Experimental Study of Leakage Through Residual Shear Cracks on R/C Walls

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1. INTRODUCTION

The negative pressure at the building of BWR or at the annulus zone of PWR should be maintained under control even in the case that S1 design basis eathquake occurs after LOCA. To consider the air-tightness of these structures after the earthquake, "leakage through residual shear cracks on boundary walls made of reinforced concrete (R/C)" becomes one of important problems.

Experiments were carried out in order to obtain the methods to estimate the amount of leakage. Three R/C flat-plate specimens were tested. In the experiments, cracks were occured by cyclic loadings and flow rate through the cracks was measured under the conditions that three levels of differencial pressures, approximately 20, 100, and 200 mmAq, were applied between both sides of plates.

In this paper, the amount of leakage through residual shear cracks on R/C walls is discussed based on the experimental results.

2. EXPERIMENTS

2.1 Specimens

Three R/C flat-plate specimens described in Table 1 and Fig. 1 were tested. The specimens have two parts to measure flow rate through cracks, and these cracks were generated by the vertical loads P as shown in Fig. 1. Main difference between the speimens is wall thickness, area ratio of steel bars (0.5%) and spacing of steel bars (250mm) are identical to all cases, as shown in Table 1. Fig. 2 shows the details of the reinforcements of the specimen. Steel plates with 22 mm thickness are used as reinforcements for bending, and deformed steel bars were welded to the steel plates.

The data of the uniaxial compression test of the used concrete are shown in Table 1. All the used steel plates and bars were produced according to the Japanese industrial standards JIS G3106 SM50A and JIS G3112 SD35, respectively.

2.2 Method of Loadings and Measurements

The adopted loading program is shown in Fig. 3. Five different peak levels of cyclic loads were applied: first one causes cracks and others are increasing up to $\tau=30$ kgf/cm^2, where "τ" denotes the average shear stress which is the quotient of load P divided by the sectional area of the specimen. Each loading levels include five cycles (both positive and negative sides).

The flow rate of air through cracks were measured at the time steps pointed by the mark "○" shown in Fig. 3. Measurments of seven points were at zero loading levels, and others were at peak levels of applied loads.

In the present experiment, two types of measuring equipments were prepared to measure the flow rates. The measuring system of flow rate shown in Fig. 4 is using "gravity" to measure small flow rate accurately. The other system is adopted for the relatively large flow rate, has a six flowmeters and works by a suction pump. Both types of measuring equipments decrease air-pressure in chamber from atmosphere as shown in Fig. 4. Differential pressures of three levels, approximately 20, 100 and 200 mmAq were applied to the test parts.

Used specimens were coated with rubber except two test parts as shown in Fig. 1 and Fig. 4. Air-tightness of measuring systems was confirmed by using the cover shown in Fig. 4. After this confirmation, the cover was removed to measure the flow rate.

During the measurment of the flow rate, the cracks were also measured simultaneously. At each measurement, the crack distribution of the surface was sketched and the width of each crack was measured at the position where the crack crossed a horizontal steel bar by the use of a microscope with 50 magnifications.

The displacements of the specimens were measured at 42 points so that the deformation of the test part could be separated into flexural and shear components.

The strains of the steel bars and the plates were also measured at 20 points.

3. EXPERIMENTAL RESULTS

The obtained results from three specimens show a similar tendency. In this paper, the results are interpreted by using the figures for the case of Specimen C.

The relationship between the average shear stress "τ" and the shear strain "γ" is shown in Fig. 5. The shear strain "γ" is the remainder when the flexural component of displacement is subtracted from the total deformation of the test part. The flexural component of deformation, not shown in the figure, is smaller than the shear component and its behaviour is seemed to be elastic.

The final crack distribution is displayed in Fig. 6. From the crack records, it is shown that the many shear cracks exist in the test part.

The relationships between the flow rate "Q" from the residual cracks and the differential pressure "ΔP", and the relashonships between "Q" and the wall thickness "t" are shown in Fig. 7 and 8, respectively. From the figures, following were made clear ; the flow rate is almost proportional to the differential pressure, and the flow rate decreases exponentially as the wall thickness increases.

4. CONSIDERATIONS

4.1 Empirical equation using "τ"

To consider estimation of leakage through residual shear cracks on R/C walls, the estimation using shear stress which is calculated by seismic load is most convenient method.

Equation (1), in which the flow rate "Q" is proportional to the differential pressure "ΔP" and to the n-th power of the average shear stress "τ" and is inversely proportional to the m-th power of the wall thickness "t", was assumed herein.

This empirical equation represents the relationships between the flow rate "Q" from the residual shear cracks and the shear stress "τ" which takes the maximum value of experienced load until the flow rate was measured.

$$Q = C \cdot \Delta P \cdot \tau^n / t^m \qquad (1)$$

where Q : flow rate per unit area (liters / min $\cdot$ m^2)

ΔP: differential pressure (mmAq)

τ : average shear stress (kgf/cm^2)

t : wall thickness (cm)

The measured datas from the residual shear cracks were substituted and the logarithms were taken for carrying out multiple regression analysis. As a result, n, m, and C were estimated as follows.

$n = 3.84 \qquad m = 2.53 \qquad C = 2.27 \times 10^{-4}$

On the assumption that the probabilistic distribution of the measured data is according to normal distribution around the regression line on a logarithmic graph, $C_{95} = 6.57 \times 10^{-4}$ giving a 95% reliability level (upper limit of 90% confidence interval).

The comparison between the empirical equation thus formulated and the measured values is shown in Fig. 9.

4.2 Empirical equation using "γ"

The estimation of the residual shear strain after an earthquake is required to estimate of the amount of air leakage through residual cracks on an R/C structure using the relationship between the flow rate and the shear strain. The estimation of the residual shear strain after an earthquake is future problem, but the flow rate is closely related to the shear strain.

In a similar manner to Equation (1) in the previous section, Equation (2) was assumed as an empirical equation.

This equation represents the relationship between the flow rate "Q" from the residual or loading cracks and the shear strain "γ" at the flow rate was measured.

$$Q = C \cdot \Delta P \cdot \gamma^{n} / t^{m} \qquad (2)$$

where γ : shear strain ($\times 10^{-3}$)

All the measured datas were substituted and n, m, and C were estimated as follows by a similar manner to that given in the previous section.

$n = 1.77 \qquad m = 1.96 \qquad C = 2.36 \times 10^{2}$

The comparison between the empirical equation thus formulated and the measured values is shown in Fig. 10.

4.3 Calculated flow rate using "Crack"

The estimation of the cracking condition after an earthquake is future problem. However, it is interesting to compare the measured flow rate with the calculated flow rate using the relationship between flow rate and the measurement results of cracks.

Theoretical equation (3) of 2-dimensional Poiseuille's flow (laminal flow of incompressible viscous fluid between two flat faces), shown in the following, is considered to be an equation for calculating the flow rate "q" from one crack.

$$q = b \cdot W^{3} \cdot \Delta p / (12\mu \cdot t) \qquad (3)$$

where q : flow rate (cm^3/sec)
W : crack width (cm)
b : crack length (cm)
Δp : differential pressure (gf/cm^2)
μ : viscosity (air is 1.856×10^{-7} gf·sec/cm^2)

The flow rate was calculated by using the empirical equation proposed by (Suzuki, Takiguchi et al. , 1987) 2) and the empirical equation proposed by (Rizkalla et al., 1982) 1) in addition to Equation (3).

These results were summarized and the relationship between ratio of measured to the calculated versus average crack width is shown in Fig. 11.

5. CONCLUSIONS

Estimation methods of leakage through residual shear cracks on R/C walls were discussed based on the experimental results.

Three R/C flat-plate specimens were tested. Cracks were generated by cyclic loadings, and flow rate through the cracks was measured.

From the experimental results, empirical equations were obtained. The amount of leakage through residual shear cracks on R/C walls can be estimated by these equations in the experimental region.

This paper is a part of joint research " The study on the earthquake resistant design of the buildings & structures considering required functions ", carried out by ten electric power companies (The Kansai, The Hokkaido, The Tohoku, The Tokyo, The Chubu, The Hokuriku, The Chugoku, The Shikoku, The Kyushu, The Japan Atomic), being cooperated by five construction companies (Taisei, Ohbayashi, Kajima, Shimizu, Takenaka).

REFERENCES

1) Rizkalla, S. H., Lau, B. L. (1982). " Leakage of Pressurized Gases through Cracks in Reinforced Concrete Structures." Structural Engineering Report, Depatment of Civil Engineering, Univ. of Manitoba

2) Suzuki, T., Takiguchi, K. et al. (1987). " Fundamental Experiments on the Leakage of Gas through Cracked Concrete Walls." Transactions of Architectural Institute of Japan, No.373, (in Japanese)

Table 1 List of specimens

Specimens	Wall Thickness (cm)	Bar Arrangement (Both Vertical and Horizontal)	Area Ratio of Steel Bars (%)	Compressive Concrete Strength (kgf/cm²)
A	20.0	2-D13 @250	0.51	259
B	44.5	2-D19 @250	0.52	243
C	60.0	2-D22 @250	0.52	260

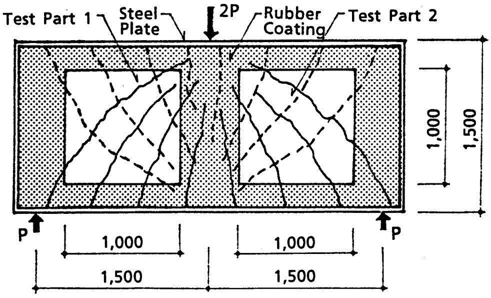


Fig. 1 Specimen geometry and loading

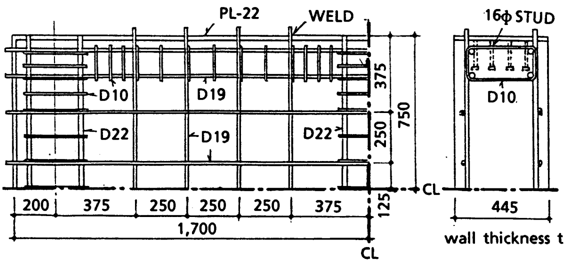


Fig. 2 Reinforcement details [B specimen]

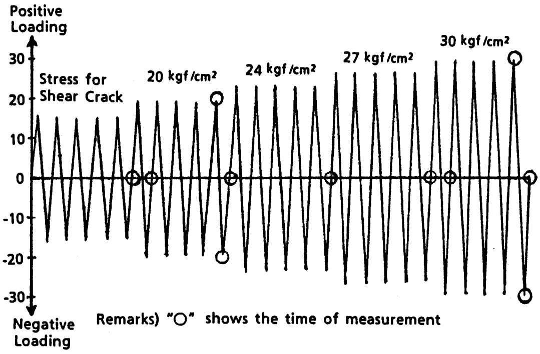


Fig. 3 Loading program

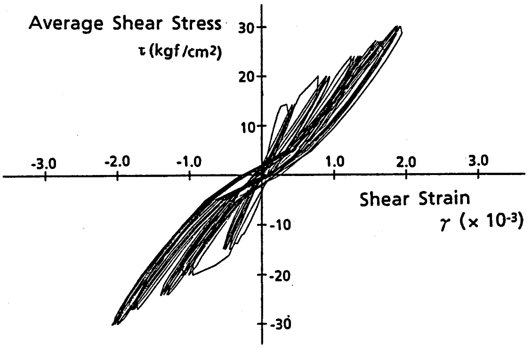


Fig. 5 Relationship between average shear stress and shear strain [C specimen]

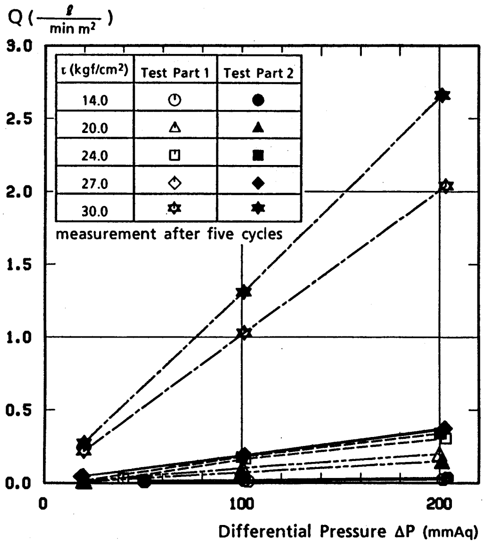


Fig. 7 Relationship between frow rate and ditterential pressure [C specimen]

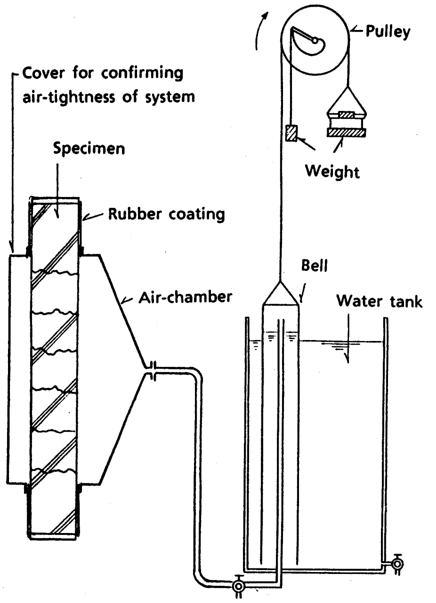


Fig. 4 Measuring system of flow rate

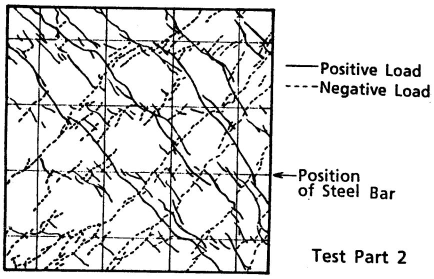


Fig. 6 Final crack distribution [C specimen]

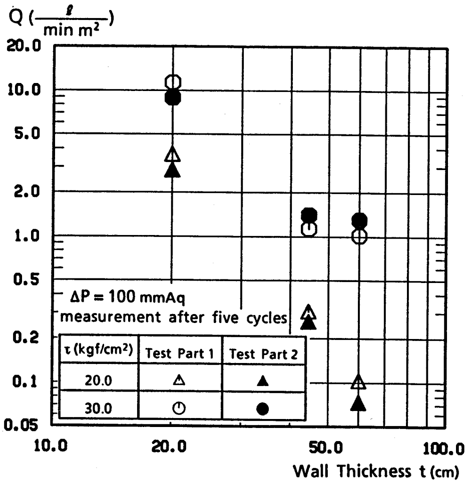
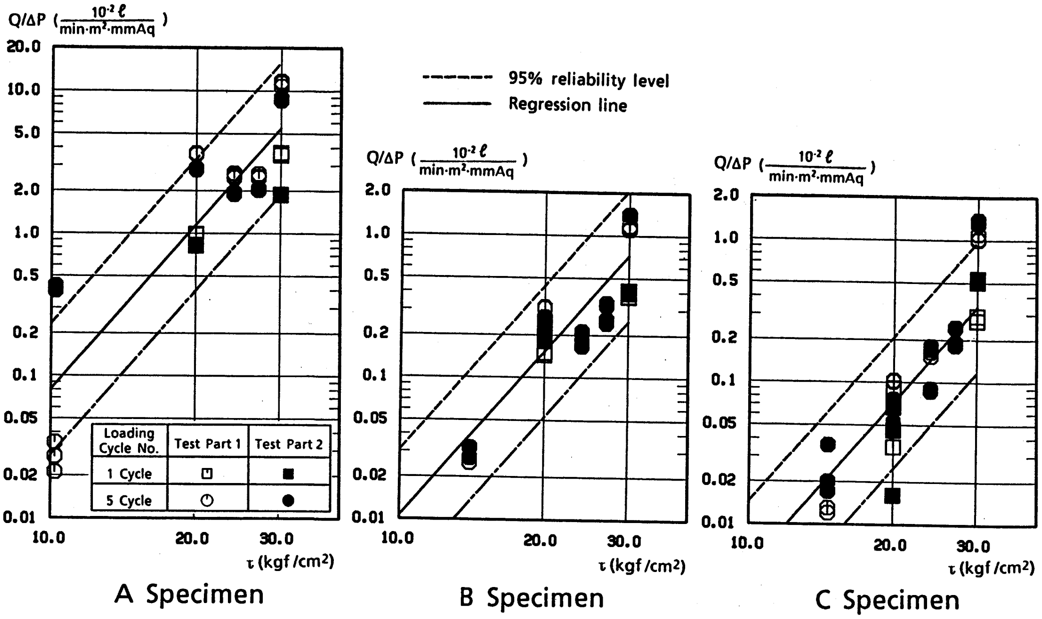


Fig. 8 Relationship between frow rate and wall thickness



A Specimen B Specimen C Specimen

Fig. 9 Comparison of measured values and empirical equation using average shear stress

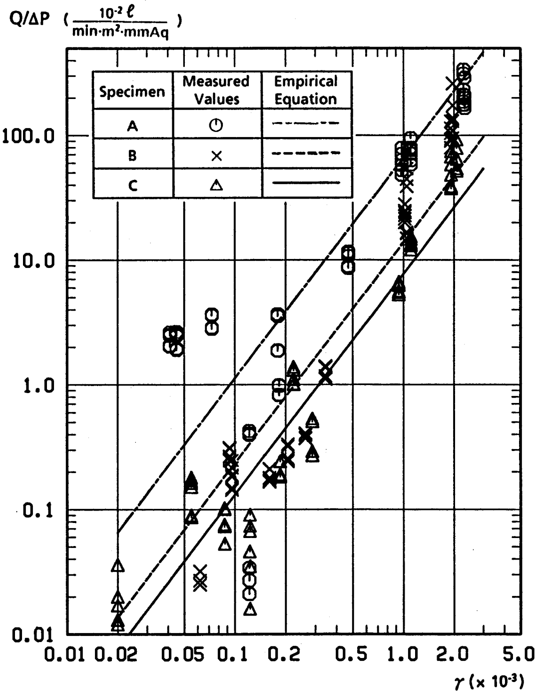


Fig. 10 Comparison of measured values and empirical equation using shear strain

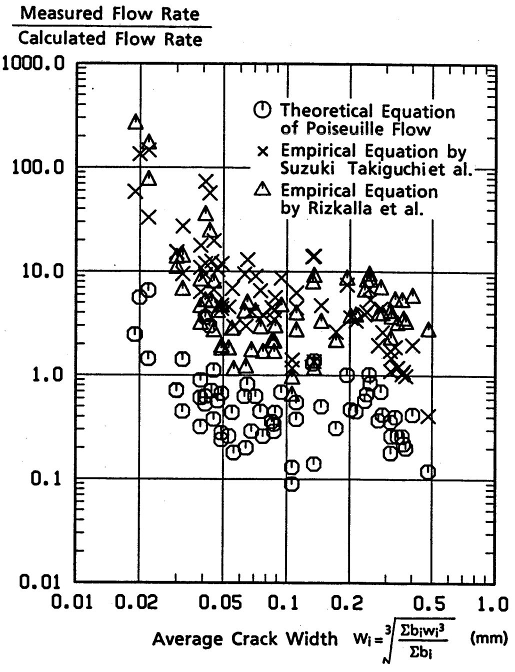


Fig. 11 Comparison of measured frow rate and calculated frow rate using crack