Experimental Study on Supporting Ability of Machinery Anchorage in Reinforced Concrete Walls

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1. INTRODUCTION

In earthquake resistant design of nuclear power plant buildings, it is important to assure that machinery anchorages in concrete element(hereafter denoted by machinery anchorage) which support important machinery,pipes etc. are not fractured (hereafter denoted by supporting ability) even if the buildings were attacked by a strong earthquake.

In this paper,a series of experiments of H-shaped walls, which were the models of reinforced concrete walls,were carried out. In the experiments, in-plane shear force to the walls and out-of-plane tensile force to the anchorages were applied simultaneously to the specimens.

Subsequently the evaluation method of supporting ability of machinery anchorages of reinforced concrete walls is discussed using the experimental results and previous studies.

2. EXPERIMENTS

The buildings in nuclear power plants are mainly composed of reinforced concerete shear walls which have a shear failure dominant characteristic.

The degradation of supporting ability is supposed to be mainly due to shear cone failure among failure modes by out-of-plane tensile force applied to machinery anchorages. It is pointed out in a previous study[1)] that the failure have a close relationship to in-plane shear force.

From this point of view,the in-plane shear force applied to the walls and out-of-plane tensile force applied to the anchorages on the walls are discussed here. Shear cone failure of concrete by out-of-plane tensile force is assumed to be the only failure mode of the anchorages.

2.1 Specimens

Nine specimens were tested. All of these had the same configuration. The loading condition shown in Table 1 was a parameter of the test.

The specimen #1 was for the investigation of in-plane shear strength without out-of-plane tensile force. The specimen #2,4,6,8 and 9 were for the investigation of in-plane shear force and shear strain when out-of-plane tensile force could not be maintained with increasing in-plane shear force under constant out-of-plane tensile force. In this study,this loading condition was employed as a basic. Out-of-plane tensile force was applied to the specimen #3 under constant in-plane displacement. The aim of the test by this specimen was to investigate the effect of the difference of loading order on the strength, comparing with the results of in-plane loading under constant out-of-plane tensile force. The specimen #5 and 7 were to investigate the shear cone failure load by out-of-plane tensile force without in-plane force.

The configuration of the specimens is shown in Fig.1. The horizontal section of the wall part is shown in Fig.2. The specimen was a partial model of the wall in the buildings. The web reinforcement was D16(SD35),and doubly arranged at 150mm interval in vertical and horizontal directions. The wall reinforcement ratio was 1.06% in both direction. The embeded steel plate simulated the anchorage was 32mm thick steel (SS41) with four welded 13mm diameter stud(SS41). The stud length below the head after welding was 70mm and the setting interval was 150mm,the same as the reinforcement interval. Mechanical property of the concrete and steel are shown in Table 2 and Table 3.

2.2 Loading method

The loading apparatus is shown in Fig.3 and Fig.4. The in-plane force was applied through 4 hydraulic actuator in the manner that pushing and pulling load are applied equally to the loading slab. The loading schedule is shown in Fig.5. The load was applied alternately in positive and negative directions controlling by the deflection angle R (divided horizontal displacement of lower level of loading slab by clear height of the wall),and was increased gradually.

In the out-of-plane loading under constant in-plane shear force for specimen #3,the loading steps were controlled by the deflection angle,and shear strain was calculated at each step. When the angle reached 2/1000, the displacement was kept constant, and out-of-plane tensile force was applied to the anchorage.

Reaction beams for out-of-plane loading were set between the loading slab and foundation slab in both sides,and out-of-plane force was applied by 2 jacks so that the tensile force in both sides would be the same and out-of-plane bending moment would not occur.

Out-of-plane loading schedule is shown in Fig.6. In-plane force was applied to the specimens #2,4,6,8 and 9 after out-of-plane tensile force was kept at a given level.

Out-of-plane tensile force to be kept was calculated from the compressive strength of concrete. They were 350 kgf/cm² for #1～#5,8,9,and 300 kgf/cm² for #6 and 7.

3.EXPERIMENTAL RESULTS

3.1 Outline of experimental results

Crack pattern of the wall after shear cone failure of specimen #8 is shown in Fig.7. The envelope curve of the relationship between in-plane force and total horizontal displacement is shown in Fig.8. The envelope curve of relationship between out-of-plane force and out-of-plane displacement is shown in Fig.9.

The failure mode of specimen #1 which was applied in-plane force only was shear failure of the web. The specimen showed a characteristic of a shear wall that the shear failure precedes as expected.

The envelope curves of in-plane loading coincided well each other as shown in Fig.8. It shows that there are slight influence of out-of-plane loading on the relationships.

The failure by out-of-plane loading was shear cone failure of concrete as expected. The ultimate strength by the failure with out-of-plane loading only was almost the same level with the strength obtained by the previous study. It was verified that the strain of reinforcement was small in case of the failure,and the reinforcement did not affect on the failure.

In in-plane loading under constant out-of-plane force, the out-of-plane displacement became larger gradually with the repetition of in-plane force. Finally the given out-of-plane force could not be carried and the failure occured. Out-of-plane displacement just before the failure was larger for smaller out-of-plane force as shown in Fig.9.

In out-of-plane loading under constant in-plane force (specimen #3),the specimen failed at relatively large out-of-plane displacement.

Experimental results are summarized in Table 4.

3.2 Relationships between in-plane loading and out-of-plane loading.

The relationships between shear strain and normalized out-of-plane force is shown in Fig.10. The relationships between normalized in-plane shear force and out-of-plane force is shown in Fig.11. The experimental results by previous studies[1) 2) 3)] were also plotted in those figures.

The experimental and calculated results were normalized in the following manner.

Normalized value of in-plane shear force: Q_e / Q_{uc}

Where Q_e : measured value of in-plane shear force in the experiment(kgf)

Q_{uc} : calculated value of in-plane shear strength without out-of-plane force[4)] (kgf)

$Q_{uc} = \tau_u \cdot A_s$

$\tau_u = \{(1-\tau_s/(4.5\sqrt{F_c})\}\tau_o + \tau_s \quad (\tau_s < 4.5\sqrt{F_c})$

$\tau_u = 4.5\sqrt{F_c} \quad (\tau_s \geqq 4.5\sqrt{F_c})$

$\tau_o = (3-1.8\ M/QD)\sqrt{F_c}$

when $M/QD \geqq 1$, $M/QD = 1$

$\tau_s = (P_V + P_H)\ {}_s\sigma_y/2 + (\sigma_V + \sigma_H)/2$

τ_u : ultimate shear stress (kgf/cm^2)

A_s : effective sectional area for shear (cm^2)

F_c : compressive strength of concrete (kgf/cm^2)

P_V : vertical reinforcement ratio

P_H : horizontal reinforcement ratio

σ_V : normal stress in vertical direction (kgf/cm^2)

σ_H : normal stress in horizontal direction (kgf/cm^2)

M/QD : shear span ratio

D : distance of both flange centers (cm)

${}_s\sigma_y$: yield strength of reinforcing bar (kgf/cm^2)

dimension of $\sqrt{F_c}$ is kgf/cm^2

Normalized value of out-of-plane force : P_e/P_{uc}

Where P_e : measured value of out-of-plane force in the experiment (kgf)

P_{uc} : calculated value of out-of-plane strength without in-plane load (kgf)

$= A_c\sqrt{F_c}$ for tensile force

$= 2A_c\sqrt{F_c}$ for punching force

A_c : effective projected area (cm^2)

In out-of-plane loading under constant in-plane force (specimen #3 and previous study),out-of-plane strength became smaller for larger in-plane shear strain.

In in-plane loading under constant out-of-plane force, in-plane shear stress and strain at out-of-plane failure level was smaller for larger out-of-plane load.

Experimental results of in-plane loading under constant out-of-plane force showed lower out-of-plane strength than that of out-of-plane loading under constant in-plane force.

4.EVALUATION METHOD OF SUPPORTING ABILITY

Generally,out-of-plane tensile strength due to shear cone failure has a tendency to decrease for larger in-plane shear force (or in-plane shear strain). It is reasonable to take account of the in-plane shearing force of the wall to evaluate the supporting ability (Fig.10,11).

According to the experimental results and other previous studies, allowable limit area related to in-plane and out-of-plane force can be drawn. It is shown in Figs.10,11 as a hatched area.

The line of $P_e/P_{uc} = 0.6$ on the ordinate is the allowable load of anchorages by ultimate strength design (lower limit of experimental values of shear cone failure strength without in-plane shear force)suggested in ref.1). The lines of $\gamma = 2\times10^{-3}$ and $Q_e/Q_{uc} = 0.6$ on the abscissa are allowable limits of shear walls based on ultimate strength in earthquake resistant design (values that have margins on experimental lower limits of ultimate shear strain and ultimate shear strength in lateral loading of shear walls) suggested in ref.5).

The hatched area in Fig.10,11 are drawn taking account of the experimental results to the suggestion in ref.1),5). It shows that in design allowable out-of-plane tensile force should be decreased a little for larger in-plane shearing strain and in-plane shear force ($\gamma \geqq 1\times10^{-3}$, $Q_e/Q_{uc} \geqq 0.4$).

5.CONCLUSIONS

A series of experiments were carried out in order to investigate the supporting ability of machinery anchorages when large in-plane shear force is applied to the wall. In the experiments, in-plane shear force to the walls and out-of-plane tensile force to the anchorages were applied simultaneously.

Using the experimental results and previous studies, the allowable limit area in the evaluation of supporting ability was suggested, in relation to in-plane shear strain or in-plane shear force and out-of-plane tensile force.

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).

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Table 1 List of Specimens

Specimen	Loading condition	
	In-plane force	Out-of-plane force
1	to maximum load	—
2	to failure of anchorage ←	constant at P=0.7×Puc
3	constant at γ=2/1000 →	to maximum load
4	to failure of anchorage ←	constant at P=0.5×Puc
5	—	to maximum load
6	to failure of anchorage ←	constant at P=0.7×Puc
7	—	to maximum load
8	to failure of anchorage ←	constant at P=0.6×Puc
9	to failure of anchorage ←	constant at P=0.45 ×Puc

Notes
Puc:calculated value of tensile strength (= Ac $\sqrt{Fc}$)(kgf)
Ac :effective projected area (cm²)
Fc :compressive strength of concrete (kgf/cm²)
γ :in-plane shear strain of wall

Table 2 Results of Concrete Material Tests

Specimen	Compressive strength (kgf/cm²)	Young's modulus (10^5kgf/cm²)	Weight per unit volume (kgf/cm²)
1~5	347	2.04	2270
6, 7	293	2.46	2270
8, 9	353	2.64	2290

Table 3 Results of Mechanical Property Tests of Steel

Specimen	Use Diameter Classification	Yield strength (kgf/cm²)	Ultimate strength (kgf/cm²)	Young's modulus (10^6kgf/cm²)	Elongation (%)
1~7	Wall reinforcement D 16 (SD35)	3980	5730	1.99	19.9
	Stud 13 ϕ (SS41)	2790	5300	2.37	—
8, 9	Wall reinforcement D 16 (SD35)	3740	5590	1.84	15.8
	Stud 13 ϕ (SS41)	2750	5095	2.03	—

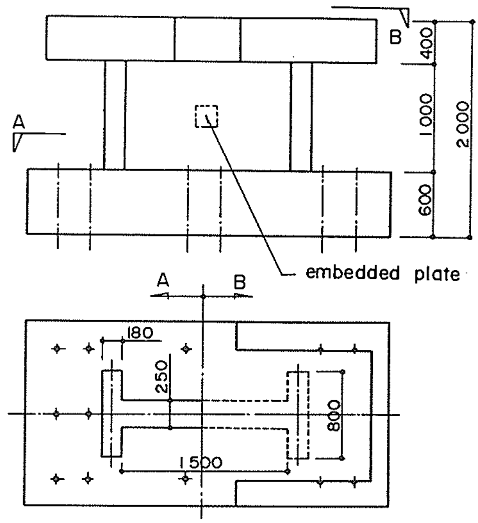

Fig.1 Configuration of Specimens

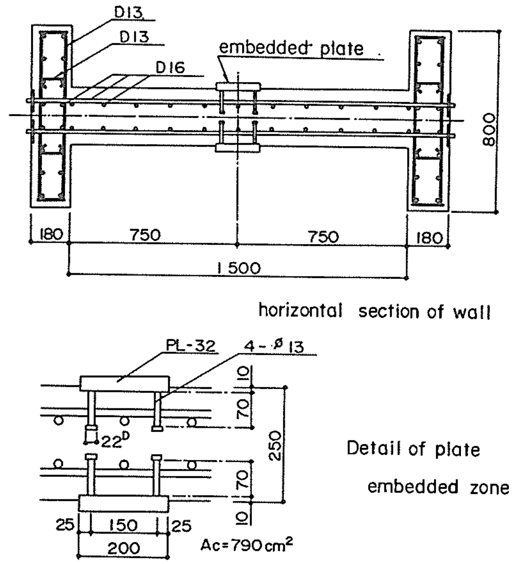

Fig.2 Horizontal Section of wall

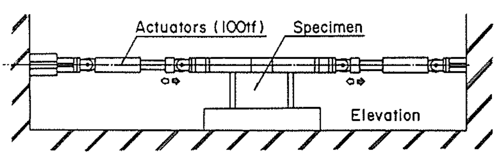

Fig.3 Loading Apparatus (In-plane)

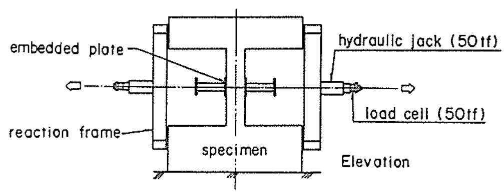

Fig.4 Loading Apparatus (Out-of-plane)

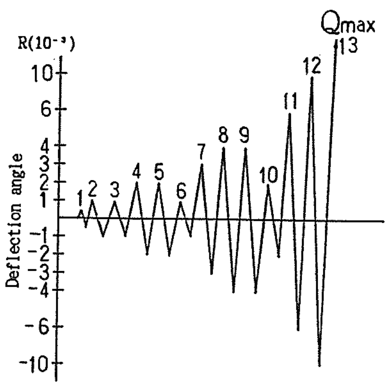

Fig.5 Loading Schedule (In-plane)

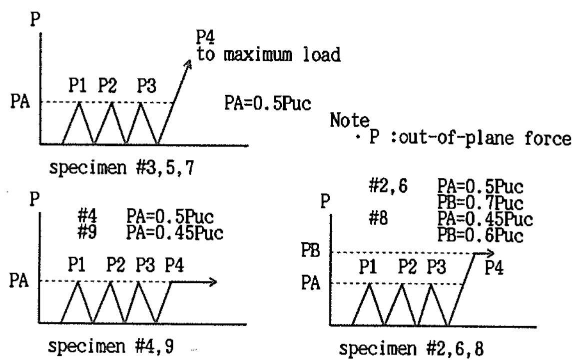

Fig.6 Loading Schedule (Out-of-plane)

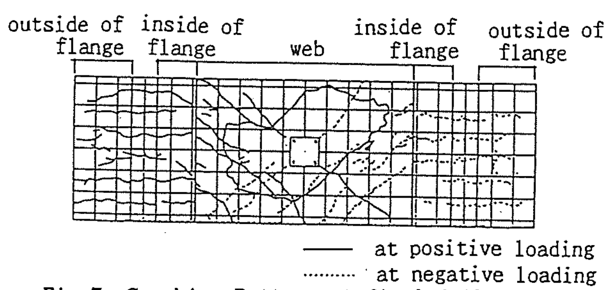

Fig.7 Cracking Pattern at final failure
(Specimen #8)

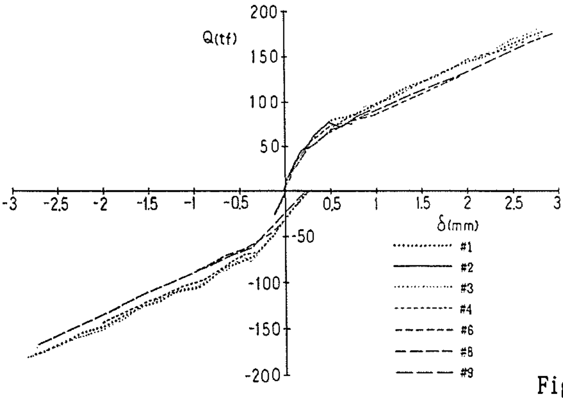

Fig.8 Envelop Curves of Relation between In-plane Load and Overall Deflection

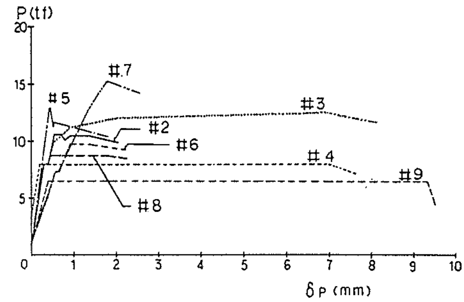

Fig.9 Envelop Curves of Relation between Out-of-plane Load and Displacement

Table 4 List of Experimental Results

Specimen	Maximum value				
	In-plane value			Out-of-plane value	
	Shear force		Shear strain	Tensile force	
	Qe (tf)	Qe / Quc	τ ($\times 10^{-3}$)	Pe (tf)	Pe / Puc
1	287	1.18	6.1	—	—
2	91	0.37	0.63	(10.5)	(0.71)
3	(143)	(0.59)	(2.0)	12.5	0.84
4	174	0.71	2.0	(7.9)	(0.53)
5	—	—	—	12.9	0.87
6	74.9	0.32	0.46	(9.7)	(0.71)
7	—	—	—	15.8	1.15
8	129	0.54	1.3	(8.8)	(0.59)
9	164	0.69	2.2	(6.6)	(0.45)

Notes · Values in the brackets are maitained values in tests.
· Qe/Quc: normalized value of in-plane shear force (cf.3.2)
· Pe/Puc: normalized value of out-of-plane tensile force (cf.3.2)

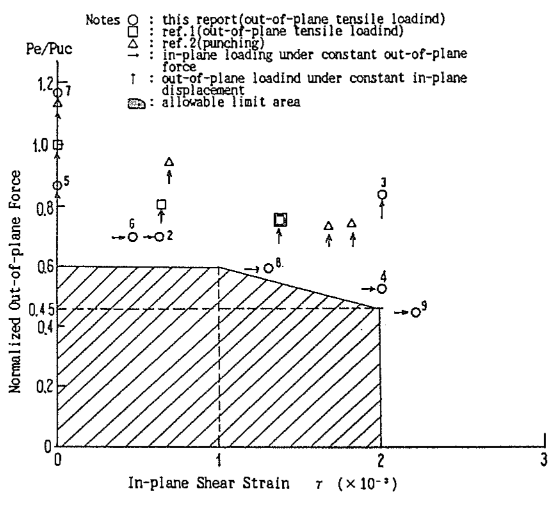

Fig.10 Relation between In-plane Shear Strain and Normalized Out-of-plane Force

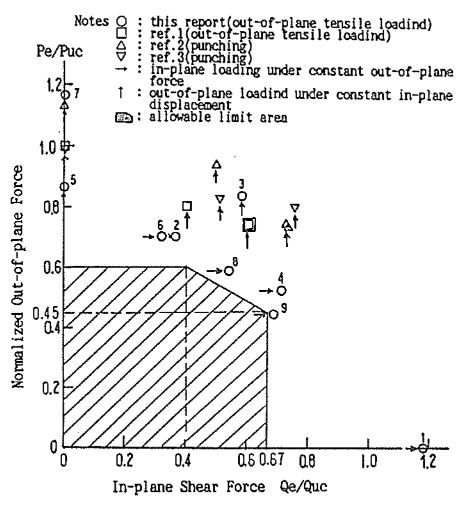

Fig.11 Relation between Normalized In-plane Shear force and Normalized Out-of-plane Force