PSEUDO-DYNAMIC TESTS ON THE MODEL OF A REINFORCED CONCRETE CONTAINMENT VESSEL SUBJECTED TO EARTHQUAKE AND THERMAL STRESSES

Toshihiko Hisada (I)
Koji Ishii (II)
Akira Endoh (II)
Naoki Tanaka (III)
Presenting Author: N. Tanaka

SUMMARY

This report explains the results of pseudo-dynamic and static loading tests performed on the model of a reinforced concrete containment vessel (RCCV) which is subjected to earthquake and thermal stresses during the normal operation. In the pseudo-dynamic test, the earthquake response behavior of the structure can be clarified while performing static loading tests.

As the results of these tests, it was confirmed that the RCCV under the thermal stresses had sufficient structural safety for seismic motion.

OBJECTIVE

In the worst case, the RCCV receives thermal stress during the normal operation, and in an accident, internal pressure and seismic force simultaneously.

Although the results of some studies on the combined stresses of the internal pressure and the seismic force have been reported[1)], examples of studies on the combined stress of the thermal load and the seismic force have not been reported. Therefore, we tested the RCCV to observe its earthquake-proofness during normal operation. The objectives of these tests are as follows.

1) To understand the mechanical characteristics of RCCV when subjected to thermal stress.
2) To understand the restoring force characteristics of RCCV which receives a thermal load during normal operation against a lateral load.
3) To prove the structural safety of RCCV during large seismic motion.

SPECIMENS

In this study, the specimens of a 1/25 cylindrical shell model shown in Fig. 1, which are the same as those used in the past test of the simultaneous application of the internal pressure and the lateral force

(I) Standing Advisor, Kajima Institute of Construction Technology, Japan

(II) Senior Research Engineer, Kajima Institute of Construction Technology, Japan

(III) Research Engineer, Kajima Institute of Construction Technology, Japan

performed by Dr. Uchida and his group[1], are used to compare the results of both tests. The specimen have both 1.6 m in diameter and height, and 6 cm in thickness, and reinforcement deformed steel bars (D6) are placed lengthwise and crosswise at intervals of 45 mm. The ratio of reinforcement is 2.4%. The shell is made of micro-concrete which contains only aggregate whose diameter is 5 mm in maximum. The mechanical properties of these materials are shown in Table 1.

TEST PROGRAM

We performed the following four kinds of tests.

a. Elastic loading test... A lateral load less than the cracking load is applied to the specimen without applying the thermal load to test the elastic stiffness.

b. Thermal loading test... The inside of the specimen is heated with a membrane coil heater and the outside is cooled with a water spray to provide a specified difference in temperature between the inside and outside of the cylindrical shell (In the case of a structural model, the temperature inside the vessel is assumed to be 57°C, and the outside temperature in winter is assumed to be 10°C. The difference in temperature between the inside face and outside face of vessel under the prescribed condition is assumed to be 26°C) to observe the behavior of the specimen (See Fig.2).

c. Pseudo-dynamic test... A lateral load equivalent to the seismic force is applied to a specimen subjected to a thermal load. For this test, a pseudo-dynamic test method[2)-4)] shown in Fig. 3 was used in which static loading tests and earthquake response analysis are conducted alternately in a single computer controlled system, and the responses of the structure are analyzed using experimentally measured restoring forces during the test. For the earthquake wave, a wave which may be produced by near field earthquake in high seismic zones suggested by MITI is used. The duration of the earthquake is six seconds (See Fig. 8). Two kinds of maximum acceleration, 400 gals and 700 gals, are input in order (The time step is 0.01 second). In the response calculation, a full-sized structure model was substituted for by a bending-shear model of one lumped mass system by using the method shown in Fig. 4.

d. Static loading test... A lateral load is applied to the specimen with a thermal load until the specimen fails to obtain the maximum strength and deformation capacity.

LOADING AND MEASURING METHOD

The test procedure is as shown in Fig. 5. For the loading test, two actuators with 100 tons capacity and two other actuators with 50 tons capacity were used to push the specimen from one side and pull it from the opposite side at the same time. For the measurements of the specimen, the horizontal displacement, vertical displacement, and swell of the cylinder shell were measured with digital displacement meters and electric dial gauges. To measure the temperature and strain of the specimen, thermal gauges and strain gauges with known thermal characteristics were stuck to vertical and horizontal steel bars.

TEST RESULTS AND DISCUSSION

The test results and the discussion thereof are as follows.

(1) Elastic loading test

When a lateral load of up to about 5 tons was applied to a specimen, the average stiffness was 345 t/cm, which is approximately 80% of the 434 t/cm calculated by considering the bending deformation and the shear deformation.

(2) Thermal loading test

The internal and external thermal transition of the shell at the middle height of the specimen is shown in Fig. 6. About one hour after heating started, the temperature was set to a steady state, and the difference in temperature between the inside face and outside face of the cylinder shell was approximately 20°C.

In a steady state, the strain of the horizontal reinforcing bars was maximum at the middle height of the cylinder shell, which was approximately 100×10^{-6}. Although the strain at the base of one vertical bar was 400×10^{-6}, the strain of other vertical bars was less than 100×10^{-6}. The tensile strain of the outside horizontal bar at the middle height was almost equal to the compressive strain of the inside bar.

From the condition of this strain, it was proved that the shell is not cracked through. The cracks were fine and appeared along the horizontal and vertical bars in a network pattern.

(3) Pseudo-dynamic test

The results of the test on the specimen are shown in (a) and (b) of Fig. 7 and Fig. 8. The maximum response value for the load, deformation, acceleration and the stiffness are shown in Table 2. The maximum response values of deflection angles were 0.32×10^{-3} and 0.64×10^{-3} rad. respectively when an acceleration of either 400 gals or 700 gals was applied (Deflection angle = δ/h, δ: Horizontal displacement of the specimen, h: Height of specimen). And the maximum strain was approximately 500×10^{-6} (measured at the vertical bar when 700 gals was input). The bending cracks and shearing cracks are both few and fine. The average stiffness measured when 400 gals was input was approximately 65% of the measured value during the elastic loading test performed at first, which means that the stiffness was lowered by 35% as a result of the thermal loading test. The acceleration amplification factor related to the response of the structure of the model structure simulated in the computer was approximately 2.0 when either 400 gals or 700 gals was input.

(4) Static loading test

The test results are shown in (c) in Fig. 7 and in a part of Table 2. The major test process is described as follows.

When a load of 75.2 tons was applied in the No. 7th cycle, the vertical bars at the base of the flanges yielded. And when the maximum load of

100.6 tons was applied, in the No. 8th cycle, the deformation was 18.5 m (deflection angle: 10×10^{-3} rad.), the specimen was twisted, and a torsional slip failure occurred at the central section of the cylinder shell where the shearing cracks were connected. This was caused by uneven forces applied by the four actuators when a part of the specimen failed. After the failure, the load was applied as the No. 9th cycle until the deflection angle was 15×10^{-3} rad., and the load was considerably lowered. Fig. 9 shows the cracking pattern at the maximum load. If the yielding load of the steel bar is calculated by supposing that the section remains plane after deflection and by assuming that the specimen is a cylindrical column, it becomes 78.8 tons, which is almost the same as the value obtained by the test. If the maximum shear strength 'Qsu' is calculated by using the experimental formula (Formula (1)) obtained by processing the experimental data statistically, it becomes 146 tons. In addition, if the maximum bending strength 'Qmu' is calculated by the formula[5] (Formula (2)) obtained by approximating the steel bars as rings and using the yield stress at the maximum strength point and by assuming the distribution of the stress of the concrete on the compressive side as a rectangle of 0.85 Fc, it becomes 111 tons. Both of these calculated values are larger than the 100.6 tons obtained by the experiment.

$$Qsu = Aw.\left[\frac{0.0679.Pt^{0.23}(180 + Fc)}{\frac{M}{QD} + 0.115} + \frac{1}{2}(Ps.\sigma y + 2.7\sqrt{Ps.\sigma y})\right] \quad \text{......... (1)}$$

$$Qmu = \frac{1}{h}.2Tr^2\pi Ps.\sigma y \frac{\sin\theta 0}{\theta 0} \quad \text{.......... (2)}$$

$$\theta 0 = \frac{Ps.\sigma y}{Fc + 2Ps.\sigma y}$$

Where,

- Aw: Cross sectional area of the web of the cylindrical shell
- Fc: Compressive strength of concrete
- $\frac{M}{QD}$: Shear-span ratio
- Pt: Ratio of tensile reinforcement
- Ps: Ratio of reinforcement in a cylindrical shell
- σy: Yield point of a reinforcing bar
- h: Height of specimen
- t: Thickness of cylindrical shell
- r: Radius of cylindrical shell

These values obtained by the tests are compared with the values in Reference 1) in Fig. 10. The strength of the specimen used in this test is approximately 80% of that of the same specimen used in Reference 1, and approximately 65% of the maximum shear strength 'Q'su' obtained by the formula (3) in which it is assumed that the horizontal bars in the webs receive the shearing force until they yield.

$$Q's = Aw.Pw.\sigma y \quad \text{.......... (3)}$$

Where,

Pw: Ratio of shear reinforcing bar of the cylindrical shell

The reason for the low strength of the specimen used in this test seems to be that the specimen failed partially because of the tortional force previously described.

CONCLUSIONS

The test results are summarized as follows.

1) When the thermal load was applied so that difference in temeprature between the inside face and outside face of the cylindrical shell was approximately 20°C, the initial stiffness of the RCCV was lowered to approximately 65%, and the shell was not cracked through.

2) The RCCV was not damaged severely even if the earthquakes with peak accelerations of 400 gals and 700 gals occurred.

3) The maximum strength measured during the static loading test was 100.6 tons, which is approximately 4.1 times as large as the maximum response loading due to the earthquake with 700 gals acceleration.

Therefore, the RCCV subjected to thermal stress during normal operation have sufficient structural safety against large earthquakes.

ACKNOWLEDGEMENTS

We are deeply grateful to Professor Okada and Takanashi of the Institute of Industrial Science, the University of Tokyo, and Chief Watabe of the Building Research Institute of the Ministry of Construction and others for their useful advices on developing the system.

REFERENCE

1) T. Uchida, N. Ohmori, T. Takahashi, S. Watanabe, H. Abe, and Y. Aoyagi; "Behavior of Reinforced Concrete Containment Models under the Combined Actions of Internal Pressure and Lateral Force", 5th SMIRT Conference, Berlin, 1979, J4/4.

2) K. Takanashi, K. Udagawa, M. Seki, and H. Tanaka; "Seismic Failure Analysis of Structures by a Computer-Pulsator On-line System", -Japanese Edition-, "Seisan-kenkyu", Monthly Journal of Institute of Industrial Science the Univ. of Tokyo, Vol.26. No.11.

3) K. Takanashi, K. Udagawa, and H. Tanaka, "Pseudo-Dynamic Tests on a 2-Story Steel Frame by a Computer-Load Test Apparatus Hybrid System", 7WCEE, Istanbul, Turkey, Sept. 1980, pp. 225 - 232.

4) T. Okada, M. Seki and Young J. Park, "A Simulation of Earthquake Response for Reinforced Concrete Building Frames to Bi-Directional Ground Motion by an IIS Computer-Actuator On-line System", 7WCEE, Istanbul, Turkey, Sep. 1980, pp. 41 - 48.

5) Architectural Institute of Japan "AIJ Standards for Structural Calculation of a Reinforced Concrete Stack", -Japanese Edition- 1976

Table 1 Mechanical Properties of Materials

Concrete

Member	Compressive Strength (kg/cm^2)	Tensile Strength (kg/cm^2)	Young's Modulus (t/cm^2)
Cylinder	324	23.3	184
Slab	372	-	-

Reinforcing Bar

Yield Strength (kg/cm^2)	Tensile Strength (kg/cm^2)	Young's Modulus (t/cm^2)	Elongation (%)
4280	5500	1900	25.0

Table 2 Test Results

Kind	Maximum Shear Force (t)	Maximum Shear Strength * (kg/cm^2)	Deflection (cm)	Elastic Stiffness (t/cm)	Acceleration Amplification Factor (Model Structure) (Gal)
400Gal Test	14.3	9.5	0.060	220	842
700Gal Test	25.6	17.0	0.118	221	1380
Static Loading Test	100.6	66.7	1,850	-	-
Refference 1)	120.0	79.6	3,620	-	

* Effective Area is a half of Cylinder Section.

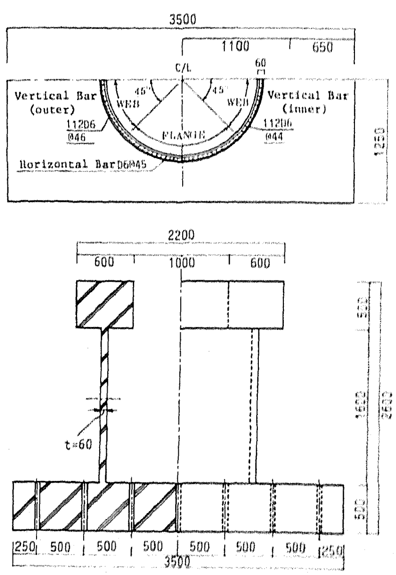

Fig. 1 Specimen

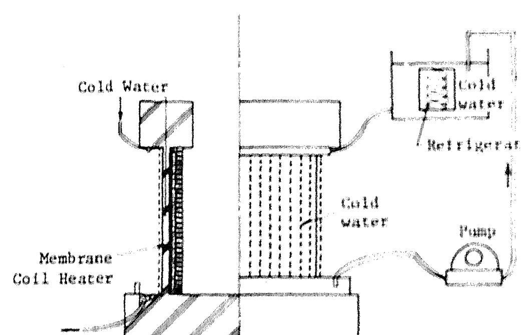

Fig. 2 Outline of Heating and Cooling Scheme

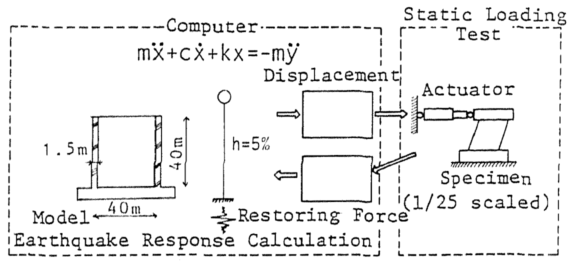

Fig. 3 Outline of Pseudo - Dynamic Testing Method

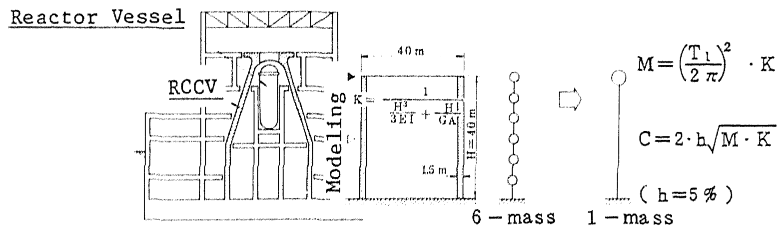

Fig. 4 Single Degree Conversion of Cylinder Shell

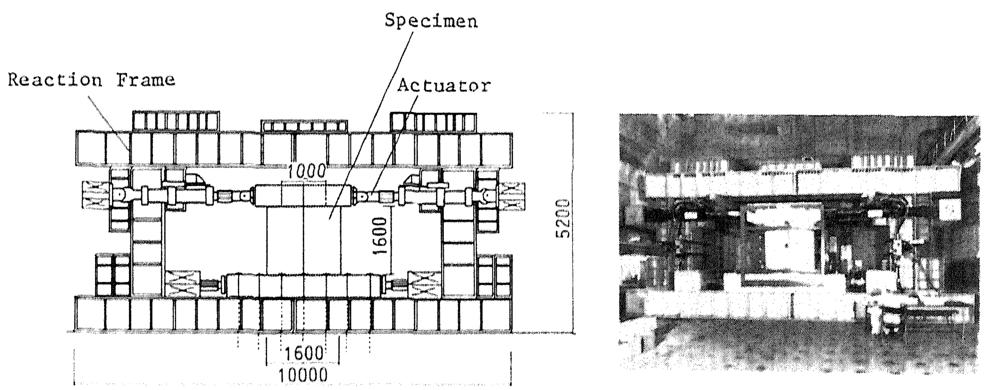

Fig. 5 Testing Setup

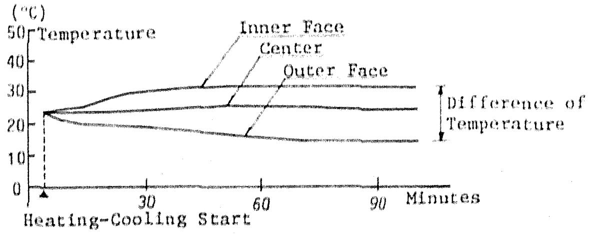

Fig. 6 Trasition of Temperature

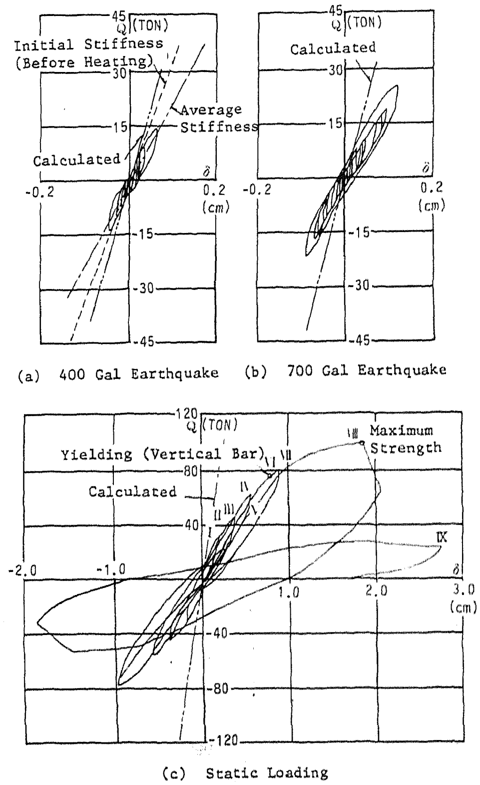

Fig. 7 Load - Deflection Curves

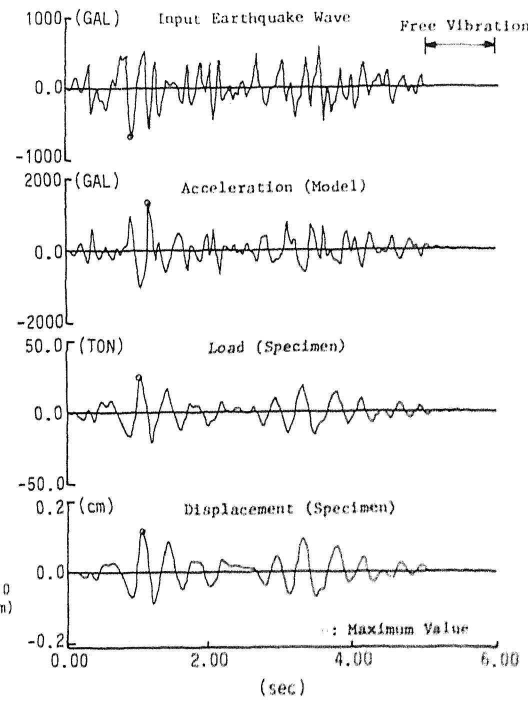

Fig. 8 Time-History of The Earthquake with 700 Gals Peak Acceleration

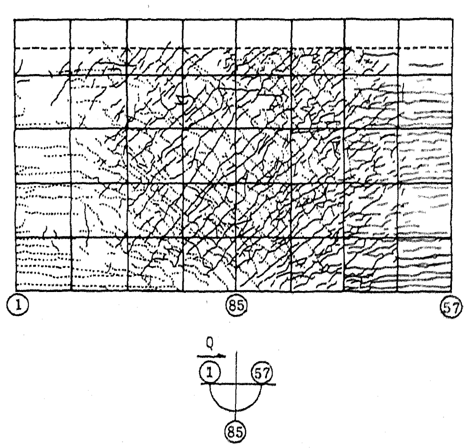

Fig. 9 Crack Pattern

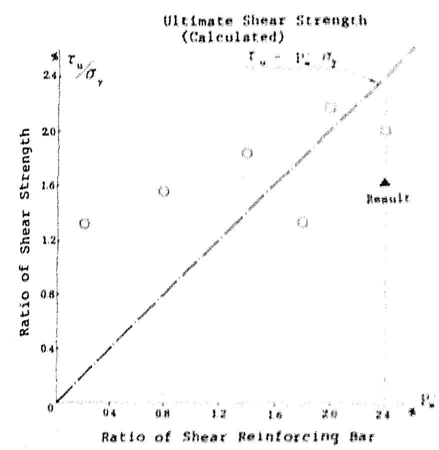

Fig. 10 Comparison of Maximum Strength