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Structural integrity tests of the prestressed concrete containment vessel at Genkai nuclear power station

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ABSTRACT : This paper presents the results of structural integrity tests(SIT) carried out for the 3-buttress type prestressed concrete containment vessel(PCCV) at Genkai Unit No.3 Nuclear Power Station(Pressurized Water Reactor, 1180 Mwe) owned by Kyushu Electric Power Company. The tests were performed in order to confirm that the PCCV had enough structural integrity for the design pressure of 4.0kgf/cm². The tests were conducted in Feb. 1993, and the maximum test pressure was 4.5kgf/cm². Displacements, strains, temperatures and cracks of the PCCV were measured. From the test results and evaluations, it was confirmed that the PCCV had sufficient structural integrity against the design pressure.

1 OUTLINE OF THE PCCV OF GENKAI UNIT NO.3

The outline of the PCCV of Genkai Unit No.3 is shown in Fig.1. The PCCV is composed of a hemispherical top dome(inside diameter:43.0m, wall thickness: 1.1m), a cylindrical shell(inside diameter:43.0m, wall thickness:1.3m) and a base mat(reinforced concrete of thickness 9.8m). The base mat has a tendon gallery to anchor inverted U tendons. The hemispherical dome and the cylindrical shell have three vertical buttresses to anchor hoop tendons. Vertical-direction prestress was introduced by inverted U tendons arranged in two orthogonal directions at the dome top, and circumferential-direction prestress by hoop tendons set at the central angle of 240 degrees. They were tensioned to assure a prestress level greater than the design pressure for 40 years. The perestressing system is the BBRV post-tensioning system with 7mm-163 wires and the capacity of one tendon is 1000t·f.

2 TESTING METHOD

2.1 Pressurization Method

The test was performed according to the pressure sequence shown in Fig. 2. The pressurization rate was about 0.1kgf/cm² per hour. Maximum pressure of 4.54kgf/cm² was reached after three days. The depressurization rate was about 0.2kgf/cm² per hour.

2.2 Measurement Method

Displacements, strains, temperatures and concrete surface cracks of the PCCV were measured.
The basic locations for measurement are shown in Fig. 1. In plan 11 points from A to K and in section 10 points from 1 to 10 were selected. Measurement locations are represented such as '7H'.

1) Displacements

Displacements were measured at 53 points on the PCCV, and at 6 points on the internal concrete structure using super invar wires(ϕ=1.2mm) and linear variable displacement transducers. In addition, displacements of the basemat were measured at 4 points by measuring slope angles. The arrangement of invar wires is shown in Fig. 3. When a direction of a wire is different from radial or vertical direction, we performed angle correction to gain an exact displacement.

2) Strains

Strain measurements were made with electrical resistance strain gages, which also can measure temperatures at the same time, at inside and outside reinforcing bars to get membrane strains and bending strains in both circumferential and meridian directions. Total points were 160.

3) Temperature

Temperatures of the PCCV were measured using thermocouples at three points, inner side, center and outer side of wall, to obtain thermal distributions. Measured points were total 265, together with strain gages. These results were used to estimate thermal displacements and thermal strains. At the same time air temperatures inside of the PCCV(8 points), and outside of the PCCV(4 points), were measured.

4) Inspection of Concrete Surface Cracks

Crack inspections were made at 8 zones which were selected considering typical stress conditions. They were the intersecting portion of the cylindrical shell and dome, the portion at mid-height of the cylindrical shell, the intersecting portion of the cylindrical shell and basemat, the intersecting portion of the cylindrical shell and buttress, a small penetration area, a periphery of E/H, and peripheries of two air locks. Measurements were conducted four times, before pressurization, in the midst of pressurization, at maximum pressure, and after the end of depressurization. Cracks were noted about the width and the length for crack widths in excess of 0.2mm.

5) On-Line Measurement System

Measurement instruments were connected with the control room by cables. Data were automatically measured and recorded, and to observe the data in real time, a 16 inch color monitor was used.

3 SIMULATION ANALYSIS

In order to predict the test result, we performed three-dimensional FEM elastic analyses. The following two models were used.

1) Overall mode(shell elements)
2) Partial model with E/H and A/L(brick and shell elements)

Adopted equivalent Young's modulus, E_e=3.97×10^5kgf/cm², was obtained similarly to the way described in Ref.2 for the specified concrete strength of 420kgf/cm².

4 TEST RESULTS AND EVALUATION

4.1 Displacements

Representative internal pressure-displacement relationships for the dome apex(vertical direction) and the periphery of the E/H(radial direction) are shown in Fig.4. The relationships show almost elastic behavior of the PCCV. Partial non-linear behavior was caused by the change in the average temperature of the PCCV wall. From Fig.5 we can see clearly the change of displacement by the change of average temperature in wall, even though internal pressure is held at a constant value. Displacement distributions of radial direction are shown in Fig.6 for representative sections C and 7. From the displacement distribution of section 7, it can be said that the displacements in theperiphery of a large opening with added wall thickness toward the inside of the PCCV become enlarged, and the displacements at the buttresses with added wall thickness toward the outside of the PCCV become small. Table.1 shows the comparison between measured and calculated displacements of the dome apex(vertical) and section 7(radial) at the maximum pressure. The ratios of the measured values to the calculated values by simulation models are an average of 0.95 for general portions and buttresses, and an average of 1.01 for the periphery of E/H. They show fairy good coincidence. Table. 1 also shows residual displacements at the end of depressurization. The average ratio of recovery was 95%. Thus, we could evaluate that the PCCV behaved elastically.

4.2 Strains

Representative relationships between internal pressure and membrane strains at mid-height of the cylindrical shell are shown in Fig7. It is said that the relationships display elasticity quite well.

4.3 Correspondence of Displacements and Strains.

Regarding radial direction, the displacements determined from membrane strains and measured displacements were compared. They showed comparatively good agreement. Hence it can be said that the measured results are precise.

4.4 Inspection of Concrete Surface Cracks

As a result of crack inspections, significant cracks raising concerns about structural integrity were not found at the maximum pressure. At eight inspection zones, only one zone had fine cracks due to shrinkage before pressurization, but we could not find cracks with widths exceeding 0.2mm at the maximum pressure.

5 CONCLUSIONS

The following conclusions can be made as a result of SIT of the PCCV for Genkai Unit No.3.
1) Pressure-displacement relationships and pressure-strain relationships were almost linear showing that the PCCV behaved elastically.
2)The measured displacements and strains coincided well with calculated values at the maximum pressure. Thus, it was also confirmed that the PCCV behaved elastically.
3) The average ratio of the displacement at the end of depressurization to the displacement at the maximum pressure was about 5%, namely the residual displacements were quite small.
4) The measured displacements agreed well with the measured strains. Thus the test results are reliable.
5) As a result of crack inspections, structural cracks were not observed.

Consequently, it was confirmed that the PCCV for Genkai Unit No.3 had sufficient structural integrity for the design pressure. Furthermore, through experiences together with 3 Units shown in Ref.1 and Ref.2, we can consider that the practices and the evaluations of SIT have been established in Japan.

REFERENCE

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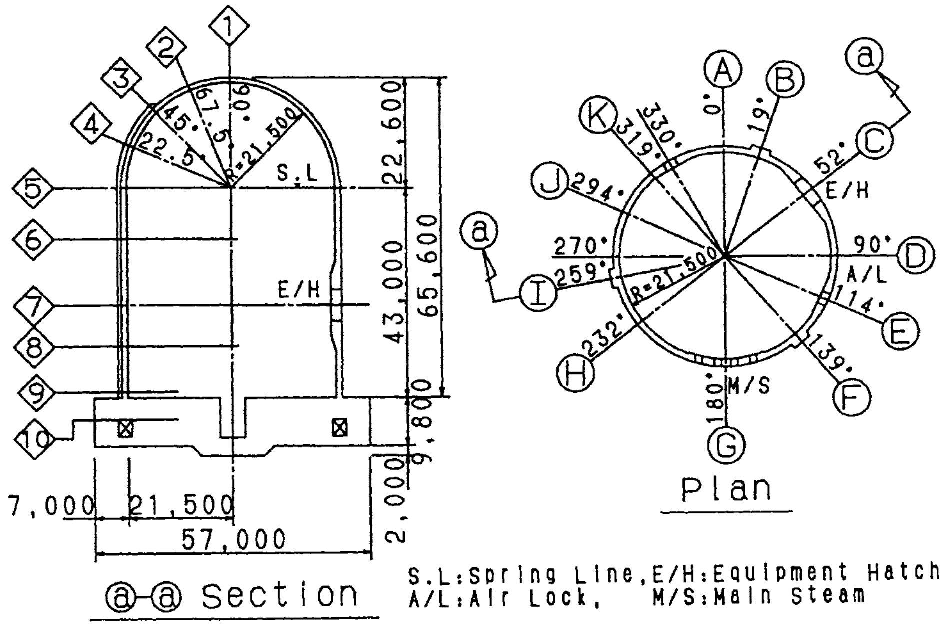

Fig. 1 Outline of PCCV and Basic Location for Measurement

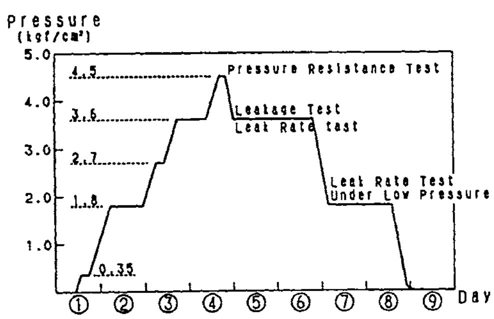

Fig. 2 Pressure Sequence

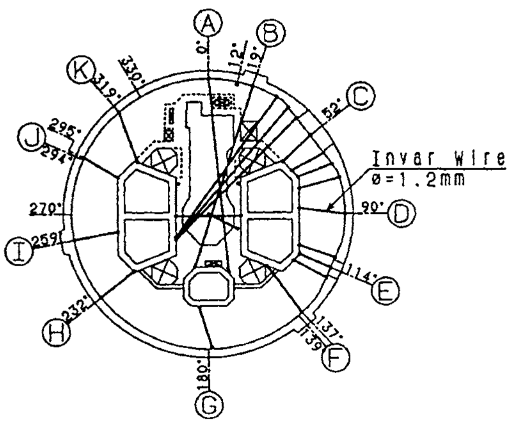

Fig. 3 Arrangement of Invar Wires

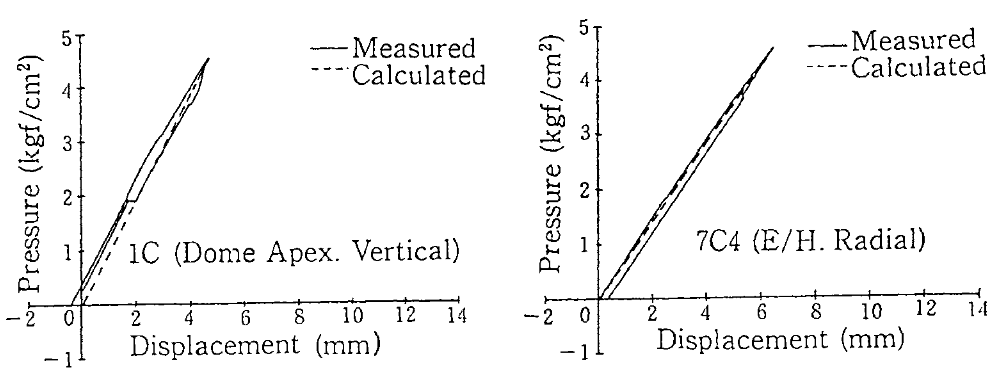

Fig. 4 Pressure-Displacement Relationship

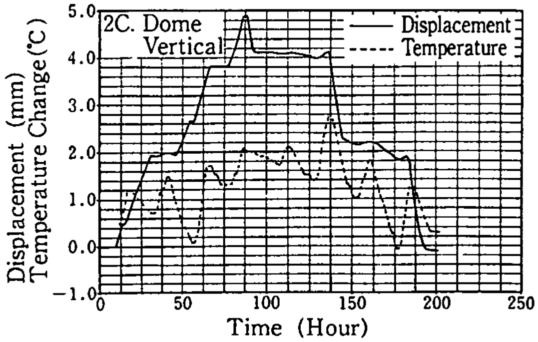

Fig. 5 Displacement and Average Temperature Variation of PCCV

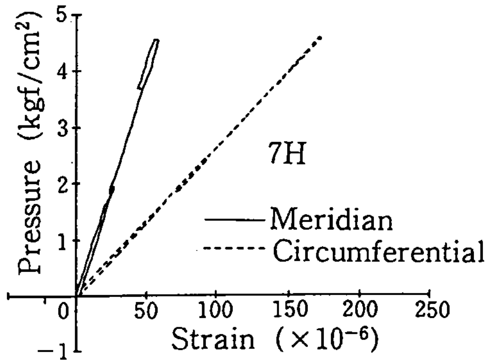

Fig. 7 Pressure-Membrane Strain Relationship

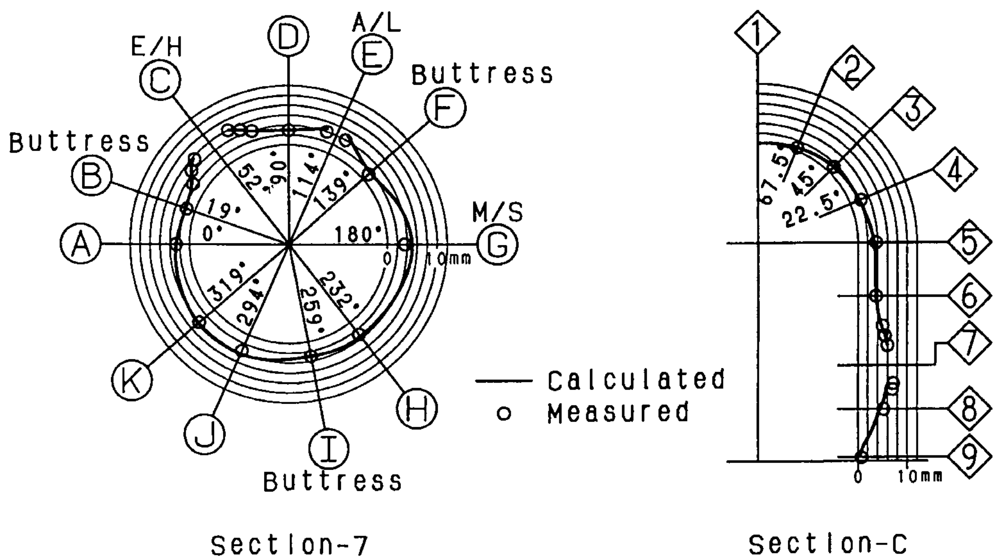

Fig. 6 Displacement Distributions of Radial Direction

Table. 1 Displacements at Maximum Pressure(4.54kgf/cm²) and Residual Displacements

Location	Direction	Maximum Displacement		δ_m/δ_c	Residual Displacement δ_r (mm)	δ_r/δ_m
		Measured δ_m (mm)	Calculated δ_c (mm)			
1C (Dome apex)	Vertical	4.52	4.60	0.98	-0.26	-0.06
7B (Buttress)	Radial	1.72	1.96	0.88	0.12	0.07
7D	Radial	3.18	2.99	1.06	0.08	0.03
7H	Radial	2.91	3.52	0.83	0.40	0.14
7K	Radial	4.21	4.57	0.92	0.19	0.05
7C3 (E/H.Left)	Radial	5.40	5.77	0.94	-0.17	-0.03
7C4 (E/H.Right)	Radial	6.13	6.16	1.00	0.23	0.04
7C9 (E/H.Above)	Radial	5.91	5.87	1.01	0.24	0.04
7C10(E/H.Below)	Radial	6.91	6.56	1.05	0.97	0.14