Experimental Study on RCCV of ABWR Plant Part 7: Horizontal Force Test of Total Model (1/6th Scale)

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1. INTRODUCTION

One of the objectives of this study is to confirm the integrity of the trial-designed RCCV structure with regard to horizontal earthquake force. Load-deformation, load-strain, cracking patterns and variation in stiffness were obtained by the experiments and these data were used for Evaluation of the integrity of the RCCV and Reliability of several kinds of design stresses. Furthermore, the data to grasp the mechanical properties at higher than design load level and horizontal ultimate strength of the RCCV were also obtained.

2. SPECIMEN AND TESTING PROCEDURE

The specimen is a 1/6-scale total model of the trial-designed RCCV. Testing program was formulated with the main purpose of grasping the structural behaviors of an RCCV connected integrally with the reactor building. The experiment was advanced by using the same specimen as shown in Fig.1 of "Out line of Horizontal Force Loading Apparatus" which was reported previously and loading steps were set up as shown in Fig.2.

Horizontal alternated force was applied to the top slab floor (T/S) and the diaphragm floor (D/F) of the specimen using hydraulic jacks at the rate of 1 : 1, so as to simulate the trial design moment and shear force of RCCV.

Besides the load of horizontal force during earthquake, internal pressure load and thermal load were applied to the specimen. After termination of the loading experiment with only the horizontal force, the combined loading experiments, namely, the combined applications of thermal load + horizontal force loading, thermal load + internal pressure + horizontal force loading were conducted.

Maximum load was confirmed by horizontal force only.

The loads acting on the specimen are given in Table 1, and the figure of the specimen after final failure is shown in Photo 1.

Measurements were made on loads, displacements, strains, temperatures and cracks.

3. TEST RESULTS

3.1 Outline of Loading Tests (Fig.2 to Fig.3)

In the horizontal force test (15th cycle), horizontal flexural cracks were found in the base portion of the cylinder at Q=360tf, of approximately 57 percent of the design load. As the load was further increased, shear cracking occurred at the web portion of the cylinder at Q=400tf, of approximately 63 percent of design load. At design load Q_D=632tf, the crack width at the web portion of the cylinder was about 0.06mm. Horizontal flexural cracking of the box walls occurred at Q=520tf, of approximately 82 percent of the design load.

At thermal + horizontal force load (21st cycle), there was little new occurrence of cracking due to load corresponding to design horizontal load other than the cracking at the time of the testing at internal pressure.

At thermal + internal pressure + horizontal force load (23rd, 24th, 25th cycles), there was little new occurrence of cracks, although there was growth of crack length and increase of crack width.

At horizontal load (31st cycle), ($1.5Q_D$), the widths of diagonal shear cracks in the cylindrical portion increased greatly compared with the widths at 23rd cycle and were about 0.20mm. New cracks were also formed.

When horizontal force was increased further (32nd cycle), the diagonal cracks in the cylindrical portion increased in number when compared with 31st cycle and cracks widths also increased. At 2,311tf (average shear stress. τ=85.5kgf/cm^2, where τ=Q/Aw, Aw=total cross-sectional area of cylindrical portion/2), which is more than 3.5 times the design horizontal load, shear crushing of concrete was observed in the vicinity of the cylinder base, but the specimen still supported the load.

On again loading with horizontal force, the bottom story web portion of the cylinder showed shear compression failure at 2,091tf.

3.2 Load-Displacement Relationships (Fig.4 to Fig.5)

When horizontal force was applied, the horizontal displacement of the specimen at the D/F slab location was δ=2.76mm deformation angle, ($R=0.83\times10^{-3}$ rad). It may be said from this value that there was still an allowance from the standpoint of deformability of other wall research work. The maximum strength was Q=2,311tf (shear stress τ=85.5kgf/cm^2), and the deformation angle at this load was $R=9.6\times10^{-3}$ rad. (D/F slab location)

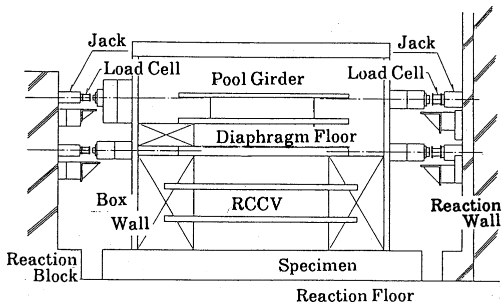


Fig.1 Outline of Horizontal Force Loading Apparatus

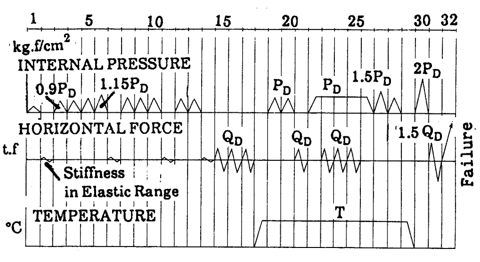
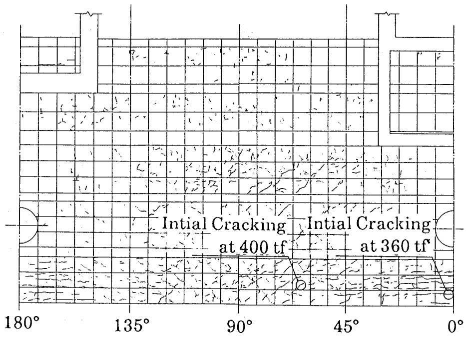


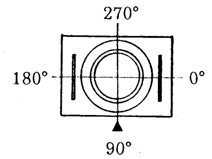
Fig.2 Loading Steps in Large-scale Total Model Experiments

Table 1 Loads Made to Acting on Specimen

Load	Description	Loading Condition
Horizontal Force	Design horizontal force Q_D τ = 23.4 kgf/cm^2 Aw (effective shearing cross-sectional area) = 27027 cm^2	632 tf (base of cylinder)
Internal Pressure	Design internal pressure (P_D)	3.16 kgf/cm^2
	Testing internal pressure ($1.15\times P_D$)	3.64 kgf/cm^2
Temperature	During normal operation (winter)	Water temperature 40°C



Cracking Pattern at 15th Cycle (Q_D=632 tf Crack Width at Cylindrical Portion about 0.06 mm)
-------- Positive Direction Horizontal Load
———— Negative Direction Horizontal Load



key plan for Fig. 3

Fig.3 Cylindrical Portion Exterior Cracking Pattern (at 632tf Horizontal Force Loading)

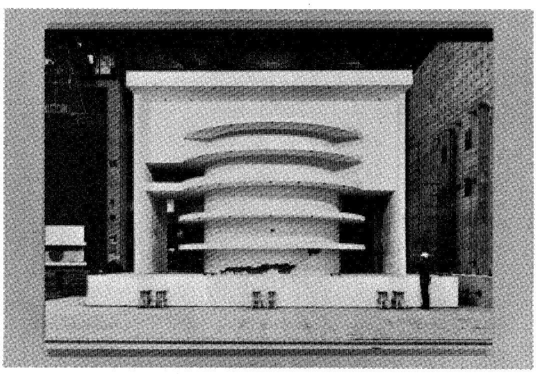


Photo 1 Ultimate Failure Condition of Specimen (General View)

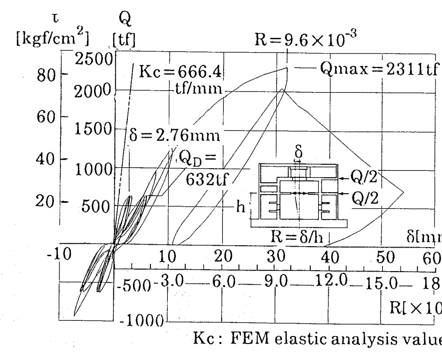


Fig.4 Horizontal Force-D/F Slab Location Horizontal Displacement

3.3 Deformation Mode (Fig.6)

Lateral deformation of the lowest story was large, but the story-drift of B2F where the tunnel opening is located was also of large deformation mode. Shear compression failure occurred at the lowest story, and B2F showed similar failure mode.

3.4 Separation of Deformation (Fig.7)

The flexural deformation at the design load level was around 20 percent and the shear deformation was 80 percent. At maximum load the ratio between flexural deformation and shearing deformation percentages became 24 : 76 for a slight increase in flexural deformation.

3.5 Load-Strain Relationships (Fig.8 to Fig.9)

The maximum value of measured strain in main reinforcement at design horizontal force was 641×10^{-6} in meridional bars at B2F of the RCCV cylindrical portion, which was 32 percent of yielding strain. The strains at other principal parts were also less than 1/4 of yielding strain, and all values were less than the long-term allowable stress intensities of the re-bars.

The first yielding of re-bars occurred at 1,541tf (2.4 times design load) with box wall base longitudinal bars, and at 1,664tf (2.6 times design load) with cylindrical portion base flange-side meridional bars, followed in order by meridional bars at the web side and then by circumferential bars at web side.

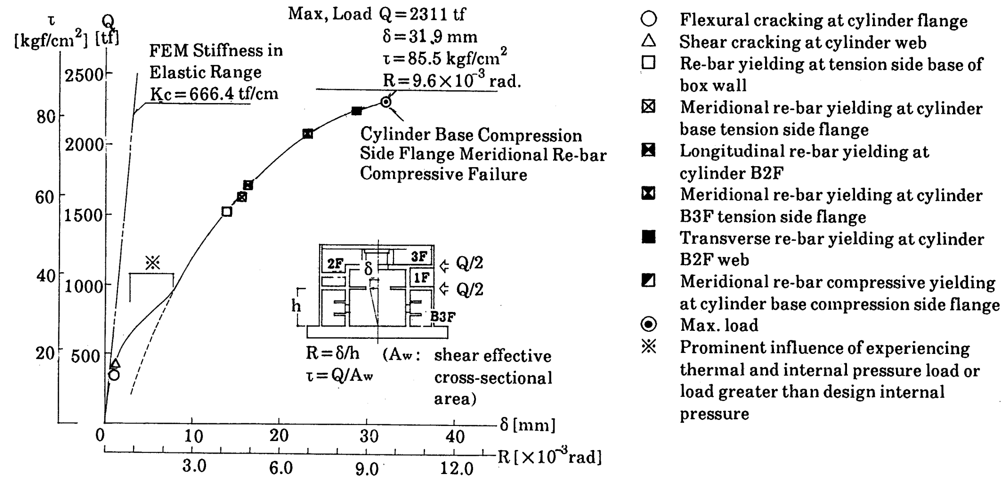


Fig.5 Horizontal Force-Horizontal Deformation (D/F Slab-Location) Envelope

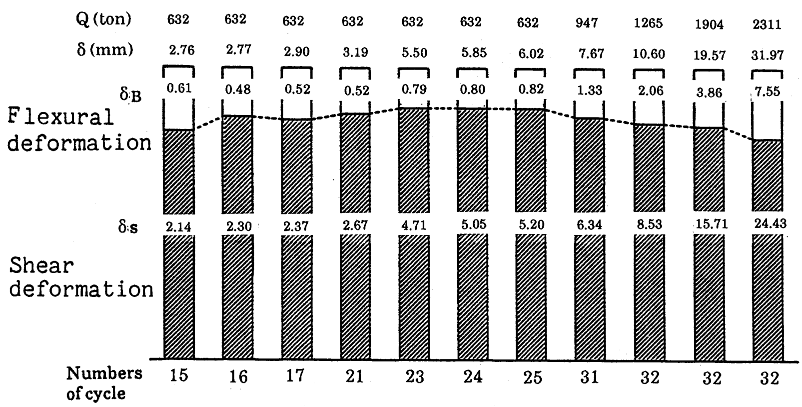


Fig.7 Separation of Deformation (D/F Slab Location)

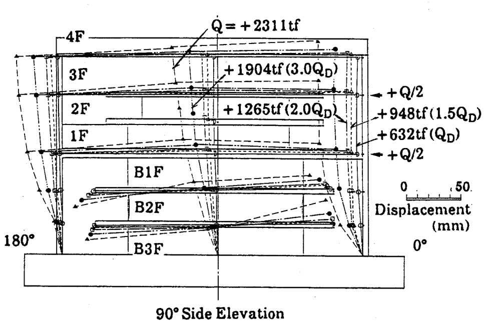


Fig.6 Deformation in Positive Direction under Horizontal Load

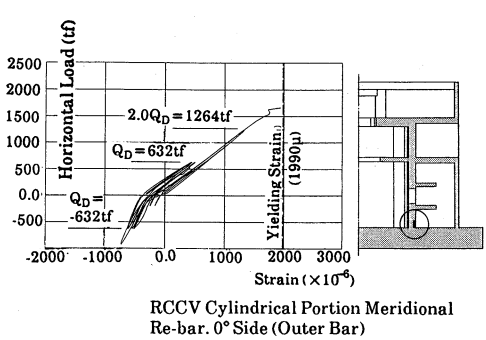


Fig.8 Re-bar Strain (Horizontal Load)

3.6 Variation in Stiffness (Table 2)

The stiffness in the elastic range were about 85 percent of FEM analysis values. Horizontal stiffness decreased after experiencing internal pressure. The reduction in stiffness due to repetitions of the design horizontal force was around 5 percent.

3.7 Various Strengths under Horizontal Force (Table 3, Fig.10)

The maximum horizontal shear force (Qmax) was 2,311tf and τ=85.5kgf/cm^2. The value was $4.95\sqrt{Fc}$ kgf/cm^2, surpassing the in-plane shear stress of $3.5\sqrt{Fc}$ kgf/cm^2 in the Draft MITI-CCV Design Code. The experimental value exceeded all of the calculated values of horizontal shear strength equations by about 20 to 40 percent.

Incidentally, the yielding load of the meridional bars of the cylindrical flange portion was 1,660tf, while the calculated value of yielding load determined by using beam theory method was around 1,550tf, and about 7 percent lower than the experimental value.

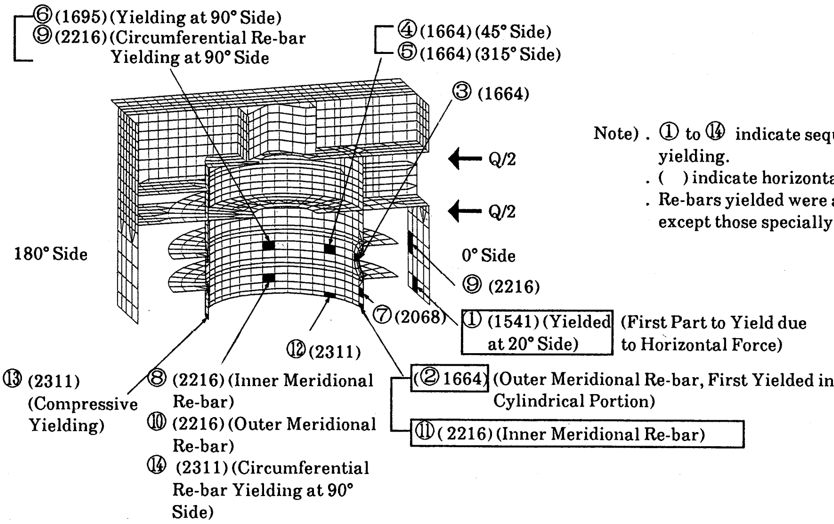


Fig.9 Parts and Sequence of Re-bar Yielding under Horizontal Load

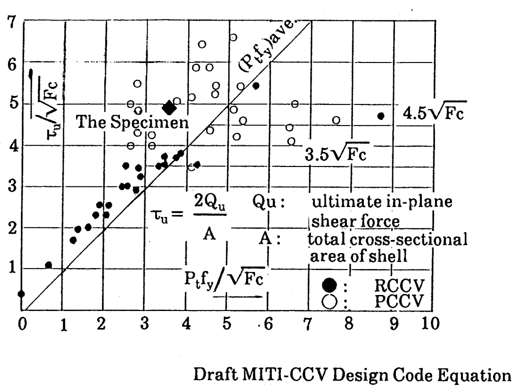


Fig.10 In-plane Shear Evaluation Equation and Results of Experiments

Draft MITI-CCV: The Technical Standard on CCV for Nuclear Power Plants of the Ministry of International Trade and Industry of Japan.

$$\tau u = \frac{1}{2}\{Pt\phi \cdot fy - \sigma_0\phi) + (Pt\theta \cdot fy - \sigma_0\theta)\}$$
$$\text{and } \tau u < 3.5\sqrt{Fc}$$

fy : Re-bar yielding stress

$Pt\phi$, $Pt\theta$: Bar ratios of longitudinal and circumferential direction.

$\sigma_0\phi$, $\sigma_0\theta$: Membrane stresses of longitudinal and circumferential direction.

Fc : Compressive strength of concrete

Table 2 Horizontal Stiffness Decrease after Action of Testing Internal Pressure (D/F Slab Location)

Cycle No.	D/F Slab Location		
	Stiffness, tf/mm (Experimental Value)	Comparison with 2nd Cycle	Comparison with FEM Analysis (666.4 tf/mm)
2nd	568.2	1.00	0.85
7th	432.2	0.76	0.65
11th	388.0	0.68	0.58
14th	390.8	0.68	0.59

2nd Cycle : Stiffness in elastic range
7th Cycle : Stiffness after experiencing internal pressure load 1.15 P_D (3.64 kgf/cm^2)
11th Cycle : Stiffness after experiencing internal pressure load P_D (3.16 kgf/cm^2) three following 7thCycle
14th Cycle : Stiffness after further repetition two times of internal pressure load at P_D (3.16 kgf/cm^2) (once maintaining the internal pressure for 6 hours)

Table 3 Comparisons of Experimental and Values Calculated (Cylindrical Portion)

Various Strengths	Experimental Value a	Calculated Value b	a/b	Remarks
Horizontal Shear Strength (tf)	2311	1636	1.41	Draft MITI-CCV Design Code
Flange Longitudinal Bar Yielding Load (tf)	1660	1550	1.07	Beam theory
Bending Strength (tf)	2311	2331	0.99	Total plasticity equation

4. CONCLUSIONS

On comprehensive judgment of the foregoing, it is considered that the experimental data obtained by large scale total model provide adequate data for evaluation of the following Integrity of the RCCV, Maximum strength of RCCV and Appropriateness of design technique.

4.1 Integrity of RCCV

With application of horizontal load, displacement at the D/F slab location at design horizontal load was 2.76mm (R=0.83 $\times 10^{-3}$ rad.). The deformation angle was small compared with the maximum deformation angles of 4 to 6 $\times 10^{-3}$ rad. in other shear wall experiments and found to be appropriate. Re-bar strains were within allowable stress intensity limits. Regarding the cracks, shear cracks were formed at the lower stories of the cylinder, but widths were small and of condition that cracks would close when loading was reduced.

4.2 Maximum Strength of RCCV

The maximum horizontal load was Q=2,311tf (τ=85.5kgf/cm^2) and 3.6 times the design horizontal load. This value was on the higher side compared with the values from various strength calculation formulae for an evaluation on the conservative side.

4.3 Appropriateness of Design Technique and Applicability of Design Criteria

The in-plane shear strength equation and other items in the Draft MITI-CCV Design Code adopted in the design resulted in a design giving an evaluation on the conservative side.

5. ACKNOWLEDGMENT

This study has been carried out as a part of a joint research study on "The Evaluation of the RCCV Configuration and Comfirmatory Test to Establish a Code".

6. REFERENCES

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