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:

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Reinforcement Ratio</th>
<th>Internal Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>C–1.8–3.0</td>
<td>1.8 %</td>
<td>3.0 kg/cm²</td>
</tr>
<tr>
<td>C–2.4–0.0</td>
<td>2.4 %</td>
<td>0.0 kg/cm²</td>
</tr>
<tr>
<td>C–2.4–3.0</td>
<td>2.4 %</td>
<td>3.0 kg/cm²</td>
</tr>
<tr>
<td>C–2.4–4.5</td>
<td>2.4 %</td>
<td>4.5 kg/cm²</td>
</tr>
</tbody>
</table>

Reinforcement ratio is the same in both horizontal and vertical direction in each specimen. The concrete strength varied from 259 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 \( \tau_y \) under lateral load and inner pressure may be predicted by Eq. (1), but further studies are needed in such a case as \( \sigma_p = 0 \).

\[
\tau_y = P_w \left( \sigma_y - \sigma_p \right)
\]

where

\( \tau_y \): average shear yield stress (shear force divided by one half of the total area)

\( P_w \): wall reinforcement ratio

\( \sigma_y \): tensile yield stress of reinforcement

\( \sigma_p \): either of the larger stress in horizontal and vertical bars by inner pressure

Also the maximum strength \( \tau_u \) was larger than the shear yield stress \( \tau_y \) 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. 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 containment. 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 $P_a$, 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.

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1. J 4/4
The cracks in cylindrical wall with constant pressure of 3.0 kg/cm² are distributed finely all over the cylinder. Under the internal pressure only, these cracks appeared along the reinforcing bar. And the crack widths were about 0.04 mm. The strains of horizontal reinforcement at middle height in cylindrical web zone of the shell wall are about $820 \times 10^{-6}$ 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 reinforcements at flange zone started to yield at about 60 ton. Both of vertical and horizontal reinforcement 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 $90^\circ - 135^\circ$ angle from loading direction. Other two specimens under the inner pressure and lateral force gave almost the same behavior.

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 $s^e$ at the middle height of the shell wall by inner pressure was calculated by Eqs. (1) and (2).

$$\sigma_{PH} = \frac{1}{P_w} \times \frac{P_a \cdot r}{t}, \quad \sigma_{PV} = \frac{1}{P_w} \times \frac{P_a \cdot r}{2t}$$

(1)

$$s^e_H = \frac{\sigma_{PH}}{E_s}, \quad s^e_V = \frac{\sigma_{PV}}{E_s}$$

(2)

Where $\sigma_{PH}$, $\sigma_{PV}$: Stress of horizontal or vertical reinforcement at middle height of cylindrical shear wall

$s^e_H$, $s^e_V$: strain of the same as the above

$r$: radius of cylinder

t: wall thickness

$E_s$: Young's modulus of elasticity in steel

$P_w$: shear reinforcement ratio in cylinder

$P_a$: 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 conclusions 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 linearly 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, deformation 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 \( \tau_y \) under lateral force may be predicted by the following formula of Eq. (3). This equation considers the effect of inner pressure of the reinforcement.

\[
\tau_y = \frac{P_w}{(1 - \frac{\sigma_p}{\sigma_y})}
\]

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

\( \sigma_y \) : tensile yield stress of reinforcement

\( \sigma_p \) : 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.

\[
P_{w'} = P_w (1 - \frac{\sigma_p}{\sigma_y})
\]

The calculated relationship of shear yield stress \( \tau_y \) 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 \( \tau_u \) was larger than the shear yield stress \( \tau_y \) 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).

\[
\sigma_1, \sigma_2 = \frac{\sigma_p + \frac{\sigma_p - \sigma_p}{2}}{2} \times \sqrt{\left(\frac{\sigma_p + \sigma_p}{2}\right)^2 + \tau^2}
\]

The shear yield stress \( \tau_y \) for test and calculation may be given by the following assumptions.

\[
\begin{align*}
\tau_{y, \text{test}} &= \frac{\sigma_0}{\mu} \\
\tau_{y, \text{calculation}} &= P_w (\sigma_y - \sigma_p) = P_{w'}, \sigma_y
\end{align*}
\]

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where $S_{cy}$ : 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 $\tau_y$ 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 $K = 0$ ($K = \sigma_2 / \sigma_1$), the ratio of experimental value to the calculated one is about 1.0. But in the range of $K \approx -1$ 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 controlled to a large extent by wall reinforcement ratio and internal pressure.

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

Also the maximum strength $\tau_u$ was larger than the shear yield stress $\tau_y$ by more than 20% under lateral load and inner pressure.

7. Acknowledgments

The authors are most grateful to Dr. K. Muto and Dr. T. Hisada for their useful advices. The authors also wish to express appreciation to Mr. M. Yamazaki and Dr. A. Endo for advising in the experiments and analyses.

Reference

Fig. 1  Outline of the prototype containment

Fig. 2  The shape of specimen

Table 1  List of specimens properties

<table>
<thead>
<tr>
<th>Specimen</th>
<th>C-1.8-3.0</th>
<th>C-2.4-0.0</th>
<th>C-2.4-3.0</th>
<th>C-2.4-4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure $P$ (kg/cm$^2$)</td>
<td>3.0</td>
<td>0.0</td>
<td>3.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Reinf. Ratio $P_H$ (%) * (Vertical, Horizontal)</td>
<td>1.8</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Reinf. Ratio $P_S$ (%) * (Radial Shear)</td>
<td>0.46</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>Material of Reinf. * (Vertical, Horizontal)</td>
<td>$2\cdotD_6, s_f y=4013$ kg/cm$^2$, $E_s=1.82\cdot10^6$ kg/cm$^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material of Reinf. * (Radial Shear)</td>
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<td></td>
<td></td>
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<tr>
<td>Material of Mortar</td>
<td>$F_c$ (kg/cm$^2$)</td>
<td>299</td>
<td>380</td>
<td>366</td>
</tr>
<tr>
<td></td>
<td>$E_c$ (x10$^5$ kg/cm$^2$)</td>
<td>2.43</td>
<td>2.49</td>
<td>2.65</td>
</tr>
</tbody>
</table>

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

Notation 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

<table>
<thead>
<tr>
<th>Specimen</th>
<th>C-1.8-3.0</th>
<th>C-2.4-0.0</th>
<th>C-2.4-3.0</th>
<th>C-2.4-4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Crack $S_{cr}^Q$ (t)</td>
<td>21.6</td>
<td>10.0</td>
<td>18.0</td>
<td>19.7</td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18.1</td>
<td>20.1</td>
<td>20.0</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td>(1.19)</td>
<td>(0.50)</td>
<td>(0.90)</td>
<td>(1.04)</td>
</tr>
<tr>
<td>Shear Yield $S_{y,H}^Q$ (t)</td>
<td>56.0</td>
<td>108.4</td>
<td>88.3</td>
<td>64.0</td>
</tr>
<tr>
<td>Horizontal</td>
<td>48.6</td>
<td>145.2</td>
<td>84.9</td>
<td>54.7</td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.15)</td>
<td>(0.75)</td>
<td>(1.04)</td>
<td>(1.17)</td>
</tr>
<tr>
<td>Shear Ultimate $S_{u,H}^Q$ (t)</td>
<td>92.0</td>
<td>120.0</td>
<td>108.0</td>
<td>90.0 *1</td>
</tr>
<tr>
<td>Horizontal</td>
<td>82.9</td>
<td>152.3</td>
<td>117.1</td>
<td>94.2</td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.11)</td>
<td>(0.79)</td>
<td>(0.92)</td>
<td></td>
</tr>
<tr>
<td>Mode of Failure</td>
<td>S + F</td>
<td>S</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>Note</td>
<td>(1); experiment  (2); calculation  (3); exp./calc.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>*1; was not tested to the ultimate strength</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S; shear failure  F; flexural failure</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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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 $\tau_y$