Experimental Study on RCCV of ABWR Plant Part 6: Internal Pressure Test of Total Model (1/6th Scale)

Hideaki Saito, Rikiro Kikuchi
Tokyo Electric Power Company, Tokyo, Japan
Osamu Oyamada, Yasuhito Maki
Hitachi Ltd., Hitachi, Japan
Yutaka Muramatsu, Makoto Hiramoto
Toshiba Corporation, Yokohama, Japan
I. Yamaguchi, T. Kei, M. Isomura
Takenaka Corporation, Tokyo, Japan

1. INTRODUCTION

The objectives of this experiment were to ascertain the integrity of the trial-designed RCCV structure and the appropriateness of the design method at the design load level with regard to internal pressure load including thermal load and horizontal load during earthquake, and to grasp the structural behaviors at higher than design load level and to check the maximum horizontal strength by using a 1/6-scale model (Saito et al.,1989). This paper reports mainly the results of internal pressure test. The results of horizontal force test are reported the paper (Part 7)

2. SPECIMEN

2.1 Configuration

A general view of the specimen is shown in Photo.1. The experimental execution condition is shown in Photo.2. The schematics of the specimen are shown in Fig.1. and Fig.2. The specimen was a 1/6-scale model of the RCCV simulating the trial design as faithfully as possible. The specimen was 12m long, 8.5m wide, and about 8.0m high. The cylindrical wall is 0.333m thick, 4.83m inside diameter and 5.28m high.

The specimen consisted of the cylindrical wall, the pool girder, the box wall and the slabs. The box wall was constructed only the flange sides within the range of one-half the trial-designed box wall length, and the confinement effect in the vertical direction was simulated. All of the slabs which were jointed to the cylindrical wall were made disk shapes so as to have the effect of the confinement of cylindrical wall expansion deformation. Furthermore, of the RCCV major openings, the top head opening and the L/D access tunnel openings located 180° apart were simulated. Instead of steel liner in the actual RCCV, rubber lining material was used in the specimen.

2.2 Reinforcing Steel Bar and Concrete

The cylindrical wall contained four layers of meridional and four layers of circumferential reinforcing steel bar (Table 1). The re-bar arrangement, the number of re-bars, and the anchoring method of the re-bars were also approximated to those of the trial-designed RCCV. The primary reinforcing bar was D13 (deformed-bar 13mm in diameter). Concrete was casted eight times story by story. The strength of concrete is about 300kgf/cm^2.

The material test results of the reinforcing bars and the concrete are shown in Table 2 and Table 3.

3. LOADING AND MEASURING METHOD

Three kinds of loads were applied on the specimen : internal pressure,lateral load and thermal load. The internal pressure load was applied in such a method that after the rubber lining material was applied on the inside surface of the specimen, the water was poured in, and the water was pressurized with high-pressure pump. The internal pressure value was evaluated at the center height position of cylindrical wall. The thermal load was applied by heating the water with boiler.

The method of alternating lateral loading was applied with eight hydraulic jacks. The loading conditions are shown in table 4. The test loading cycle is shown in Fig.3. The internal pressure load was applied at maximum up to twice the design internal pressure ($2P_D$=6.32kgf/cm^2). The deformations of each specimen section were measured from the steel frame standing on the basement by displacement tranceducers. There were about 280 tranceducers, about 600 strain gauges for reinforcing bars and about 160 displacement thermocouples embedded in the containment wall and slab.

4. INTERNAL PRESSURE LOADING TEST

4.1 Outline of Loading Test

Cylindrical wall cracking at the testing pressure $1.15P_D$ (SIT;3.64kgf/cm^2) is shown in Fig.4. The initial vertical cracking was observed in the second base floor (B2F) at the internal pressure 2.4kgf/cm^2. Then, bending cracks were occurred at the upper face of the top slab at the periphery of the top head opening at $0.9P_D$ (=0.9×3.16kgf/cm^2), however, the crack widths were small, and about 0.04mm wide. Cracks at the design internal pressure Pd and 1.15Pd were both about 0.04mm wide. The cracks did not grow any further when the pressure was maintained for an additional two hours. Unloading the internal pressure, the crack widths returned to the width before the loading in all sections.

At the internal pressure load of 2.0 times the design internal pressure, diagonal cracks on the pool girder (at the position of the cylindrical wall joint) were increased, and cracks around the top slab opening grew. The widths of cracks at that time were under 0.10mm.

4.2 Deformation

The load-radial deformation of the RCCV at the second base floor (B2F) is shown in Fig.5. The initial stiffness value obtained from the experiment was 1.09 time the corresponding FEM elastic analytical value.

The deformation mode at the each load level (90° to 270° section) is shown in Fig.6.

The specimen bulged as whole. In particular, the deformation progressed from the pressure $1.15P_D$ to $1.5P_D$. The cylindrical wall was bulged more at B2F where the opening was located. The B2F radial displacement reached a little more than twice that of B3F or B1F at the pressure 1.15Pd.

4.3 Re-bar Strain

The relationship between the internal pressure and the re-bar strain is shown in Fig.7, as an example, for the B2F circumferential re-bar. The values of the re-bar strain at the major sections at the pressure 1.15Pd was shown in Fig.8. The maximum strain value of the main reinforcing bars at that pressure load was 738μ (37 percent of yielding strain) in circumferential reinforcement at B2F of the cylindrical wall. The re-bar strains were less than 1/3 of yielding strain at the other sections also, and all were values less than the long-term allowable stress intensities of the re-bars.

At the pressure twice the design internal pressure (6.32kgf/cm^2), the meridional reinforcement of the cylindrical wall at the connection with the pool girder reached the yield strain. The diagonal reinforcement around the L/D access tunnel opening also yielded at the same load.

4.4 Maintenance of Pressure

The rate of the radial displacement increase due to maintenance of internal pressure at the second base is shown in Fig.9. The rate of the circumferential re-bar strain increase at the same place (B2F) is shown in Fig.10. The displacement and strain both remarkably increased within 30 minutes after the start of the maintenance, but they were relatively stable thereafter. The displacement recovery rates of main sections are shown in table 5. The results satisfied the judgement criteria (ASME) against the testing internal pressure (SIT) that "the displacement recovery ratio after 24 hours shall be higher than 70%".

4.5 Comparison between FEM Elastic Analytical Results and Experimental Results.

The initial stiffness at the main sections agreed well with analytical results (Table 6). The measured displacements at the testing internal pressure ($3.64kgf/cm^2$) were larger than the analytical value due to the reduction of rigidity by cracking of the RCCV before (Fig.11). The analytical and measured strain distributions of circumferential re-bar of the cylindrical wall ($1.15P_D$) are shown in Fig.12. This figure also shows the re-bar strains when the maintenance of the pressure for two hours started and ended. The experimental results were on the safe side because the reinforcement ratio was determined with no tensile strain of concrete in design.

Resultant stresses determined from measured reinforcement strains were smaller than the corresponding analytical values.

5. CONCLUSION

The major results obtained by the internal pressure test were as follows:

A. At the testing internal pressure (SIT;$1.15P_D=3.64kgf/cm^2$), the cracks were fine (the crack widths were about 0.04mm or less), and the cracks closed after the pressure was removed. The strains of main reinforcements were less than 37% of the yield strain, and the resultant stresses were conservatively.
B. After maintenanced pressure was removed, displacement recovery ratio at the testing internal pressure were more than 74%.
C. The cylindrical wall had a strength capable of withstanding more than twice the design internal pressure.

The integrity of the RCCV was confirmed and the design method was conservatively. The test results satisfied the design standards.

6. ACKNOWLEDGMENT

This study has been carried out as a part of a joint research study on " Evaluation of the RCCV Configuration and Confirmatory Test to Establish a Code" (Saito et al., 1989)

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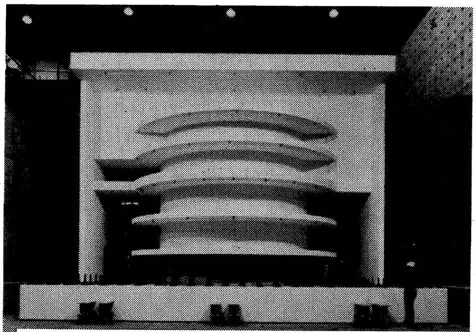
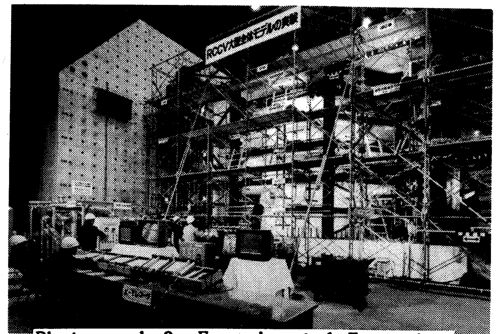


Photograph 1 Overall View of Specimen (90° side)



Photograph 2 Experimental Execution Conditions

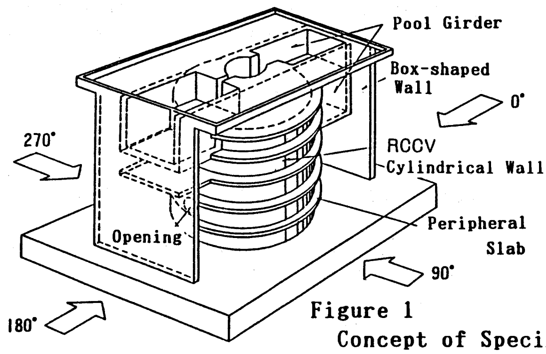


Figure 1 Concept of Specimen

Table 2 Test Results of Re-bars

Re-bar	Location of Use	σ_y (kgf/cm²)	σ_t (kgf/cm²)	ε_y (μ)	ε (%)
D6	Tie bar	3090	4090	1760	35
D10	Slab radial bar Opening ring bar Operating floor	3860	5460	2000	19
D13	Main reinforcement (RCCV, Box Wall, Pool Girder) Slab circumferential bar	3820	5500	1990	30

σ_y: Yield Point σ_t: Tensile Strength
ε_y: Yielding Strain ε: Elongation

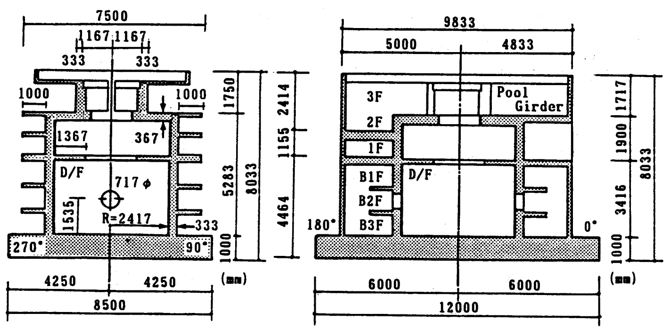


Figure 2 Specimen Configuration and Dimensions

Table 3 Test Results of Concrete

	Field Curing (Curing in Sealed Condition)		
	$c\sigma_B$	E_c	$c\sigma_t$
(Start)	283	2.37	20.7
(End)	316	2.14	23.4
Total average	299	2.26	22.4

$c\sigma_B$: Compressive Strength (kgf/cm²)
E_c : Elastic Modulus (x10⁵kgf/cm²)
$c\sigma_t$: Splitting Strength (kgf/cm²)

Table 1 Comparison Between Trial-Designed Re-bar Ratio and Specimen Re-bar Ratio of Cylindrical Wall (RCCV)

	Circumferential — Trial Design Arrangement	P_t (%)	Circumferential — Specimen Arrangement	P_t (%)	Vertical — Trial Design Arrangement	P_t (%)	Vertical — Specimen Arrangement	P_t (%)
Top Slab	1.33 layers D51@150	*1 0.90	1.33 layers D13 @57	0.90	*2 D51~2x320	0.67	D13~1x192 D13~1x 96	0.67
D/F Slab	1.5 layers D51@150	1.01	1.5 layers D13 @57	1.01	D51~2x320 D41~1x160	0.78	D13~1x192 D13~1x144	0.79
	1.33 layers D51@150	0.90	1.33 layers D13 @57	0.90				
	2 layers D51@275	0.74	2 layers D13@104	0.74				
	2 layers D51@300	0.68	2 layers D13@113	0.68	D51~2x320 D41~1x320	0.8	D13~2x192	0.90

*1 Pt : reinforcement ratio in one side of section

*2 the number of reinforcements

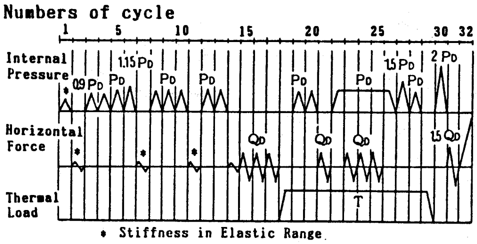
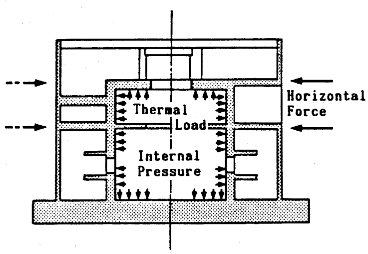


Figure 3 Test Loading Cycle

Table 4 Loads Applied on Specimen

Load	Description	Loading Condition
Internal Pressure Load	Design internal pressure (P_D) Testing internal pressure (SIT)	3.16kgf/cm² 3.64kgf/cm²
Lateral Load	Design horizontal force (Q_D) $\tau = 2Q_D/A$ $= 23.4$kgf/cm²	632 tf (base of cylindrical wall)
Thermal Load	During normal operation (winter)	Water temperature 40℃



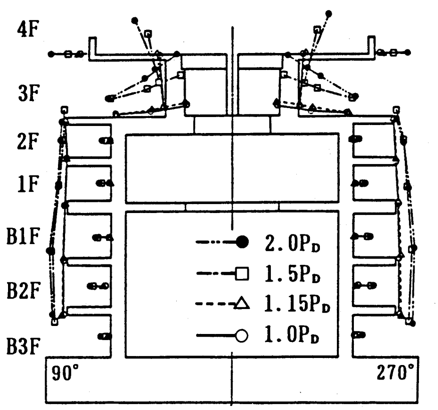


Figure 6 Deformation under Internal Pressure Load

Note) Radial direction deformation only at cylindrical portion and 4F slab (vertical direction not measured)

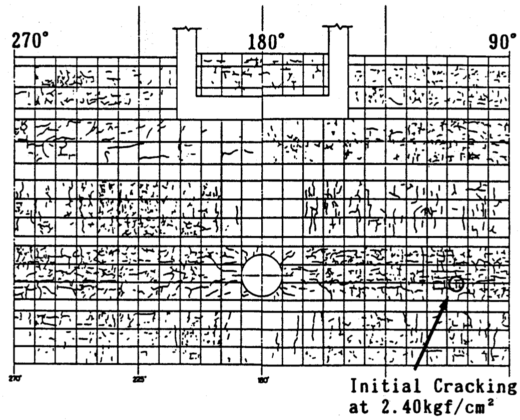


Figure 4 Cylindrical Portion Exterior Cracking Pattern (at $1.15P_D$)

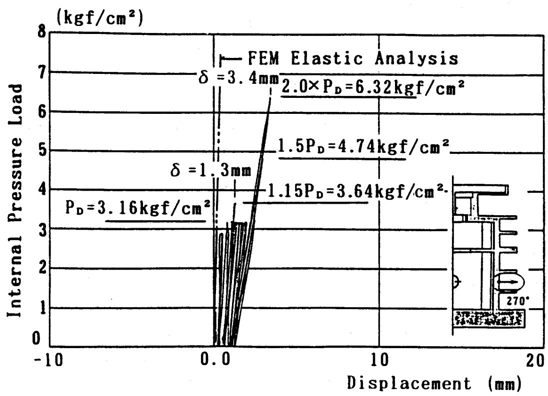


Figure 5 Cylindrical Portion B2F Radial Direction Displacement

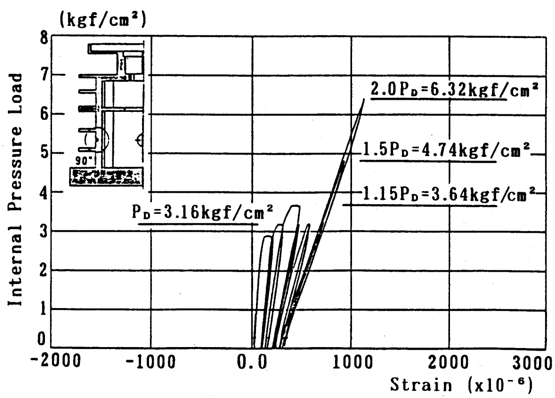


Figure 7 Cylindrical Portion B2F Circumferential Re-bar Strain

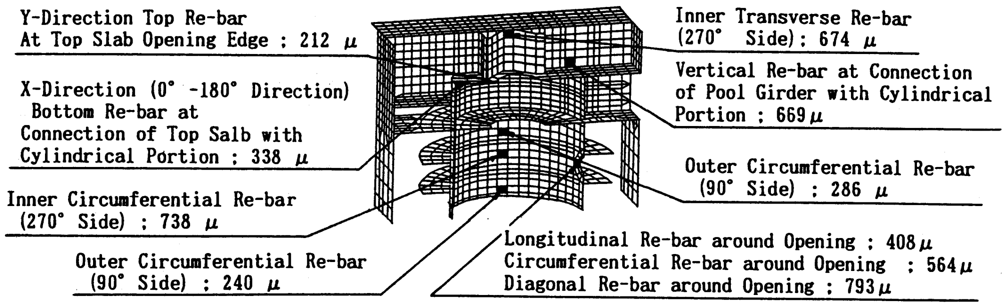


Figure 8 Re-bar Strains at Principal Parts under Internal Pressur Load (3.64kgf/cm², 6 Cycle)

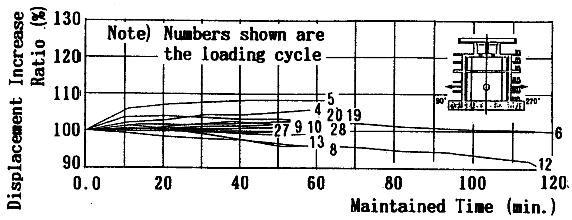


Figure 9 Dispalcements due to Maintenance of Internal Pressure [Cylindrical Portion (B2F) Radial Direction]

Table 5 Displacement Recovery Rates (after Removal of 3.64 kgf/cm² Internal Pressure)

Part		Direction	Rate
Top Slab / Opening Edge	(0°) (180°)	Vertical Vertical	84% 83%
Pool Girder / Middle top	(90°) (90°)	Vertical Out-of-plane	93% 80%
Cylindrical Wall / B2F	(90°) (270°)	Radial Radial	74% 91%

Note) Recovery rates were those based on load-displacement relationship six hours after removal of pressure.

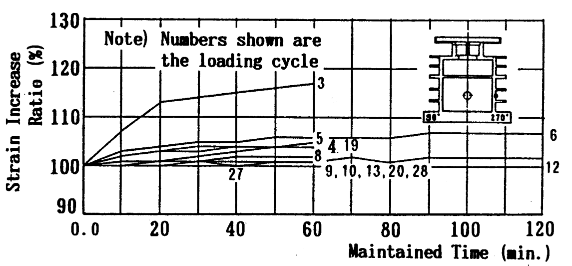


Figure 10 Re-bar strains due to Maintenance of Internal Pressure [Cylindrical Portion (B2F) Outer Circumferential Reinforcement]

Table 6 Comparion of Initial Stiffness (kgf/cm²/cm)

Part	Exp.	FEM	Exp/FEM
Top Slab (0°) /Opening Edge Vertical direction	3.40	3.50	0.97
Pool Girder /Middle Top Vertical direction	7.74	7.95	0.97
Cylindrical Wall /B2F (90°) Radial direction	18.68	17.14	1.09

* Tangent modulus at P_D=0.8kgf/cm²

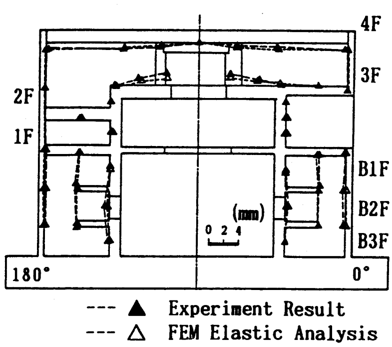


Figure 11
Comparions of Deformation Properties at Testing Pressure (1.15P_D)

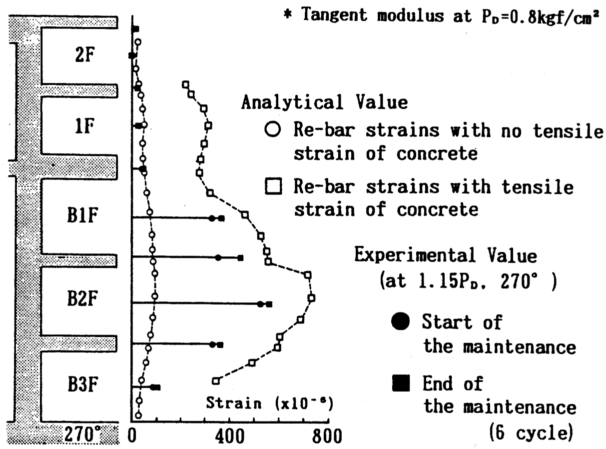


Figure 12 Strain Distributions of Outer Circumferential Re-bars