Study on steel plate reinforced concrete panels having a opening subjected to cyclic in-plane shear.

Masahiko Ozaki[1)], Hiroshi Osuga[2)], Tatsuo Nakayama[3)], Naoyuki Adachi[2)]

1) Office of Civil Engineering and Architecture Headquarter, The Kansai Electric Power Co., Inc., Japan
2) Nuclear Facilities Division, Obayashi Corporation, Japan
3) Technical Research Institute, Obayashi Corporation, Japan

ABSTRACT

This paper describes the experimental and analytical results of the steel plate reinforced concrete structure(SC) having a opening, for the purpose of confirming the fundamental behavior of SC shear wall. Six specimens having a opening were loaded in cyclic in-plane shear, and were compared with the results of the specimen having no opening. FEM analysis was done for the making up for the experimental data. Finally, we proposed the reduction ratio by the opening for design.

INTRODUCTION

The SC structure consists of a flat composite plate made by connecting a pair of surface steel plates in which stud bolts are built with partitioning webs and filling the boxes so-formed with concrete. The stud bolts operate as shear connector between steel plate and concrete.

The SC structure has several merits from the points of view of the structural aspects and the efficiency of execution works;

1) As the surface steel plates be the form work in the execution work, the execution works periods will be reduced.
2) No wooden form work is used, the destruction of the environment will be reduced.
3) They will be able to set up the mechanic support after concrete casting. And it has flexibility to set up supports.

Previously, several papers for the study of SC structure were presented [1],[2],[3],. One of the authors presented the experimental results of the panels of SC structure[4]. But the response of SC panel having a opening had not been studied yet. Having a opening, the strength of the panel may be reduced. And stress concentration makes the surface plate yield earlier. The effect of the stress concentration may change the response of the panel having a opening.

The investigation of the reduction ratio of SC panel having a opening is beneficial for the design of SC structures. This paper provides new test data pertaining to the behavior of SC panels having a opening. And the reduction ratio for the opening was proposed for design.

EXPERIMENTAL PROGRAM

The experimental program involved the testing of six SC panels having a opening and one SC panel having no opening. The latter specimen may call the standard specimen after this. These panels were subjected to cyclic loads of in-plane shear. The test panels were 1200×1200mm in plan dimension, with a thickness of 200mm.Typically, the panels had a opening in the center of the panel. There were two types of the opening; a circular opening and a square opening. Whichever the type of the opening, the square root of the ratio of the opening area divided by the area of the SC panel was 0.15 in common. The corner of the square opening had small curvature.

The reinforcement around the opening had two variations made of steel plate; sleeve reinforcement and plate reinforcement. The plate of the sleeve had 4.5mm thickness for circular opening and 2.3mm thickness for rectangular opening. The plate reinforcement has common thickness of the surface plate (3.2mm). The reinforcement area had a half of the opening diameter width.

The reinforcing steel plate was 3.2mm in common. Details pertaining to the panel construction were shown in Fig.1. Specimen test parameters are given in Table 1.

The concrete for each panel was hand-batched using 10mm stone. The panels and test cylinders were sealed and cured for 7 days and tested at approximately 80 to 180 days of age. The properties of concrete, determined from cylinders tested at the time of the panel tests, are listed in Table 3.

Table 1 Test Specimen

Specimen	Thickness of surface plate(t)	Stud			Types of opening	Reinforcement
		Pitch (B)	Diameter	B/t		
S3-00NN	3.2	100	5	31	—	—
S3-00HN					Circular opening (Diameter=207)	—
S3-00HR						Sleeve
S3-00HP						Plate
S3-00RN					Square opening (180×180)	—
S3-00RR						Sleeve
S3-00RP						Plate

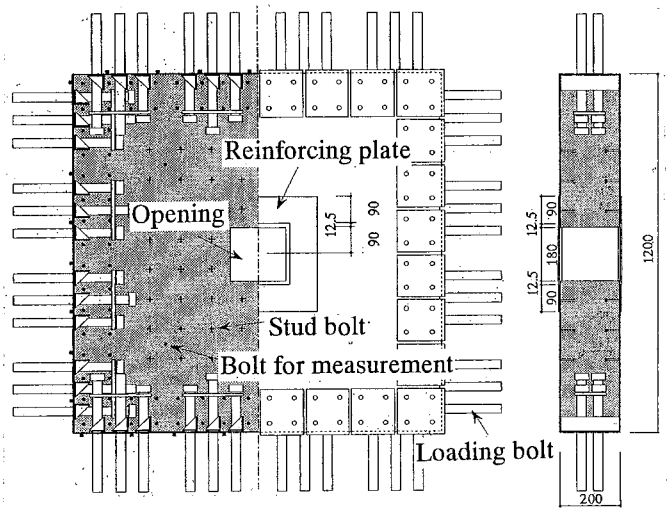

Fig. 1 Specimen Properties(S3-00RP)

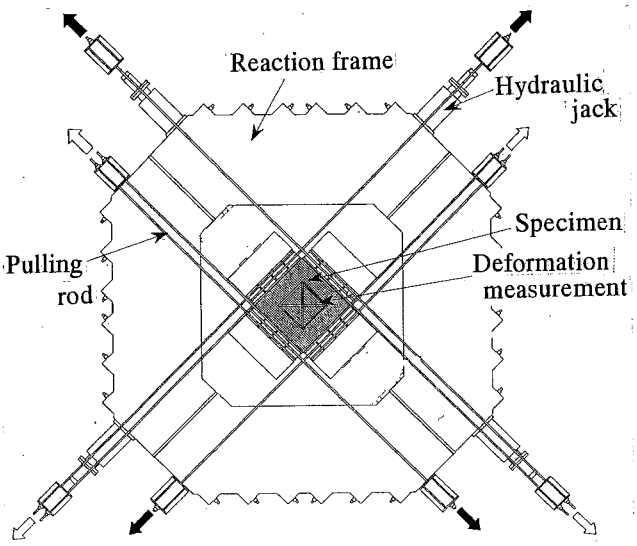

Fig. 2 Load Setup

Table 2 Loading Stages

Loading stages	①	②③	④⑤	⑥	⑦	⑧⑨	⑩	⑪⑫	⑬⑭	⑮
Shear strain ($\times 10^{-3}$)	0.5	1.0	2.0	1.0	3.0	4.0	2.0	6.0	12.0	17.0

Uniform in-plane forces were applied to the panels using the shear bolts test facility(Fig.2). The facility was comprised of a self-reacting frame containing 4 hydraulic jacks. The loading stages are shown in Table 2. To investigate the condition under large scale deformation, three loading stages were added for the loading stages of three specimens having a square opening (S3-00RN, S3-00RR, S3-00RP) and one of the specimens having a circular opening (S3-00HP).

The wire strain gage was used for the investigation of strain concentration near the opening and the inclination to decrease of strain concentration from the edge of the opening.

Electric strain gage measurements were made in the X-, Y-, and diagonal directions on both sides of the steel plate's surface.

TEST RESULTS

A summary of test results is given in Table 3. In all specimens, the cracking strength and the yield strength each appeared at almost same shear strain.

The shear strain at the cracking strength of the standard specimen was almost equal to those of the specimens having a opening. And the shear strain at the yield strength of the standard specimen was almost equal to those of the specimens having a opening, too. However the shear strains at the maximum strength of the specimens having a opening were almost twice or three times as large as those of the standard specimen. Therefore the discussion of the reduction ratio of the maximum strength , which is based on the standpoint putting only the strength in question not the shear strain, is not good

for the determination of the skeleton curve of SC panels having a opening.

Therefore we will determine the nominal ultimate strength. Other experimental study which planed for H shaped specimen constructed by SC shown the shear strain of 6.0×10^{-3} at the maximum strength[5]. Considering the results of this experimental study and the result of the standard specimen from this study, we determine the ultimate strength at the shear strain of 6.0×10^{-3}.

By the reinforcement around the opening, the strength of the specimens having a opening tend to increase in comparison with the strength of those without reinforcement.

Load Deformation Relationship

Shear load – deformation response are given in Fig. 3. The load – deformation response were very ductile. Except for the standard specimen, ultimate response of deformation for six specimens having a opening, were determined the limitations of the deformational capacity of the facility (around 17.0×10^{-3}). The specimens which reinforced with steel plate had small cracking on surface plate at the loading stage at the shear strain of 12.0×10^{-3}. But the cracking had not immediately grown at the end of the all load stages.

The comparisons of the responses from the point of view of the load – deformation envelope are shown in Fig. 4. In the range of the reinforcement of this experiment, the plate reinforcement was more effective than the sleeve reinforcement. The discussion of the relationship between the amount of the reinforcement and its effectiveness will be made after.

Ultimate Condition of Concrete

Ultimate condition of concrete is shown in Fig. 5. After all loading stages, the surface plate was driven from the specimen to observe the ultimate condition of concrete. Fig. 5 shows that the cracking of SC panels is very sparse.

Strain Near Opening

Strain distribution near opening ($\varepsilon\ \theta$) is shown in Fig. 6. The strain distribution in this figure was selected as shown in Fig. 6. In this figure, the dotted line shows the distribution of the calculated result in elasticity. This distribution was fitted at the point of the distance of 530mm from the opening's center. This figure shows the strain near opening exceeded after yielding of the surface plate. Strain concentration near opening and shear strain relationship is shown in Fig. 7.

Table 3 Experimental Results

Specimen	Material properties				Experimental results					
	Concrete		Steel plate		Cracking strength	Yield strength	Ultimate strength	Maximum strength	Elastic stiffness	Yield stiffness
	σ_B σ_T	Ec ν c	σ y	Es ν s	Qc γ c	Qy γ y	Qu* γ u*	Qu γ u	Gc	Gy
S3-00NN	41.9 2.83	2.71 0.200	349	1.99 0.274	311 0.134	3070 3.01	3610 6.05		12.9	4.26
S3-00HN	42.4 3.14	2.70 0.200	348	1.98 0.282	254 0.127	2230 2.01	2920 6.00	3240 19.1	10.8	4.62
S3-00HR	42.4 3.24	2.71 0.210	355	2.00 0.279	270 0.082	2710 3.01	3060 5.63	3580 17.9	14.9	3.75
S3-00HP	31.7 2.85	2.72 0.193	380	1.93 0.267	251 0.129	2510 2.38	3470 5.94		9.53	4.39
S3-00RN	32.9 2.78	2.66 0.194	386	2.00 0.269	146 0.075	2160 2.45	2800 6.10	3020 11.9	10.8	3.67
S3-00RR	32.1 2.76	2.49 0.186	385	1.99 0.272	250 0.082	2170 2.43	2930 6.05	3350 11.4	12.7	3.72
S3-00RP	32.7 2.76	2.66 0.193	369	2.01 0.281	246 0.115	2500 2.86	3060 6.15	3210 11.5	11.8	3.65

Note: Material properties : unit σ_B · σ_T · σ y (MPa) 、 Ec ($\times10^4$ MPa) 、 Es ($\times10^6$ MPa)
Ultimate strength : Strength at shear strain of 6.0×10^{-3}
Experimental results : unit Qc · Qy · Qu (kN) 、 γc · γy · γu ($\times10^{-3}$) 、 Gc · Gy ($\times10^3$ MPa)

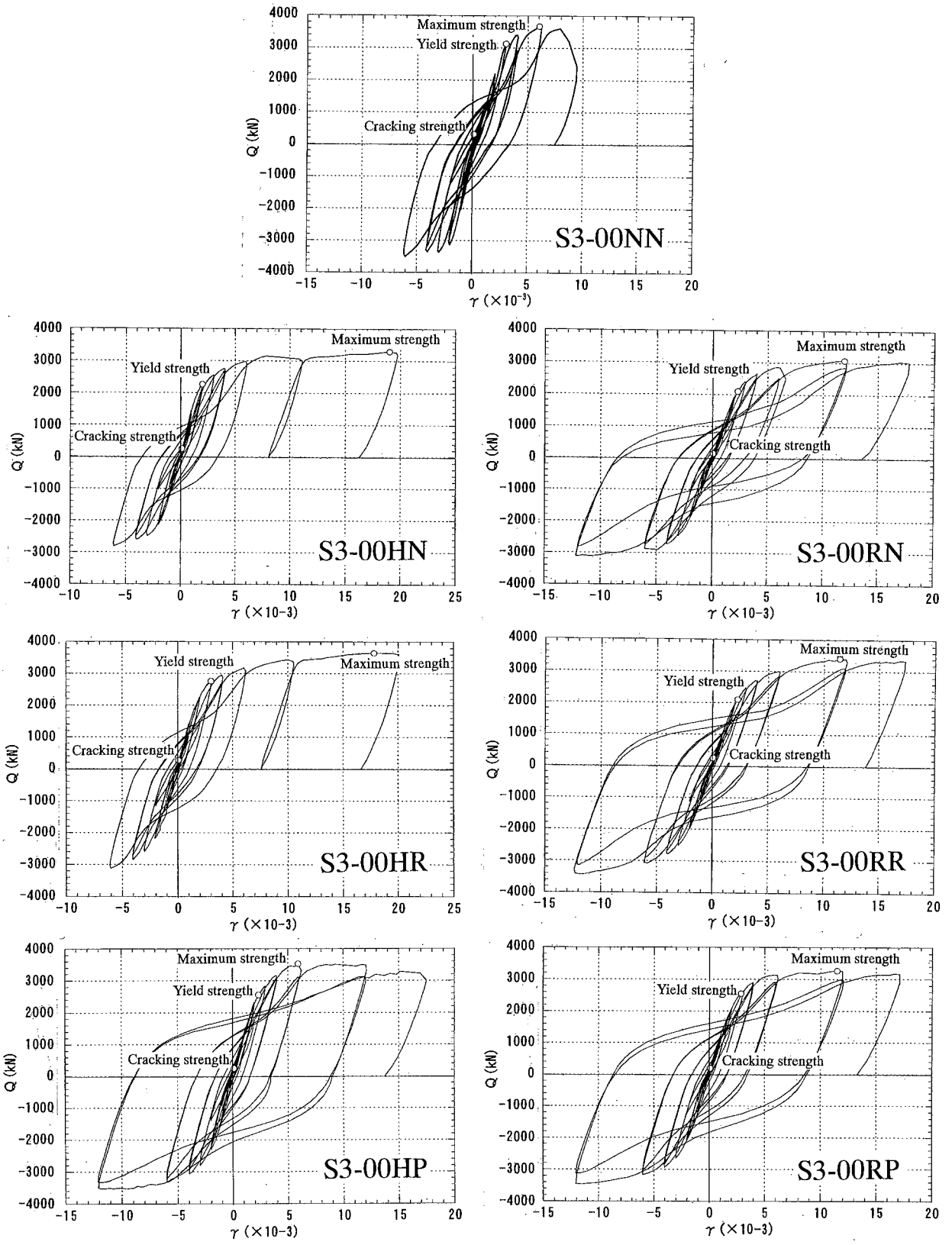

Fig. 3 Load-Deformation Relationship

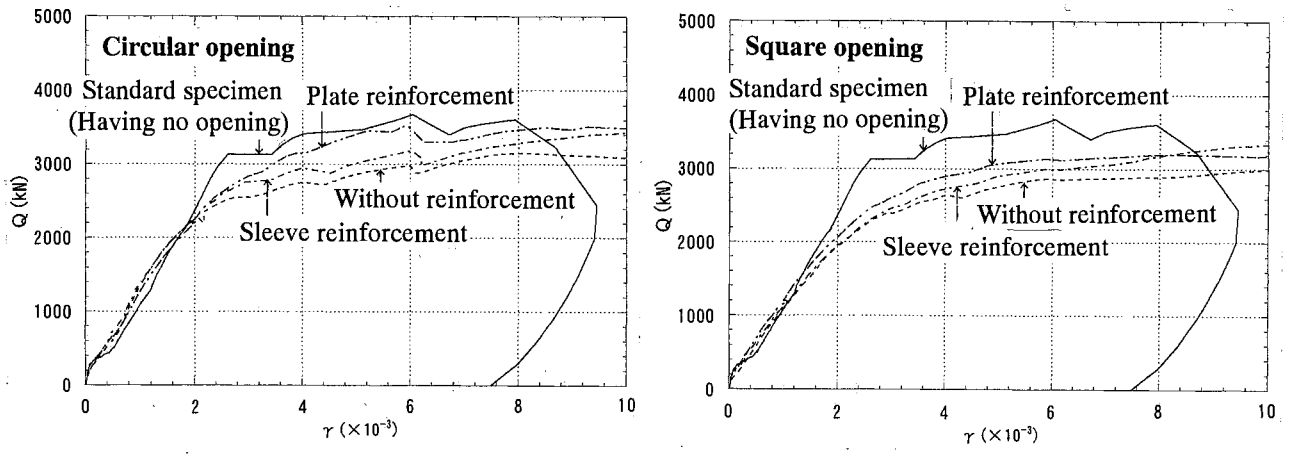

Fig. 4 Comparison about Envelopes

The strain near opening of the specimen having a opening without reinforcement increased almost linearly by the shear strain increase. But, the strain of the specimen with reinforcement checked the increase of the shear strain.

CONSIDERATION OF THE EXPERIMENTAL RESULTS

Reduction Ratio due to opening for Stiffness or Strength

We determine the reduction ratio due to opening for tangential stiffness, yield strength and ultimate strength (K1,K2 and K3). Fig. 8 shows the determination of each of them. In the experiment, the property of concrete was deviated. Therefore we tried to standardize the reduction ratio by way of the multiplication of the square root of the concrete strength of the standard specimen divided by that of the specimen having a opening. Fig. 9 shows the results of the calculation for the reduction ratios. The results of the calculation were based on the reduction ratio for reinforced concrete wall. That is,

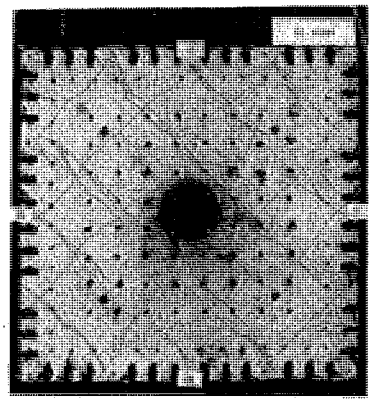

Fig. 5 Ultimate Condition of Concrete

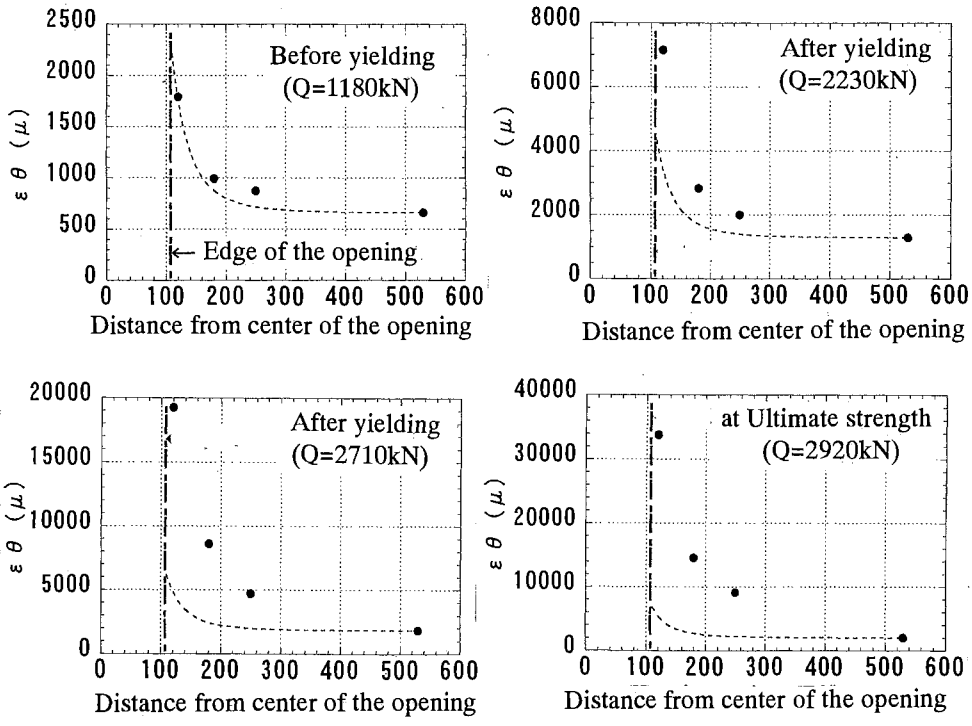

Fig. 6 Strain near Opening

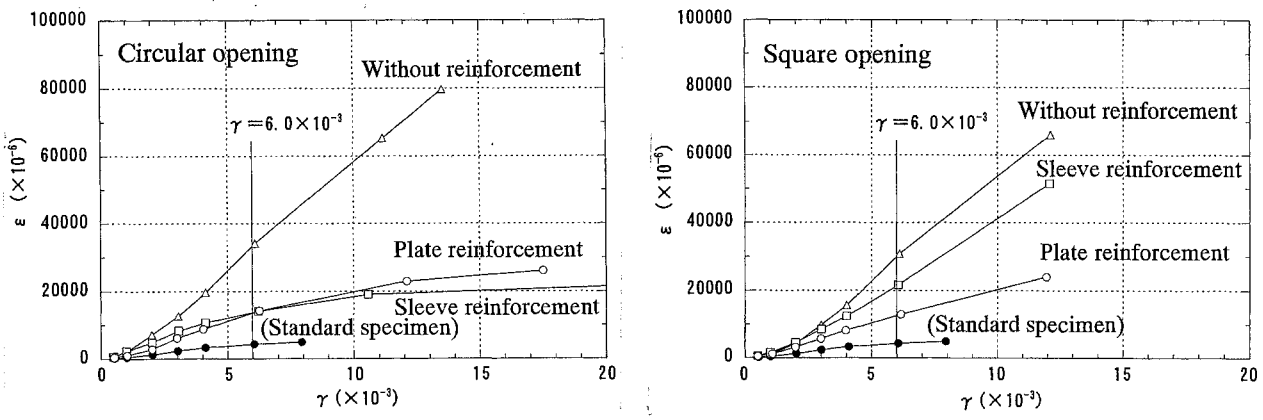

Fig. 7 Strain near Opening and Shear Strain

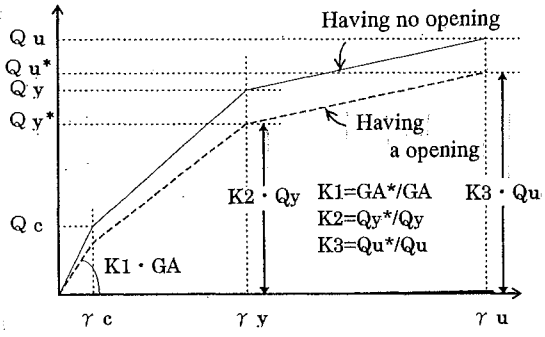

Fig. 8 Determination of Reduction Ratios

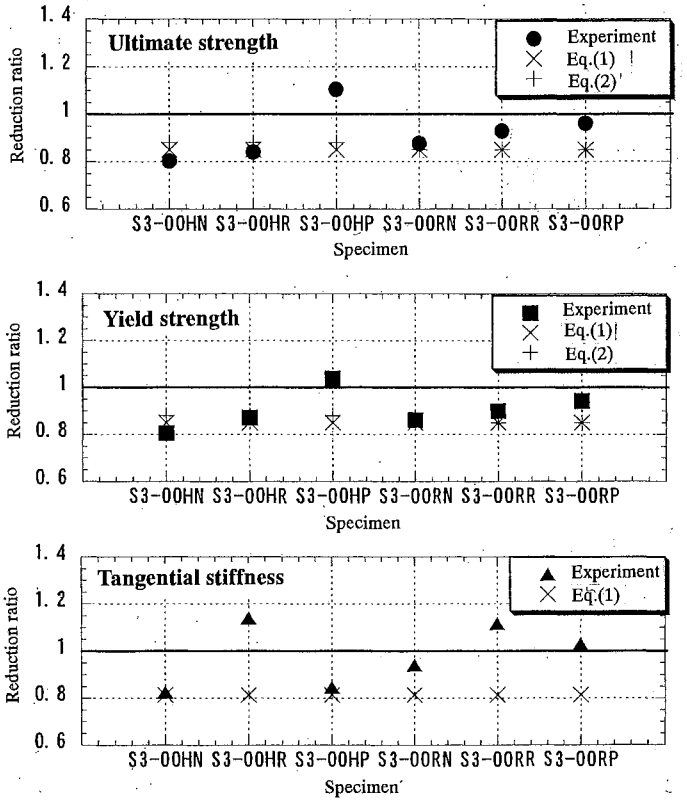

Fig. 9 Experimental Results and Calculative Results

1) Design recommendation in Japan for the wall having opening[6] is,

$$\gamma rc = \min\left(1-\frac{lo}{l},\ 1-\sqrt{\frac{holo}{hl}}\right) \tag{1}$$

in except that the term $\sqrt{\frac{holo}{hl}}$ shall not exceed 0.4.

2) Ono and Tokuhiro[7] proposed as follows,

$$\gamma ot = \sqrt{\frac{\sum Ae}{hl}} \tag{2}$$

where, h is the height of wall and l is the length of wall. And ho is the height of opening and lo is the length of opening. Ae is the compression field area of the wall.

The results of Eq. (1) and (2) show the good agreement with the experimental results. So, for SC panels, these equations for RC walls represent good applicability.

Effectiveness of the amount of reinforcement

The effectiveness of reinforcement in terms of the total amount is shown in Table 4. The effectiveness for yield strength and ultimate strength is focussed here in. We consider the effectiveness as the amount of steel reinforcement. Hence,

$$\text{Strength per total amount of reinforcement} = \Delta q / qs \tag{3}$$

where, Δq is the difference in strength between the reinforcing specimen having a opening and the specimen having a opening without reinforcement. qs is the total amount of the reinforcement.

Table 4 shows the effectiveness of the reinforcement of the steel plate is more effective than that of the sleeve reinforcement. So, finite element analysis describes in next chapter for the reinforcement used the steel plate.

Table 4 Effective Strength

Specimen	Concrete strength (Mpa)	Yield strength		Ultimate strength		Amount of steel	Effective strength	
		Qy (kN)	Δ q	Qu (kN)	Δ q	q s (cm^3)	For Qy	For Qu
S3-00HR	42.4	2710	74	3060	22	599	124	37
S3-00HP	31.7	2510	104	3470	168	701	148	240
S3-00RR	32.1	2170	6	2930	29	173	35	168
S3-00RP	32.7	2500	60	3060	47	680	88	69

FINITE ELEMENT ANALYSIS

Basic response subjected in plane shear of SC panels having a opening was investigated by the experience described before. But experimental data had limitation. Then the finite element analysis was planed for the investigation of the relationship between the reinforcing area and reinforcing thickness. Loads were monotonically increased in constant ratio until failure occurred.

Analytical Model

The analytical models were 1200×1200mm in plan dimension with a thickness of 200mm as the same to the test panels. But in this analysis, using symmetry, one-quarter the test panel was modeled(Fig.10). The thickness of the one side surface plate was modeled as 2.00mm. The scale of the opening was the same for the test panels. The partitioning web plate was modeled as the rod element because of the partitioning web plate to be shouldered mainly nodal force. The stud bolts were not considered for the analytical model.

Analytical model parameters are opening types(circular opening, square opening), thickness of the reinforcement steel plate(a half, equal, twice of the surface steel plate thickness)and the width of the reinforcement(0.25,0.50,0.75,1.00 times of the diameter of circular opening or the side of square opening).

Before the analysis described, the test analysis was done for evaluate the accuracy of this method.

Constitutive Relations

Constitutive relations generally used for RC structures were applied in this analysis. The stress-strain relationship in compression was modeled after Fafitis-Shah[8] and Darwin-Pecknold[9]. In tension, tension stiffening was considered after Izumo et al. (parameter c=0.8)[10]. Shear transfer on crack surface was considered after Al-Mahaidi[11]. Stress-strain relationship for steel plate was modeled in bi-linear.

ANALITICAL RESULTS

The load-deformation relationship of the test analysis was shown in Fig.11 in comparison with the experimental results. They were in good agreement. Therefor, the constitutive relationships described before have good accuracy for SC panels not only for RC structures.

The reduction ratios due to opening derived by the analysis are shown in Fig.12. This figure shows the reduction ratio can be represented only as the amount of the reinforcing steel plate. The vertical axes show the quotient of strength or stiffness, which the reduction ratio, given from the finite element analysis, divided by the reduction ratio calculated from Eq.(1). The horizontal axes show the quotient of reinforcing area, which the reinforcing area in section divided by the lost area of the surface steel plate for opening(Fig.13). The figure shows that the quotient of strength or stiffness increases linearly as the quotient of reinforcing area increases. Especially, the quotient of the yield strength and the ultimate strength show the same manner. These analytical results show the quotient of strength or stiffness depends only on the quotient of the reinforcing area, not on the width of the reinforcing area.

CONSIDERATION OF THE ANALYTICAL RESULTS

Reduction ratio considering reinforcement

If we were able to evaluate the strength or stiffness by the calculation method based upon rational theory, the effect of reinforcement could be considered for the reduction ratio for opening.

Practically, the calculation method for SC structure was based upon rational theory (truss mechanism) and the results of the calculation method are in good agreement with the experimental results[4].

Therefor, the reduction ratio for SC panel could be considered the effect of the reinforcement. The reduction ratio considering reinforcement is given by the recursion formula of the results of the finite element analysis.
Hence,

In case of circular opening ; $K' = 0.065\ rs + K$
In case of square opening ; $K' = 0.057\ rs + K$

where, rs is the quotient of reinforcing area, which the reinforcing area in section divided by the lost area of the surface steel plate for opening. K is the reduction ratio for the panel without reinforcement. The results of these equations shall not exceed 1.00.

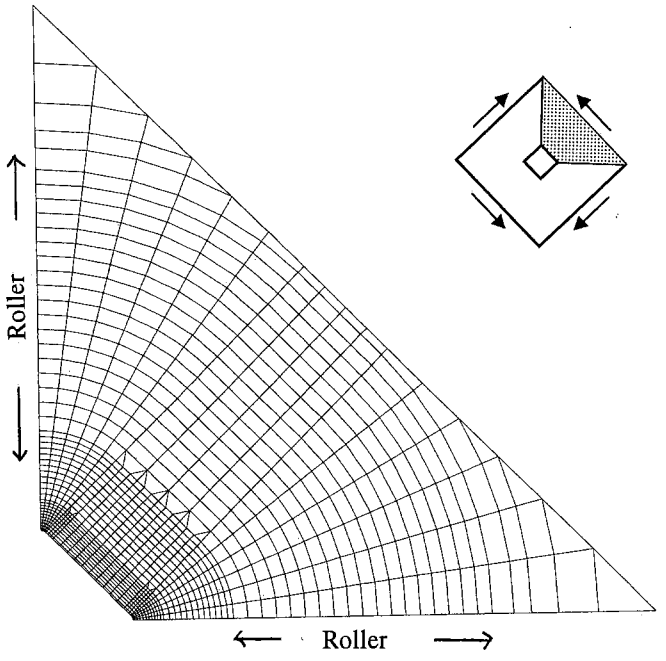

Fig. 10 Analytical Model (Square opening)

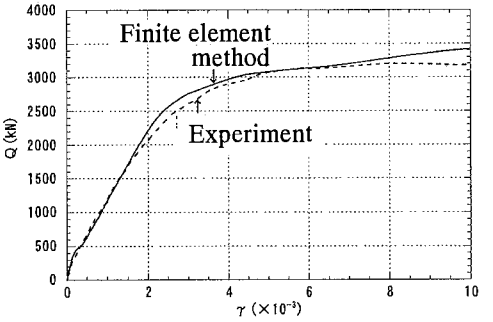

Fig. 11 Experimental Results and Analytical Results

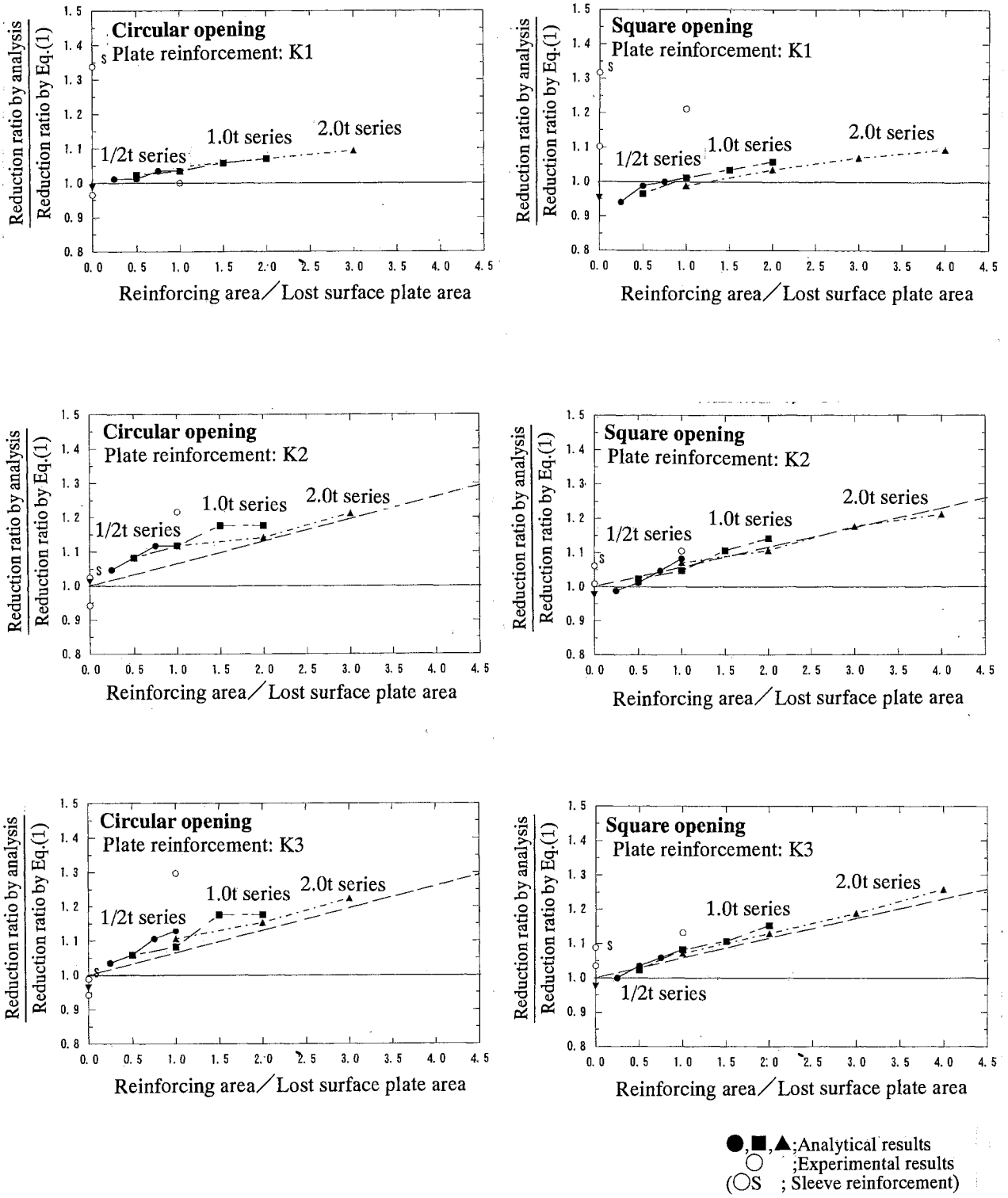

Fig. 12 Reduction Ratios and Reinforcement

CONCLUSIONS

The experimental and analytical study of the steel plate reinforced concrete structure (SC) having a opening was carried out for the purpose of confirming the fundamental behavior of SC shear wall. The conclusion is mainly bellow,

1) Although specimens have a opening, the responses under loading were very ductile.
2) Strain near opening increase linearly as the applied load increase. But the reinforcement kept the strain in lower value.
3) The reduction ratio for the panel having a opening can be estimated by the calculation method for RC structure.
4) The calculation formula for the considering reinforcement was proposed.

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