T\tau_u$	${}_b\tau_u$ 1)	${}_s\tau_u$ 2)	${}_T\tau_u/{}_b\tau_u$	${}_T\tau_u/{}_s\tau_u$	
B - 6	256	38.2	31.8	28.6	42.9	1.11	0.74	flexure
B -10	258	54.0	45.0	41.8	58.0	1.08	0.78	flexure
B -16	190	70.0	58.4	62.6	78.8	0.93	0.74	shear
B -10R	231	74.0	61.6	65.0	75.2	0.95	0.82	shear
BL-10	281	132.4	55.2	56.6	54.9	0.98	1.00	shear
BL-16	259	180.0	75.0	86.6	74.7	0.87	1.00	shear

1) Bending strength by approximate eq.
2) Modified PCA eq. $\tau_u=(1.9-0.7h/l)\sqrt{Fc}+0.5(p_{wv}+p_{wh}\,h/l)\sigma_y$

h ; Shear span, l; Web wall length
Pwv; vertical reinforcement ratio
Pwh; Horizonal reinforcement ratio
σ_y ; Yielding strength of reinforcement

Table-3 Details of Specimen

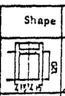
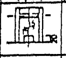
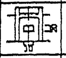
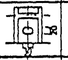
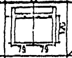
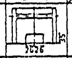
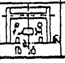
Specimen	Shape	Opening Area	Peripheral Reinforcement
I-1			
I-2		600cm P=0.32	H D13 V 2-D10
I-3		600cm P=0.32	H D13 V 2-D10
I-4		514cm P=0.29	2-D13
IL-1			
IL-2		1820cm² P=0.31	H D16 V D16 D 4-D6
IL-3		1530cm² P=0.28	D16
IL-4		2153cm² P=0.341	H D13 V D13 D D13

Table-4 Test Results

Specimen	Fc (kg/cm²)	h/l	$\frac{\sqrt{A_o}}{\sqrt{A_w}}$	Tests	Calculated ①		Test/Cal ①
				Qu (t)	bQu (t)	sQu (t)	
I -1	244	0.96		27.4	21.4	34.7	0.79
I -2	244	0.96	0.32	20.5	21.6	20.7	0.99
I -3	243	0.96	0.32	21.2	21.4	20.7	1.02
I -4	243	0.96	0.29	21.9	21.4	20.7	1.06
IL-1	249	0.76		59.5	48.9	64.8	0.92
IL-2	327	0.76	0.31	49.3	47.9	44.7	1.10
IL-3	327	0.76	0.31	50.7	47.9	44.7	1.13
IL-4	249	0.76	0.34 (0.27)	53.3	54.2	45.8	1.16

1) bQu; Bending strength by the approximate eq.
2) sQu; Shear strength, both sides of the opening by the modified PCA eq.

Table-5 Test Results

Name of Specimen	Fc (kg/cm)	Test		Calculated			Failure mode
		P_1 (t)	P_2 (t)	${}_sQ_u$		${}_bQ_u$ (t)	
				P_1 (t)	P_2 (t)		
BO-1	212	34.5	21.0	34.8	19.8	43.0	shear of without opening side
BO-2	190	44.0		53.4		43.0	shear of opening side

bQu; Bending strength by the approximate eq.
sQu; Shear strength, both sides of the opening by the modified PCA eq.

Table-6 Test Results

Specimen	Fc (kg/cm²)	h/l	$\sqrt{Ao/Aw}$	Tests	Calculated ①		Test/Cal①	Calculated ②		Test/Cal②
				Qu (t)	1) bQu (t)	2) sQu (t)	(Qu/sQu)	3) Quo (t)	4) rQu (t)	(Qu/rQu)
IO - 1	218	0.5	0.25	21.5	48.3	22.3	0.96	30.2	22.7	0.95
IO - 2	218			23.7	48.3	22.3	1.06	30.2	22.7	1.04
IO - 3	218			25.3	48.3	22.3	1.13	30.2	22.7	1.11
IO - 4	218			25.7	48.3	22.3	1.15	30.2	22.7	1.13
IO - 5	182			24.7	47.3	22.3	1.10	28.9	21.7	1.14
IP -10	180			23.7	42.7	23.6	1.00	31.3	23.5	1.00
IX -10	180			29.0	42.7	26.7	1.09	31.3	23.5	1.23
ISO-10	300		0.15	25.7	43.8	31.0	0.83	35.1	30.7	0.84
I -10	170			33.0	42.5	30.5	1.09	28.5		

1) bQu; Bending strength by the approximate eq.
2) sQu; Shear strength, both sides of the opening by the modified PCA eq.
3) Quo; Shear strength, without opening
4) rQu; Quo x (1-P), P=$\sqrt{Ao/Aw}$ (peripheral ratio)

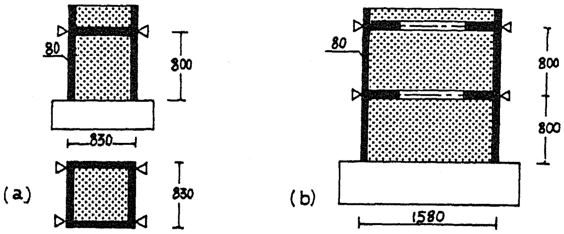


Fig.1 Specimen

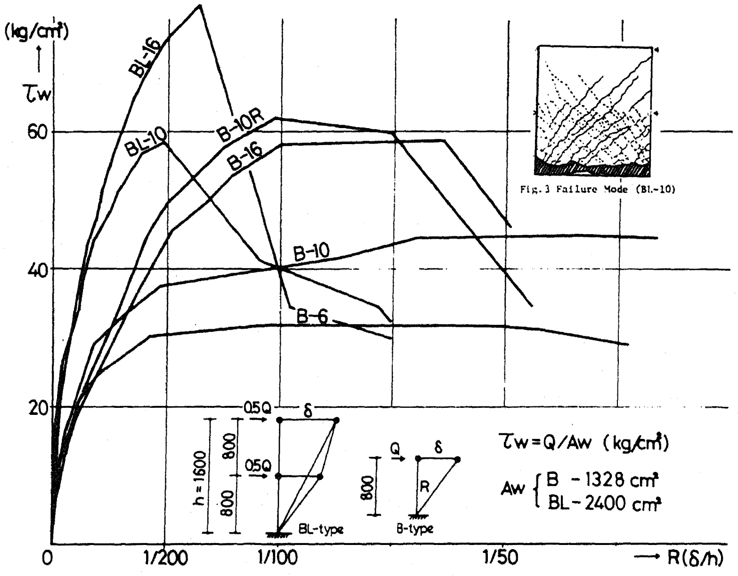
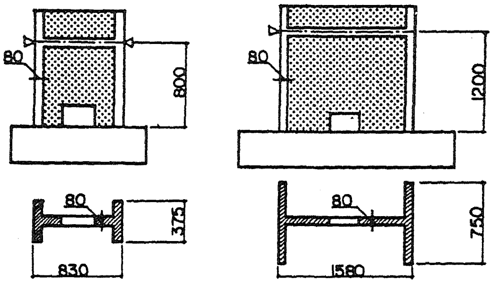


Fig.3 Failure Mode (BL-10)

Fig.2 Load-Deflection Curve



I-TYPE IL-TYPE

Fig.4 Specimen

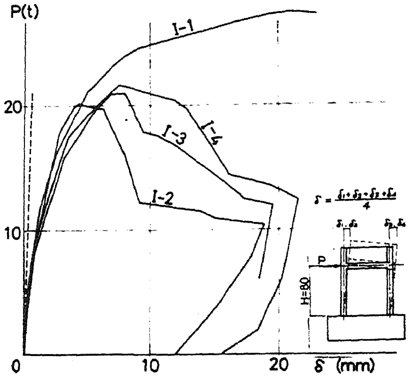


Fig.5 Load-Deflection Curve

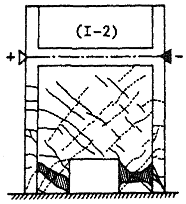


Fig.7 Failure Mode

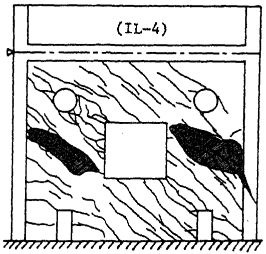


Fig.8 Failure Mode

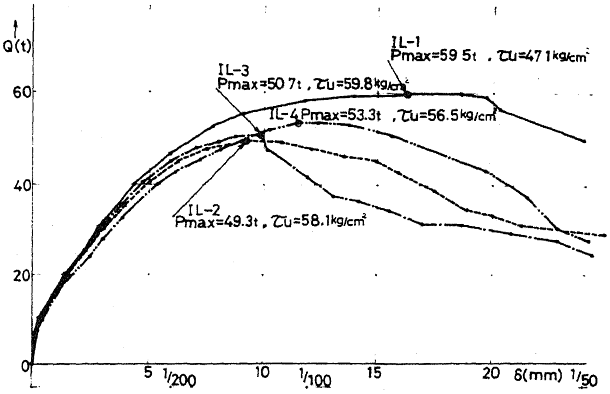


Fig.6 Load-Deflection Curve

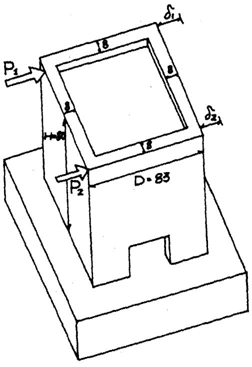


Fig.9 Specimen

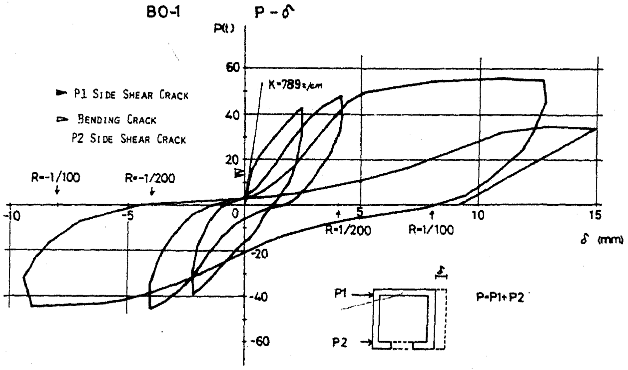


Fig.10 Load-Deflection Curve

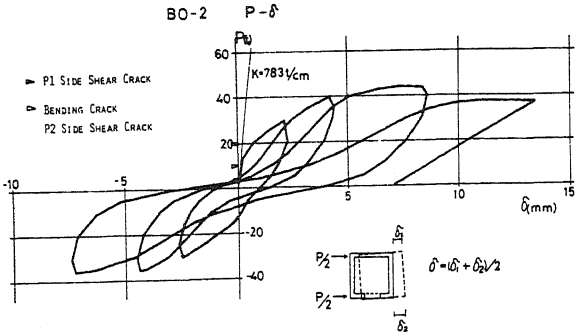
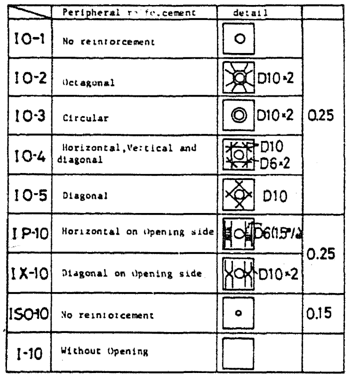


Fig.11 Load-deflection Curve



	Peripheral reinforcement	detail	
IO-1	No reinforcement		0.25
IO-2	Octagonal	D10×2	
IO-3	Circular	D10×2	
IO-4	Horizontal,Vertical and diagonal	D10 D6×2	
IO-5	Diagonal	D10	
IP-10	Horizontal on Opening side	D6(15°/	0.25
IX-10	Diagonal on Opening side	D10×2	
ISO-10	No reinforcement		0.15
I-10	Without Opening		

Fig.12 Variety of Peripheral Reinforcement

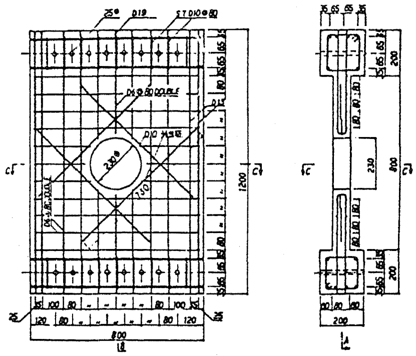


Fig.13 Details of Specimen

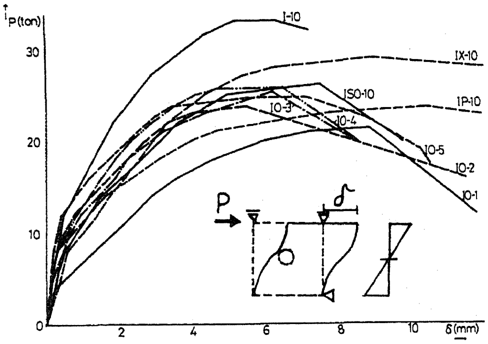


Fig.14 Load-Deflection Curve

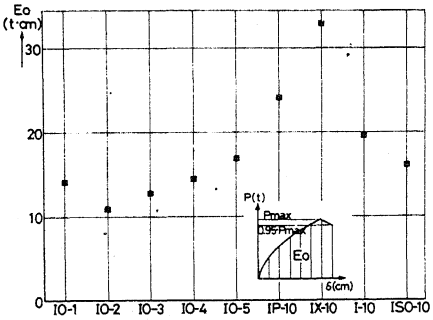


Fig.15 Comparison of Energy