BEHAVIOR OF REINFORCED CONCRETE CONTAINMENT MODELS UNDER THE COMBINED ACTION OF INTERNAL PRESSURE AND LATERAL FORCE

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SUMMARY

This paper presents the experimental studies on reinforced concrete containment vessels (RCCV) under the combined action of internal pressure and earthquake load. The object is to investigate the shear strength and ductility of RC containment vessels.

Four cylindrical specimens of the same scale were tested. The scale is almost one/twenty fifth of prototype containment vessels. The gross dimensions are 160 cm in height, 154 cm in inside diameter, and 6 cm in wall thickness. Reinforcement ratio and internal pressure in specimens are as follows:

Specimen	Reinforcement Ratio	Internal Pressure
C$-$1.8$-$3.0	1.8 %	3.0 kg/cm²
C$-$2.4$-$0.0	2.4 %	0.0 kg/cm²
C$-$2.4$-$3.0	2.4 %	3.0 kg/cm²
C$-$2.4$-$4.5	2.4 %	4.5 kg/cm²

Reinforcement ratio is the same in both horizontal and vertical direction in each specimen. The concrete strength varied from 299 to 389 kg/cm². Specimens were tested with only internal water pressure at first. Then, tests were performed under the combined action of internal pressure and alternately repeated cyclic lateral load. The conclusion of the test results and analysis are as follows:

1) Under the internal pressure only, the cracks appeared along reinforcing bars. But they recovered almost to close when the pressure was removed.

2) Specimens with internal pressure showed large ductility although their strength was reduced by some amount under lateral force. The specimen C$-$2.4$-$0.0 without internal pressure showed the large strength under lateral load, but it failed suddenly with small shear deflection.

3) The shear strength and ductility under the lateral load are controled to a large extent by wall reinforcement ratio and internal pressure.

4) The shear yield stress τ_y under lateral load and inner pressure may be predicted by Eq. (1), but further studies are needed in such a case as $\sigma_p = 0$.

$$\tau_y = P_w (\sigma_y - \sigma_p) \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

where
- τ_y : average shear yield stress (shear force divided by one half of the total area)
- P_w : wall reinforcement ratio
- σ_y : tensile yield stress of reinforcement
- σ_p : either of the larger stress in horizontal and vertical bars by inner pressure

Also the maximum strength τ_u was larger than the shear yield stress τ_y by more than 20 % under lateral load and inner pressure.

1. Objective

Recently reinforced concrete containment vessels (RCCV) have been adopted in place of steel containment vessels in some part of the world, but in Japan, reinforced concrete containment vessels were not constructed until now. Because in such a country as Japan where severe earthquakes occur so often, structural safety of RC containment is dominated distinguishedly by earthquakes. Therefore, these types of research have just been started in Japan.[1] This paper presents the experimental studies on RCCV models under the combined action of accidental pressure and earthquake load.

The object is to investigate the shear strength and ductility of RC containments. And the factors used in this experiment are reinforcement ratios and internal pressures in cylindrical wall specimens.

2. Design of Test Specimens

The typical containment structure for nuclear power plant consists of a concrete shell which has cylindrical wall. Outline of the prototype containment is shown in Fig. 1. The shape of specimens is shown in Fig. 2. The scale is almost one/twenty fifth of prototype containment vessel. The gross dimensions are 160 cm in height, 154 cm in inside diameter and 6 cm in wall thickness. And reinforcement ratio P_w, internal pressure Pa, etc. are listed in Table 1. The same reinforcement ratio is adopted in the test specimens in vertical and horizontal directions. The main mechanical characteristics of the materials are also summarized in Table 1. Deformed bars of 6 mm in diameter are used for vertical and horizontal reinforcements, and 2.6 mm wire is used for radial shear reinforcement. Concrete used in the test was designed to have a compressive strength of about 240 kg/cm^2 at 28 days, but they varied from 299 to 389 kg/cm^2.

3. Test Procedure

The base mat of specimen was fixed on the loading steel frame by prestressing bars. The loading procedure consisted of two basic steps. At first, only internal pressure test was performed. The required internal pressure was given by water pump into the rubber bag installed inside the cylindrical wall.

As the second step, the inner pressure was maintained constant by water pump, and the horizontal load was applied statically and repeatedly in alternative directions by hydraulic jacks at the top stub of specimen.

The over-all view of testing apparatus is shown in Fig. 3. The total deflection and the displacement of cylindrical wall, etc. were measured by dial gauges and electric deflection gauges. The strains in steel were measured by electric wire strain gauges. Also the cracks were observed by naked eyes and the crack width was measured by crack gauges.

4. Experimental Results

The test results of all specimens are listed in Table 2. The lateral force – sway deflection curves at the top stub are shown in Fig. 4. And load – strain curves of the web zone in horizontal reinforcement at middle height of cylinder are shown in Fig. 5. The crack pattern example by the constant pressure of 3.0 kg/cm^2 in specimen C-2.4-3.0 is shown in Fig. 6, and that by shear at the maximum lateral force is shown in Fig. 7.

Following is the brief description of the observed experimental behaviors of typical example specimens C-2.4-3.0 and C-2.4-0.0.

C-2.4-3.0   The cracks in cylindrical wall with constant pressure of 3.0 kg/cm² are distri-
buted finely all over the cylinder. Under the internal pressure only, these cracks appeared
along the reinforcing bars. And the crack widths were about 0.04 mm. The strains of hori-
zontal reinforcement at middle height in cylindrical web zone of the shell wall are about
820×10^{-6} with the constant pressure of 3.0 kg/cm². During the lateral load application the
shear cracks were first observed at approximately 20 ton. And vertical tension reinforce-
ments at flange zone started to yield at about 60 ton. Both of vertical and horizontal rein-
forcement at the web zone yielded in shear after the load reached 84.0 and 88.3 ton. At 108
ton, this specimen failed in shear at the shear compression zone of 90° – 135° angle from
loading direction. Other two specimens under the inner pressure and lateral force gave
almost the same behavior.

C-2.4-0.0   This specimen was loaded by the lateral force only without internal pressure.
The flexural bending cracks and shearing cracks appeared first at about 10 ton. The initial
rigidity of this specimen is larger than other specimens with the internal pressure. Upon
further increase of lateral force, more shear cracks appeared, and their width and length
increased. At 90 ton, tension reinforcements yielded in the critical bottom end region of
cylindrical flange zone. Also reinforcements at the web yielded in shear at 108.4 ton.
And this specimen failed suddenly at 120 ton with explosive sound, leaving wide shear crack.
The maximum load was the largest of the four specimens, but deformation ductility was the
smallest of them. Thus the behavior of this specimen was rather different from other three.

5.   Analyses of Test Results
    1)   Internal pressure – reinforcement strain relationship
The reinforcement strain s^ε at the middle height of the shell wall by inner pressure was
calculated by Eqs.(1) and (2).

$$\sigma_{PH} = \frac{1}{p_w} \cdot \frac{Pa \cdot r}{t} \quad , \quad \sigma_{PV} = \frac{1}{p_w} \cdot \frac{Pa \cdot r}{2t} \tag{1}$$

$$s\varepsilon_H = \frac{\sigma_{pH}}{Es} \quad , \quad s\varepsilon_V = \frac{\sigma_{pV}}{Es} \tag{2}$$

Where σ_{pH}, σ_{pv} : Stress of horizontal or vertical reinforcement at middle height of
                    cylindrical shear wall
    $s^\varepsilon H, s^\varepsilon v$: strain of the same as the above
        r   : radius of cylinder
        t   : wall thickness
        Es   : Young's modulus of elasticity in steel
        p_w : shear reinforcement ratio in cylinder
        Pa   : applied internal pressure

This equation was obtained from the reinforcing bar only, taking no concrete effect into
consideration. Computed value by Eqs.(1) and (2) is shown in chain lines in Fig. 5.
Experimental results agree well with the calculated values.

    2)   Lateral load – sway deflection relationship
Fig. 8 shows the envelopes of the lateral load – sway deflection relationship. Limited con-
clusions may be drawn from this figure as follows.
The initial rigidity of each specimen with internal pressure is less than that without pres-

sure. The shear yielding strengths and the ultimate strengths in the web zone increase linear-
ly to the reinforcement ratio P_w, and decrease to the intensity of the internal pressure P_a.
Also the ductility of specimens varied according to P_w and P_a. On the other hand, deforma-
tion ductility becomes vise versa. The less ductile specimen shows the shear failure, and
the more ductile specimen shows the flexural failure or combination failure of flexure and
shear, as in the case of ductile columns.

3)   Analysis of shear strength

The specimen C-2.4-0.0 without internal pressure showed large shear strength under the
lateral force, but specimens with inner pressure showed less shear strength under lateral
force. So the theoretical value of yield stress τ_y under lateral force may be predicted by
the following fomula of Eq. (3). This equation considers the effect of inner pressure of the
reinforcement.

$$\tau_y = P_w (\sigma_y - \sigma_p) \tag{3}$$

Where τ_y :   average shear yield stress (shear force divided by one half
             of total area)

σ_y :   tensile yield stress of reinforcement

σ_p :   either of the larger stress in horizontal or vertical bars by
         inner pressure

The calculated values agree fairly well with experimental values except specimen
C-2.4-0.0. The lateral force – shear strain relationship calculated by Eqs. (1), (2) and
(3) is shown in chain lines in Fig. 5.

When the reinforcement is assumed to resist simultaneous action of lateral force and
inner pressure, the effective shear reinforcement ratio P_w' for lateral force only can be
expressed as follows.

$$P_w' = P_w (1 - \frac{\sigma_p}{\sigma_y}) \tag{4}$$

The calculated relationship of shear yield stress τ_y to effective shear reinforcement
ratio P_w' is shown in a straight line in Fig. 9. The dots show the experimental results.
Experimental results agree well with the calculated value up to $P_w' = 1.5$ %. The result of
specimen C-2.4-0.0 deviates from the calculation, which suggests the necessity of other
assumption.

Also the maximum strength τ_u was larger than the shear yield stress τ_y by more than 20 %
under lateral load and inner pressure.

4)   Principal stress

When the normal stress by overturning moment is neglected, the principal stresses can be
obtained by Eq. (5).

$$\sigma_1, \sigma_2 = \frac{\sigma_{pH} + \sigma_{pV}}{2} \pm \sqrt{(\frac{\sigma_{pH} - \sigma_{pV}}{2})^2 + \tau^2} \tag{5}$$

The shear yield stress τ_y for test and calculation may be given by the following
assumptions.

$$\tau_{y.test} = \frac{sQ_y}{\pi r t}$$

$$\tau_{y.calculation} = P_w (\sigma_y - \sigma_p) = P_w'.\sigma_y \tag{6}$$

where s^Qy : lateral load at shear yield in the horizontal reinforcement

The comparison between the calculated principal stress $\sigma_{1.cal.}$ and the experimental value $\sigma_{1.exp.}$ at the shear yield stress τy under the inner pressure and lateral force is shown in Fig. 10. As is evident from the figure, in the range of the principal stress ratio $\kappa \doteqdot 0$ ($\kappa = \sigma_2/\sigma_1$), the ratio of experimental value to the calculated one is about 1.0. But in the range of $\kappa \doteqdot -1$ such as a specimen (C-2.4-0.0) without inner pressure, experimental value is less than that calculated. This implies the necessity of other assumption considering concrete effect. When the normal stress by overturning moment is taken into account, the compared values move to the dark dots as are shown by arrows in Fig. 10.

6.   Conclusion

Tests under constant pressure and multi cycle lateral force were carried out on four specimens. And the following conclusions are given from the test results and analyses.

1)   Under the internal pressure only, the cracks appeared along reinforcing bars. And their width was less than 0.08 mm. But they recovered almost to close when the pressure was removed.

2)   Under the internal pressure and lateral force, the cracks were distributed finely all over the cylinder.

3)   Under lateral force, specimens with internal pressure showed large ductility although their strength was reduced by some amount. The specimen C-2.4-0.0 without internal pressure showed the large strength under lateral load, but it failed suddenly with small shear deflection.

4)   The shear strength and ductility under the lateral load are controled to a large extent by wall reinforcement ratio and internal pressure.

5)   The shear yield stress τy under the combined action of lateral load and internal pressure may be predicted by Eq. (3).

Also the maximum strength τu was larger than the shear yield stress τy by more than 20 % under lateral load and inner pressure.

7.   Acknowledgments

Reference

1)   K. Ichikawa, Y. Aoyagi, Y. Watanabe, "Design Concept of Concrete Containment Vessels for Shear and Thermal Stresses," 5th SMiRT Conference Berlin, Germany, (1979).
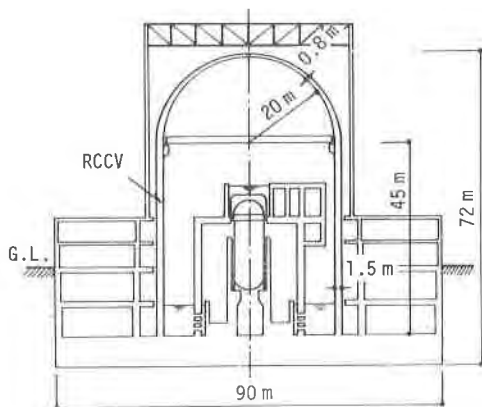
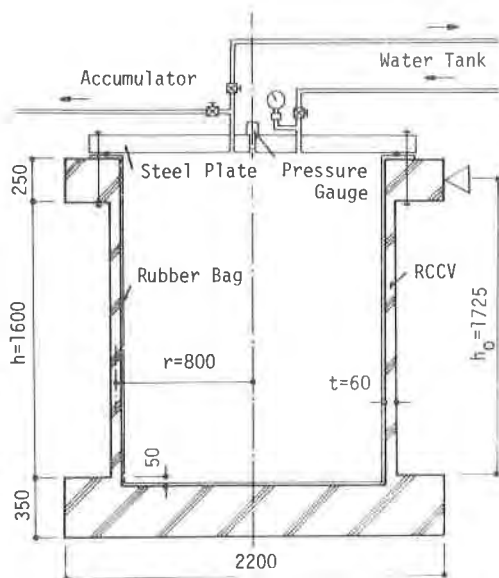Fig. 1   Outline of the prototype containment

Fig. 2   The shape of specimen

Table 1   List of specimens properties

Specimen	C-1.8-3.0	C-2.4-0.0	C-2.4-3.0	C-2.4-4.5
Pressure P (kg/cm^2)	3.0	0.0	3.0	4.5
Reinf. Ratio P_W (%) (Vertical, Horizontal)	1.8	2.4	2.4	2.4
Reinf. Ratio P_W (%) (Radial Shear) *	0.46	0.55	0.55	0.55
Material of Reinf. (Vertical, Horizontal)	2-D6, sσy=4013kg/cm^2, Es=1.82x10^{6}kg/cm^2			
Material of Reinf. (Radial Shear)	2.6ϕ, sσy=4180kg/cm^2, Es=2.15x10^{6}kg/cm^2			
Material of Mortar Fc (kg/cm^2)	299	389	386	340
Ec $(x10^5 kg/cm^2)$	2.43	2.49	2.65	2.49

* was arranged within the region of about 20 cm
  from the top and bottom end of shell.

Notaion of test specimens

C - 2.4 - 3.0

→ Internal pressure (3.0 kg/cm^2)
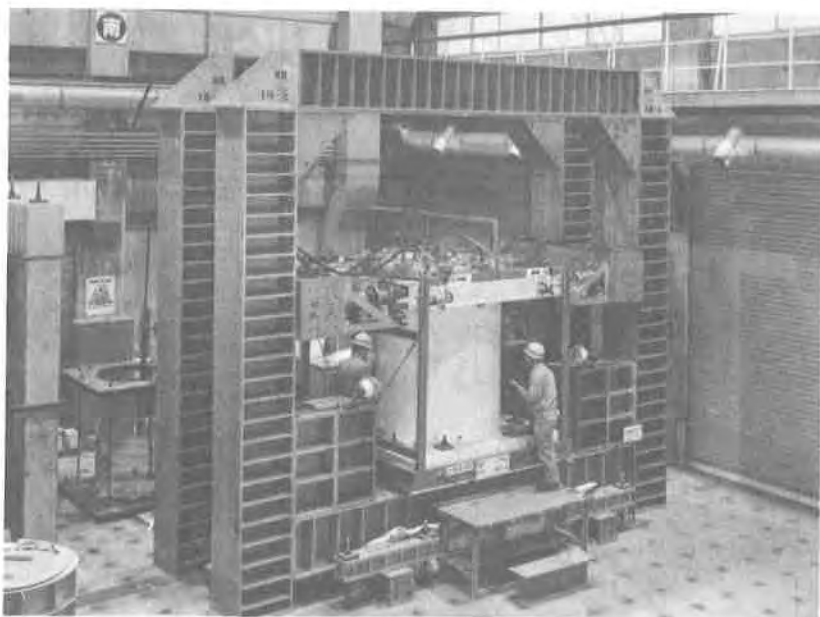→ Reinforcement ratio (2.4%)
→ Cylindrical specimen

Fig. 3   Over-all view of testing apparatus

Table 2   Test results of specimens

Specimen		C-1.8-3.0	C-2.4-0.0	C-2.4-3.0	C-2.4-4.5
Shear Crack $_SQ_{cr}$ (t)	(1)	21.6	10.0	18.0	19.7
	(2)	18.1	20.1	20.0	19.0
	(3)	(1.19)	(0.50)	(0.90)	(1.04)
Shear Yield $_SQ_{y.H}$ (t) Horizontal	(1)	56.0	108.4	88.3	64.0
	(2)	48.6	145.2	84.9	54.7
	(3)	(1.15)	(0.75)	(1.04)	(1.17)
Shear Ultimate $_SQ_{u.H}$ (t) Horizontal	(1)	92.0	120.0	108.0	90.0 *1
	(2)	82.9	152.3	117.1	94.2
	(3)	(1.11)	(0.79)	(0.92)	———
Mode of Failure		S + F	S	S	——— *1

Note   (1); experiment   (2); calculation   (3); exp./calc.
        *1; was not tested to the ultimate strength
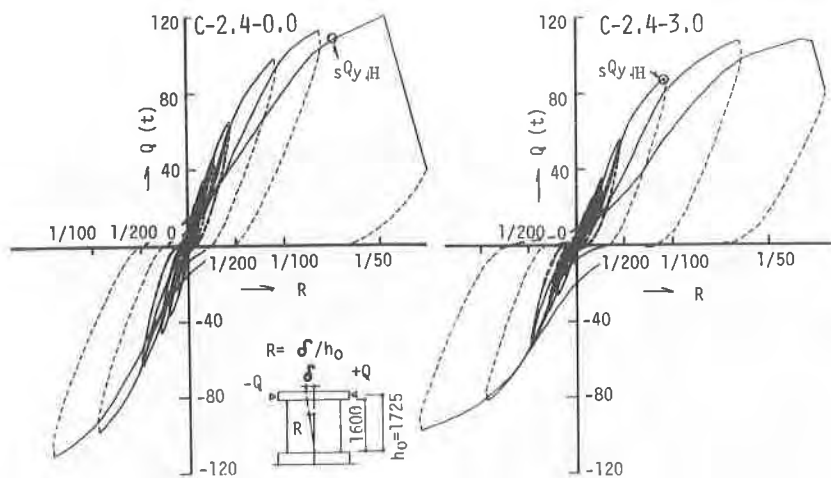   S; shear failure   F; flexural failure

Fig. 4   Lateral force - sway deflection curves
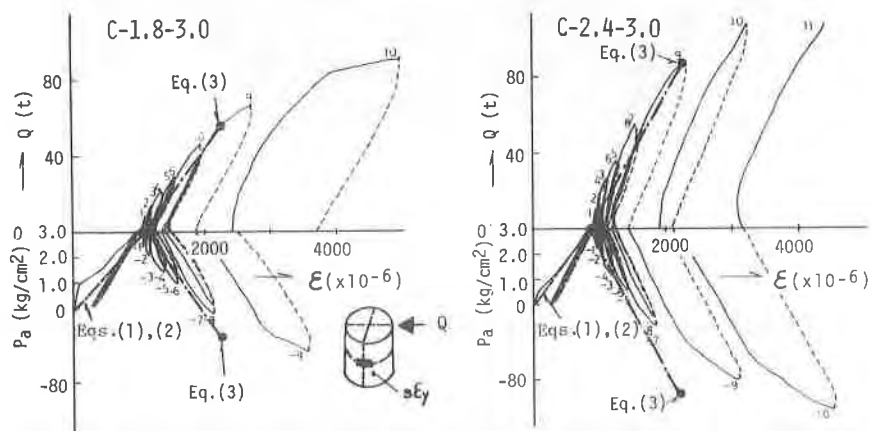

Fig. 5   Load - strain curves in horizontal reinforcement

Fig. 6   Crack pattern at the internal
          pressure only

Fig. 7   Crack pattern at the maximum
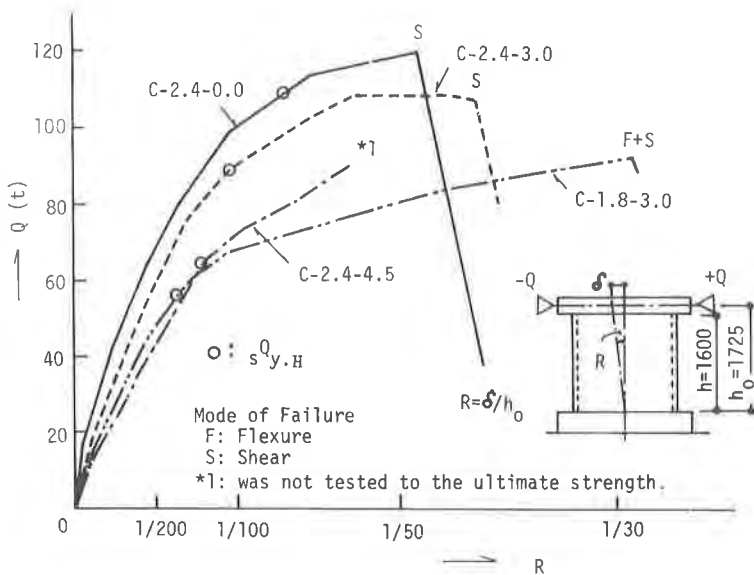   lateral force

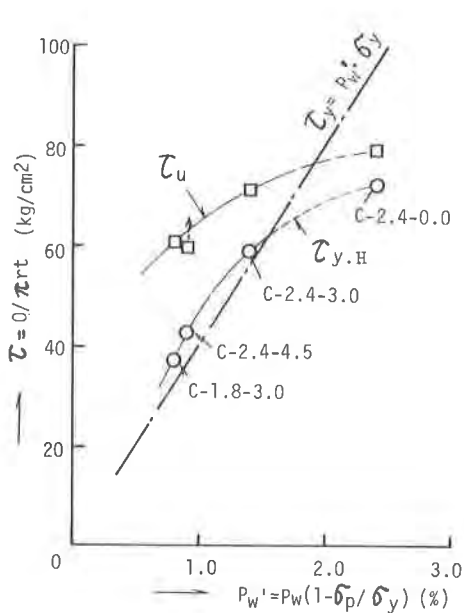Fig. 8   Envelope of the lateral force - sway deflection curves

Fig. 9

Shear yield stress - effective shear
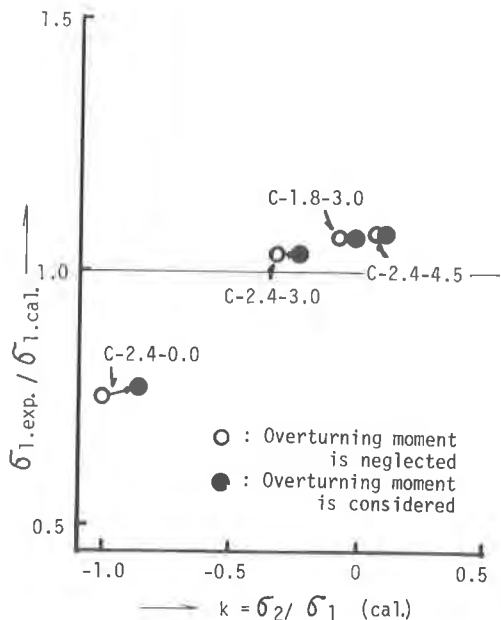reinforcement ratio relationship

Fig. 10
Comparison between the calculated principal
stress $\sigma_{1.cal.}$ and the experimental value
$\sigma_{1.exp.}$ at the shear yield stress τ_y