EXPERIMENTAL STUDY OF AIR LEAKAGE FROM CRACKS IN REINFORCED CONCRETE WALLS

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ABSTRACT

Nuclear power plant buildings must be air tight even if shaken by an earthquake of the strongest level (S1 level) of structural design after cooling materials have been lost.

This study was intended to research air leakage through shear cracks in walls. Tests were done on a three-dimensional one-tenth-scale specimen based on a part of a prototype BWR nuclear power plant. During the tests, the specimen was subjected to lateral load which simulate those caused by earthquakes. The amount of air passing through cracks in the specimen was measured at every level of lateral loading, while the load was being applied and also after it had been removed.

It was found that only very small amounts of air passed through cracks. Because nuclear power plant buildings have very thick walls, the air tightness of these buildings appears to be secure even after an accidental loss of cooling materials followed by a severe earthquake.

1. OBJECTIVES

A nuclear power plant structure must be airtight even after coolant has been released within the structure and it then experiences the strongest earthquake for which it has been designed (an S1 earthquake). Regulations limit air leakage to 100% per day at an atmospheric pressure difference of 62.7 Pa [6.4 mm aq.] for BWR type nuclear power plant.

This study was aimed at acquiring knowledge about the characteristics of air leakage from cracks in power plant structures caused by horizontal earthquake motion. Horizontal excitation experiments were performed on a structural model built to examine the aseismic properties of BWR nuclear power plant structures.

2. SPECIMEN

The specimen consisted of four walls contiguous with a foundation slab. A rigid slab was placed on top of the specimen for loading purposes. The wall were 2.00 m X 0.75 m. Wall thickness was 12 cm, or approximately one-tenth the thickness of an actual power plant wall. The design strength of concrete was 35 MPa [360 kgf/cm²]. The shear reinforcements of walls were arranged double crosswise and consisted of deformed bars 10 mm in diameter with a pitch of 9 cm. Ratio P_w was 1.32 %.

All interior surfaces of specimen except the walls were coated with elastic paint to enhance airtightness.

3. TESTING METHOD

3.1 Loading Procedure

Fig. 1 shows a schematic of the testing apparatus.

A constant vertical force of 1.9 MPa [20kgf/cm*2] was applied to the slab above the specimen by hydrolic jack throughout the test. A series of lateral loads in alternating directions were applied to the slab by hydrolic jacks. At the specimen's walls cracks width and deformation angle were measured during each loading of which peak load was controled by initial cracks load or a constant deformation angle and after the load was removed. Finally the specimen was destroyed to maximize deformation.

3.2 Measurement of air leakage

Table 1 showed estimation of the amount of air leakage.

The amount of air leakage was measured during and after loading in the minus cycle region. The two methods used to estimate air leakage which showed table 1. The method used was determined according to the amount of air leakage. Method A was used when there were few cracks in the walls. After air was withdrawn from within the specimen to a specified level of vacuum and the specimen was sealed tightly, the amount by which air pressure rose within the specimen as a consequence of air leaking into it was measured.

Method B was used when there were many cracks in the walls and much air leakage. Air was drawn from the specimen so that air pressure inside it was inclementally lowered to -490 Pa [-50mm aq.] until the difference between outside and inside pressure was constant, and the volume of air removed from the specimen was measured. For each increment, pressure difference P and amount of sucking air Q were measured, and the relationship between P and Q was estimated.

Table 1 Estimation of the amount of air leakage

Method	Formura	Note
A	$Q = \frac{100}{H} \cdot V \cdot \left(\frac{P_2}{P_1} \cdot \frac{T_1}{T_2} - 1 \right)$	Q : Amount of air leakage [ℓ/hr] H : Measuring time [hr] V : Volume of testing chanber [ℓ] P1, P2 : Absolute pressure of inside [mb] T1, T2 : Absolute temperature of inside [K]
B	$Q = a \cdot S \cdot \Delta P^{1/n}$	Q : Sucked air rate [ℓ/hr] a : Coefficient of air leakage [ℓ/hrm ² mmAq] S : Area of testing wall [m ²] n : Coefficient [1 ≤ n ≤ 2]

Fig. 1 Schematic of test apparatus

4. TEST RESULTS

Table 2. showed a list of test results. Fig.2 shows representative cracking patterns, and Fig.3 illustrates the relationship between averaged shear stress and deformation angle. The relationship between coefficient of air leakage and deformation angle is shown in Fig. 4, that between coefficient of air leakage and averaged shear stress at peak load in Fig. 5, and that between air leakage rate and pressure difference in Fig. 6.

Fig. 2 Cracking patterns

Fig. 3 Load deflection curve

Table 2 List of test results

Cycle	Loading condition	Condition of specimen			Test results of air leakage (Volume 3100ℓ)				
		Average shear stress (kgf/cm ²)	Deflection angle (×10 ⁻³)	Crack width (mm)	Method of air leakage measurement	Coefficient air leakage (ℓ/hrmmAg)#4	Amount of air leakage (ℓ/h m ²)#5	Rate of air leakage (%/day)#5	
Initial		0.0	0.0		A #1	** #7	**	**	
-①	Peak	15.2	0.16	* #6	A	**	**	**	
	removed	0.0	0.07	*	A	**	**	**	
-②	Peak	30.4	0.52	*	A	0.11	0.70	1.6	
	removed	0.0	0.13	*	A	0.11	0.70	1.6	
-③	Peak	41.7	1.02	0.10	A #2	(0.6)			
	removed	0.0	0.14	*	A	0.08	0.51	1.2	
-④	Peak	57.3	2.0	0.15	B #3	2.0	12.8	29.7	
	removed	0.0	0.28	*	A	0.14	0.9	2.1	
-⑥	Peak	69.8	3.0	0.25	B	6.0	38.4	89.1	
	removed	0.0	0.39	0.04	A	0.21	1.34	3.1	
-⑦	Peak	81.2	4.02	0.35	B	12.2	78.1	181.4	
	removed	0.0	0.52	0.06	A	0.17	1.09	2.0	
-⑨	Peak	95.8	5.95	0.65	**#8	**	**	**	
	removed	0.0	0.88	0.20	B	0.4	2.56	5.9	

Note #1: A; Method using comparison of atmospheric pressure
#2: A; Estimated value from incline to decrease pressure at sucking constant air
#3: B; Measurement keeping a constant pressure difference and a constant amount of sucking air
#4: $a = Q / (S \Delta p)$, a; Including error, S: Area of tested wall equals 3m²
#5: Value is at 6.4mm aq. pressure difference between inside and outside
#6: *; Crack width below 0.04mm
#7: **; Measured error is large
#8: ***: Air leakage could not be measured because air leakage to great

4.1 At a few cracks on the wall

The design stress corresponding to earthquake level S1 occurred at the peak load of the second load cycle. Immediately after the initial bending and shearing cracks occurred, cracks width was less than 0.04 mm. The rate of air leakage was very low, only 1.6 % per day at for an atmospheric pressure difference of 62.7 Pa [6.4 mm aq.]. As the amount of air leakage was very small and there was a large error in measuring by Method A after load had been removed was estimated on safe the side using the maximum values for atmospheric pressure and the absolute temperature inside the specimen.

4.2 At many cracks on the wall

The peak load of seventh cycle was greater than the maximum design load. At this point, the cracks were wide and the amount of air leakage increased when loading was removed. The amount of air leakage from cracks existing after loading was removed was proportional to lateral force, while the amount of air leakage from cracks at peak load increased geometrically as the cracks widened and their number increased.

When there was little air leaked it amounted to roughly 2.5 μhrm^2 at atmospheric pressure difference of 62.7 Pa [6.4mm aq.] as coefficient of leakage (n) estimation Method B was about 1. The modulus of air leakage (a) was equal to or less than 0.4 after the specimen had undergone extensive deformation.

The Electrical Society of Japan performed similar air tests, though the test procedure (specifications of specimen, concrete strength, web reinforcement ratio, axial load etc.) differed from used by the authors of this report. The value for coefficient of air leakage obtained in this tests conducted by the authors of this report were very small and on the safe side compared with caluculated using the formulas specified in the report on the work done by the Electrical Society of Japan.

Fig. 4 Amount of air leakage from cracks remaining after loading removed

5. CONCLUSIONS

Test results are as follows.

- a. At the S1 level of the strongest earthquake event in design, there were a few initial cracks in the wall of the specimen. These cracks were very narrow, being less than 0.04 mm wide. Air leakage was very slight at 1.6 % per day, as estimated by Method A at a difference of atmospheric pressure inside and outside the specimen of 62.7 Pa [6.4 mm aq] during peak lateral loading.

Fig. 5 Relationship between shear stress and coefficient of air leakage

Fig. 6 Relationship between difference of atmospheric pressure and amount of air leakage

- b. The amount of air leakage during the peak load of each loading cycle increased geometrically as estimated by Method B, in accordance with increases in the number and width of cracks. When the amount of air leakage was over 100 % per day at an assumed difference between atmospheric pressures inside and outside the specimen of 62.7 Pa [6.4 mm aq], the walls were greatly deformed at a deformation angle $R=4 \times 10^{-3}$ rad. This was near the point of collapse of the specimen.
- c. The amount of air leakage from cracks existing after loading was removed was slight. It is proportional to the peak lateral load and was about 6 % per day even after the specimen was destroyed, and never reached 100% per day.

This study clarified that the few cracks occurred in the shear walls of a specimen made of reinforced concrete and that very little air leaked through the walls at the S1 level of earthquake loading. Because it is said that the amount of air leakage is in inverse proportion to wall thickness, and nuclear power plants have very thick walls, the air tightness of such buildings is secure even in the event of a large earthquake.

REFERENCE

- 1) Electrical Society of Japan, 1988.03.09, "Research Report of Air Leakage through the Remained Shear Cracks on Reinforced Concrete Walls"