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RESTORING FORCE CHARACTERISTICS OF SHEAR WALL SUBJECTED TO HORIZONTAL TWO DIRECTIONAL LOADING

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SUMMARY

The objective of this study is to investigate the elasto-plastic behavior of RC seismic shear wall subjected to horizontal two-directional loading. Static loading tests of box type and cylindrical type shear wall were performed adopting various loading patterns on X-Y plane. According to the test results, resultant shear force - total deformation angle relationship under two-directional loading is analogous to that under one-directional loading. And furthermore, our simulation analysis results by a computer program of elasto-plastic FEM, which has four way multi-directional active crack model, considerably well agreed with the test results.

INTRODUCTION

In the current seismic design of nuclear power plant (NPP) buildings in Japan, seismic design loads in the two orthogonal, horizontal directions are obtained independently by seismic response analyses, whereas actual seismic forces jolt the buildings in three directions simultaneously. Therefore, it is important to clarify the seismic response characteristics of an NPP building under three-dimensional earthquake excitation and to evaluate the seismic margin properly up to the ultimate state. Nuclear Power Engineering Corporation (NUPEC) had conducted a project entitled "Model Tests of Multi-Axis Loading on RC Shear Walls" from 1994 to 2003, and Japan Nuclear Energy Safety Organization (JNES) succeeded to the project in October 2003. The objectives are to clarify the effects of multi-directional forces on the ultimate strength of reinforced concrete (RC) seismic shear wall. The project is commissioned by the Ministry of Economy, Trade and Industry (METI) of Japan. This paper describes a summary of the two directional horizontal loading tests that were conducted as a part of the project, and simulation analysis results.

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TWO-DIRECTIONAL HORIZONTAL LOADING TESTS

Test Specimen

The shape of shear wall and loading patterns are major parameters of this test. Four box type specimens and two cylindrical type specimens were identified by the name as shown in Table 1. Fig.1 shows the loading patterns adopted in the test. The peak deformation ratio of Y direction to X direction shall be 0.8 for all loading patterns except for circular loading so as to grasp the influence on the hysteresis due to several levels of orthogonal deformation and damage.

Table 1 Test Specimens and Loading Patterns

Specimen name	Wall shape	Shear span ratio	Loading pattern
SB-B-01	Box	0.80	Rectangular
SB-B-02			Cross
SB-B-03			Diagonal Cross
SB-B-04			Circular
SB-C-01	Cylinder	0.63	Rectangular
SB-C-02			Cross

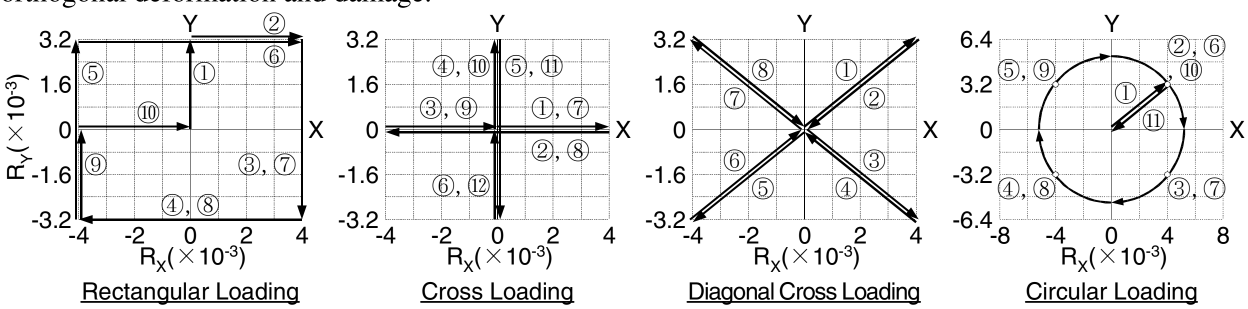

Fig.1 Loading Patterns

Fig.2 and Fig.3 show the shapes and dimensions of test specimens. The thickness of shear wall is 75mm. The loading point is at the center of the loading slab, 1200mm heights from the top of the base slab. The clear span height of shear wall is 1000mm. The width of shear wall of the box type specimen is 1575mm. The shear wall diameter of the cylindrical wall is 1910mm, which was determined so that the effective shear area (and the ultimate shear strength) is nearly equal to that of the box type specimen. So the shear span ratio of each type of test specimens are M/Qd=0.8 (box type) and M/Qd=0.63 (cylindrical type).

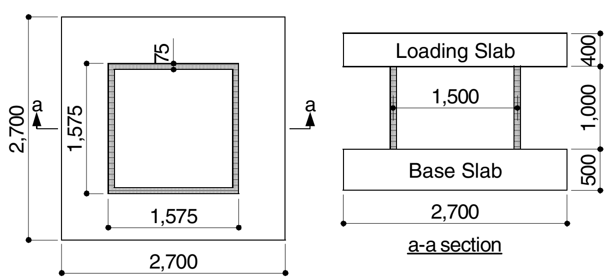

Fig.2 Box Type Specimen

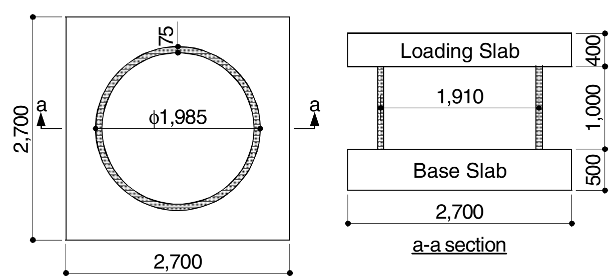

Fig.3 Cylindrical Type Specimen

Reinforcing bars of D6 (6mm in diameter) are placed both inside and outside of each wall in the vertical and horizontal directions in 70mm pitch. The wall-reinforcement ratio is approximately 1.2% for both types of test specimen. Table 2 shows the material test result of the reinforcing bars.

Table 2 Material Property of Reinforcing Bar

Property	Unit	Value
Young's Modulus	GPa	200
Yield Strength	MPa	375
Tensile Strength	MPa	493
Tensile Strain at Fracture	μ	28000

Table 2 shows the concrete material test results on the test day. Pea gravel concrete with coarse aggregate (maximum size of 10mm) is used for the wall part of test specimens.

Table 3 Material Property of Concrete

Item	Unit	Test Specimen					
		SB-B-01	SB-B-02	SB-B-03	SB-B-04	SB-C-01	SB-C-02
Young's Modulus (Ec)	GPa	30.7	30.7	32.0	32.0	31.9	32.2
Compressive Strength (σ_b)	MP	41.3	39.7	34.9	31.0	34.3	31.8
Peak Strain (ε_u)	μ	2060	2022	1817	1579	1896	1544
Poisson's Ratio (ν)	N/A	0.18	0.17	0.19	0.19	0.20	0.18
Tensile Strength (F_t)	MP	1.74	1.70	1.56	1.44	1.54	1.47

Note) Tensile strength was calculated using eq. $F_t=0.73*0.20*\sigma_b^{2/3}$

Loading Setup

The loading setup is shown in Fig.4. Test specimens are fixed on the test floor of a laboratory with PC steel bars. Horizontal shear force is applied by two couples of push-pull 1MN actuators, which are mounted on four sides of the loading slab. And furthermore, two 500kN jacks apply torsion force to prevent rotation of the loading slab in the X-Y plane. Four 30kN jacks with PC steel bars supply constant axial force through the loading block installed on the upper part of the loading slab. The axial stress, 1.47MPa, was determined by survey of actual NPP buildings.

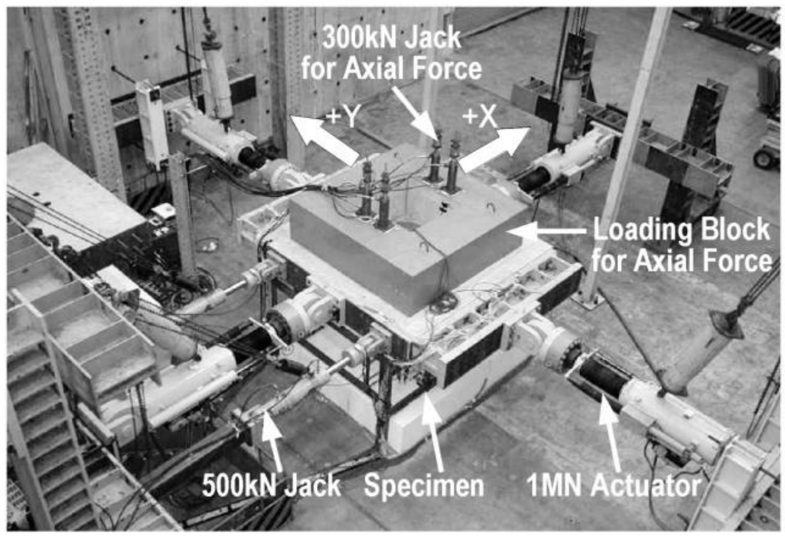

Fig.4 Loading Setup

Test Results

Maximum Shear Force and Ultimate State

Table 4 shows maximum shear force and total deformation angle at the maximum shear force of each test specimen. Fig.5 shows ultimate state of test specimens, SB-B-04 and SB-C-02. SB-B-04 shows the compression failure with shear slip of the bottom of the wall. On the other hand, SB-C-02 shows the shear slip failure along cracks of the wall.

Table 4 Maximum Shear Force and Total Deformation Angle at Maximum Shear Force

Specimen		SB-B-01		SB-B-02		SB-B-03		SB-B-04		SB-C-01		SB-C-02	
Direction		X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
(1)	Q(kN)	1376	815	1596	24	1261	965	1559	83	1233	588	1567	8
	R($\times10^{-3}$)	4.01	3.20	5.76	0.04	4.00	3.19	4.94	1.29	11.91	7.96	5.80	0.00
(2)	Q(kN)	7	1381	5	-1325	1090	-1034	-29	-1504	-35	1189	20	1576
	R($\times10^{-3}$)	-0.02	3.19	-0.03	-3.23	5.80	-4.64	1.31	-4.96	-0.01	3.15	-0.02	13.13
(3)	Qv(kN)	1600		N/A		1588		1610		1440		N/A	
	R($\times10^{-3}$)	4.01	3.20	N/A	N/A	4.00	3.19	3.95	3.19	5.78	4.78	N/A	N/A

Note) (1): at the step in maximum Q in X-direction (2): at the step in maximum Q in Y-direction
(3): at the step in maximum resultant shear force, $Qv=sqrt(Qx^2+Qy^2)$

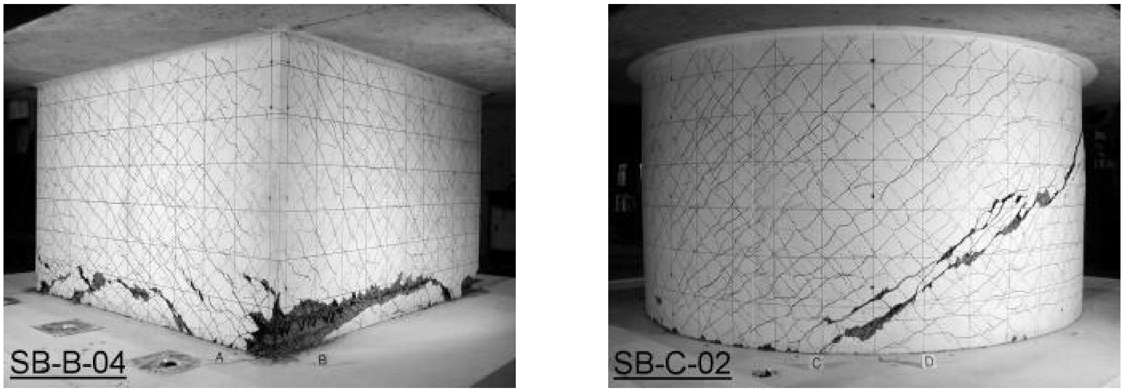

Fig.5 Ultimate State of Test Specimens

Relationships between Shear Force and Total Deformation Angle

Fig.6 shows the relationships between shear force and total deformation angle. Total deformation angle is defined by dividing the displacement at the bottom of the loading slab by the wall heights (=1000mm).

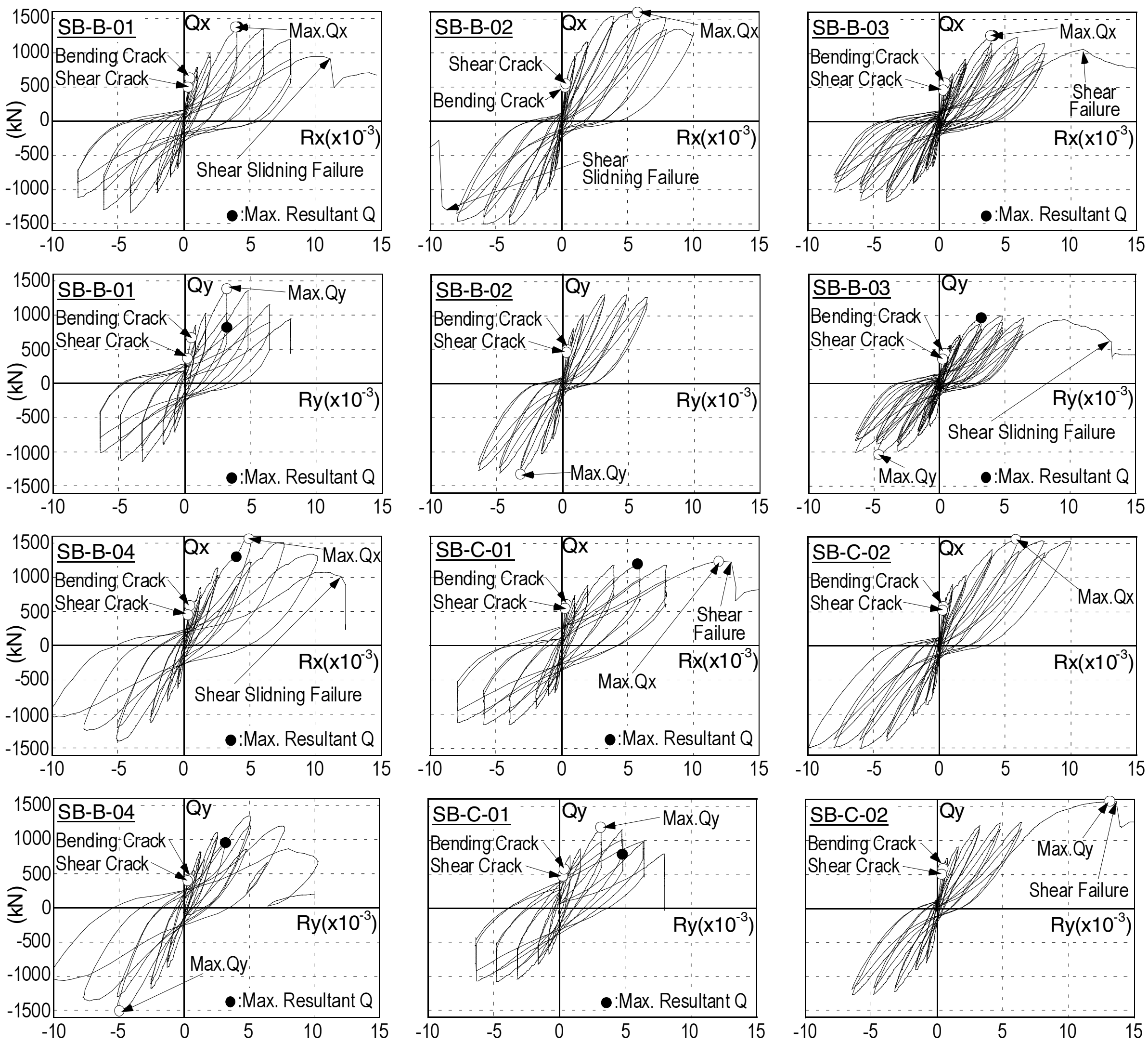

Fig.6 Relationships between Shear Force and Total Deformation Angle

Shear Force Orbit

Fig. 7 shows the relationships between orthogonal in-plane lateral shear forces of Qx and Qy extracted from the test result of rectangular loading (SB-B-01 and SB-C-01) and circular loading (SB-B-04). The occurrence points of maximum value of resultant shear force, Qv, are also shown in the figure. The resultant shear force, Qv, is calculated as $Qv=sqrt(Qx^2+Qy^2)$. In case of rectangular loading, the orbit tends to be convex for the box type wall and to be concave for the cylindrical wall. On the other hand, the orbit of circular loading is diamond-shaped and tilted in clockwise.

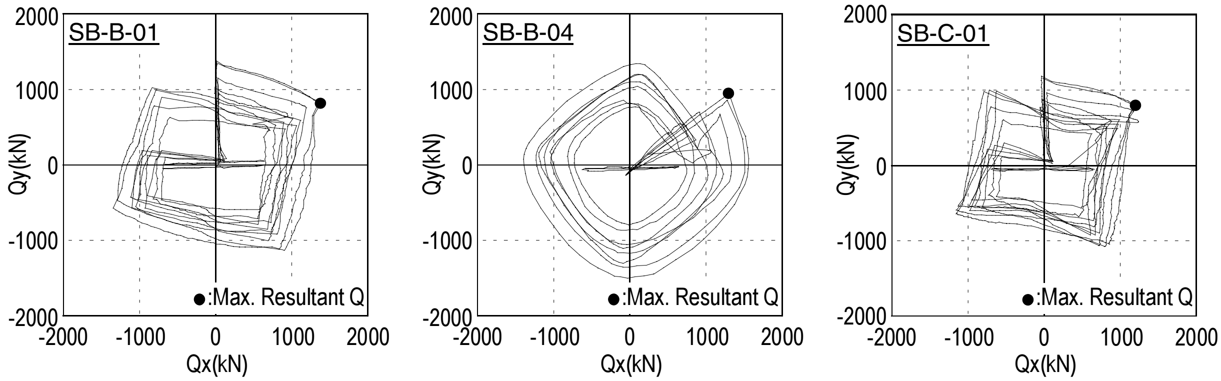

Fig.7 Shear Force Orbits

Evaluation of Test Results

Comparison of Envelope Curves

Fig.8 compares the envelope curves of resultant shear force and total deformation angle for three box type specimens, SB-B-01, SB-B-02 and SB-B-04. One of the diagonal loading test result[1], one-directional loading of box type specimen, is also superimposed on Fig.8. Since there is an about 15% difference of concrete compression strength among the specimens, each envelope curve is normalized by $_cQ_{JEAG}$, calclated one directional maximum shear strength based on the Japan Electric Association Guide (JEAG)[2]. From this figure, we can find out that up to the maximum resultant shear force the envelope curves of two-directional loading are higher than that of one-directional loading.

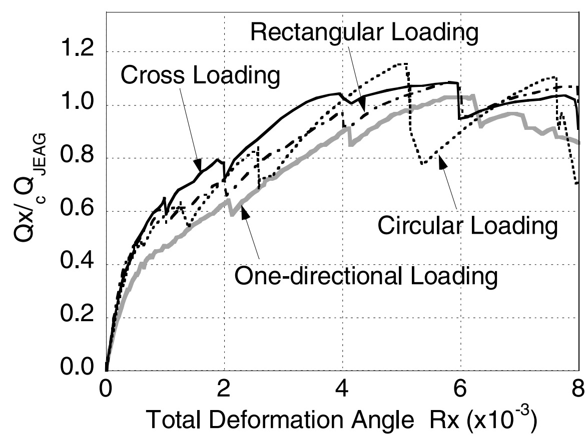

Fig.8 Comparison of Envelope Curves

Maximum Shear Force in the X-Y Plane

Fig.9 shows the maximum shear force of each test specimen in the X-Y loading plane. The test results of the diagonal loading test[1] are also plotted in Fig.10. Each shear force value is normalized by $_cQ_{JEAG}$. In the diagonal loading test, box type specimens were tested by the diagonal loadings in 0, 26.4 and 45.0 degree to the normal axes. From the figure, for most of test results, resultant shear forces have closed but somewhat larger values than the referencing arc. This means the influence of the loading path is not so effective on the maximum value of the resultant shear force.

Fig.10 shows shear deformation angle at the maximum shear force in the X-Y deformation plane. From this figure, for all of test results, the shear deformation angle in each directions of X and Y are larger than 4/1000. This means the ultimate shear deformation angle, γ=4/1000, prescribed in JEAG is still available under two-directional horizontal loadings.

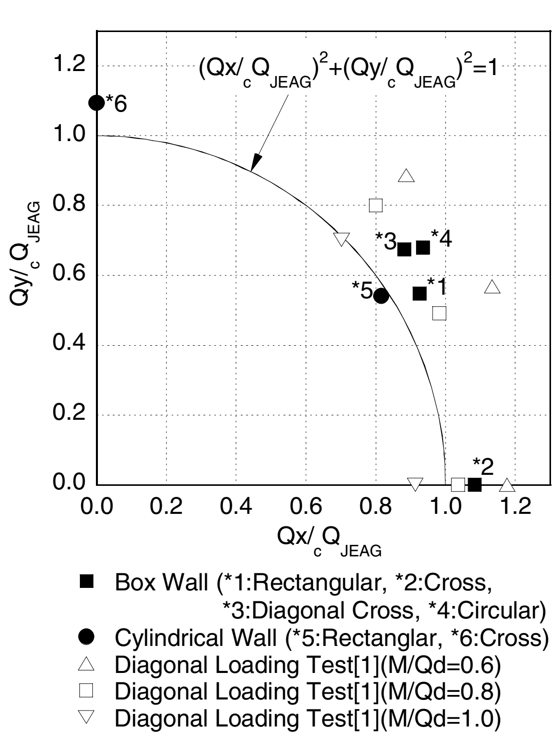

Fig.9 Correlation of The Maximum Shear Force

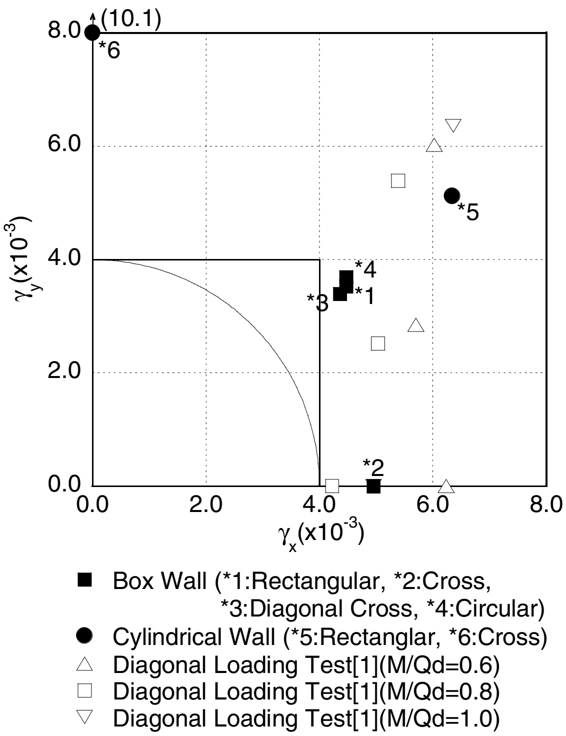

Fig.10 Correlation of Shear Deformation Angle at The Maximum Shear Force

Analogy between Envelope Curve and Design Formula

Fig.11 compares the skeleton curve for the JEAG model with the envelope curve of the resultant shear force and the total deformation angle. From these figures, we can find out that the envelope curve for the resultant shear force and the total deformation angle would exhibit a similar tendency to the JEAG model that considered one-directional loading.

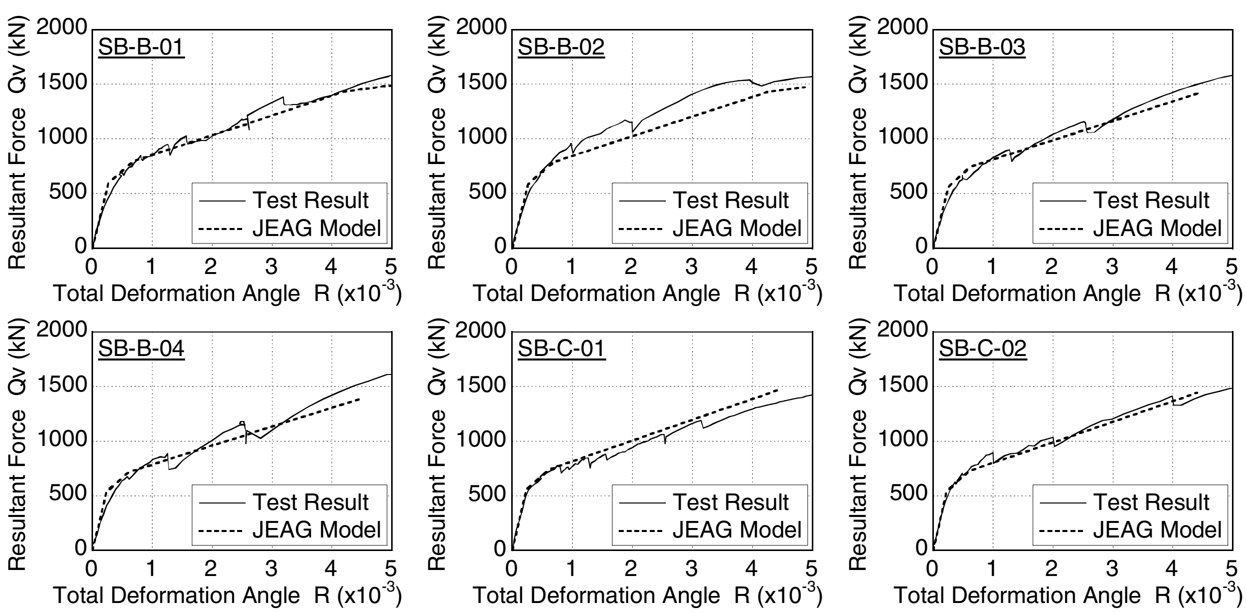

Fig.11 Analogy between Envelope Curve and JEAG Model

SIMULATION ANALYSIS

Program used in analysis

Fig.12 shows outline of non-orthogonal cracking model up to four way directions[3] introduced into a program used in analyses. About the detail of constitutive models in the program, see reference [4][5].

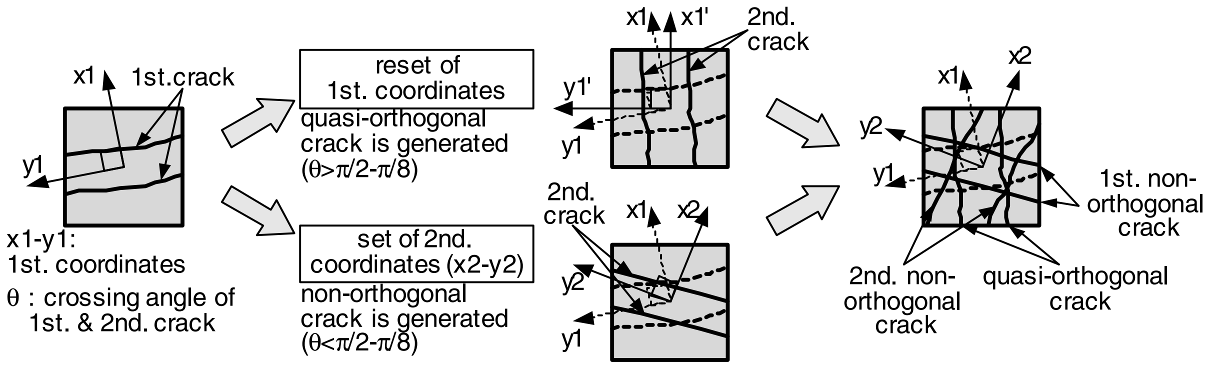

Fig.12 Non-orthogonal cracking models up to 4-way directions

Analysis Model

Fig.13 shows the analytical model of box type wall and cylindrical type wall for analyses. The analytical model is the 3-dimensional FEM model in which the wall and upper slab are modeled with 8-node quadrilateral isoparametric layered shell elements. For the boundary condition of the model, the wall elements are placed at upper surface of base slab. The material properties used in the analyses are the same as test specimens.

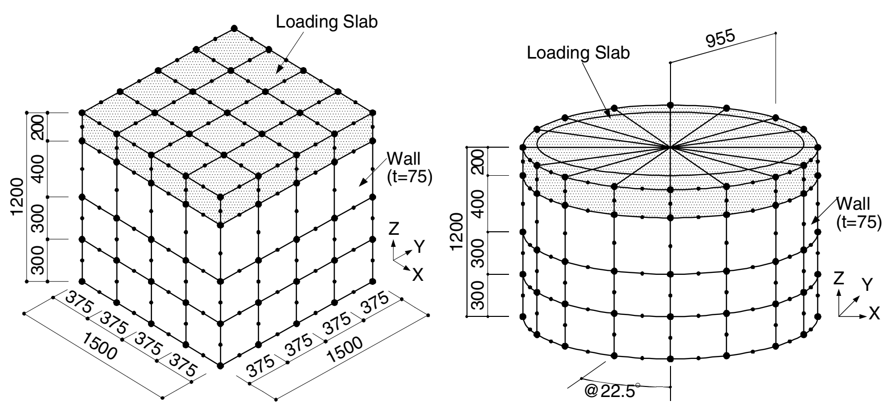

Fig.13 Analysis Model

Analysis Results

Fig.14 shows comparison of shear force - total deformation angle with test and analysis. Fig.15 shows comparison of X-Y shear force orbit with test and analysis. According to these figures, analytical results by the four way cracking model considerably well agreed with the test results.

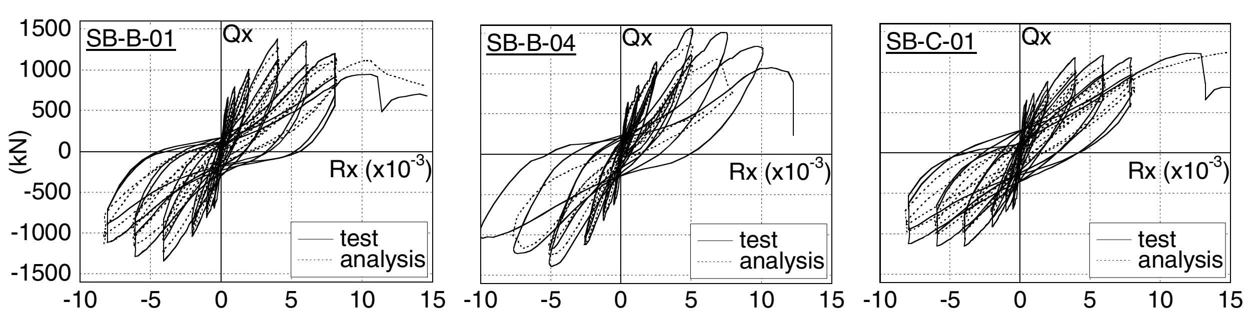

Fig.14 Comparison of Shear Force - Total Deformation Angle with Test and Analysis

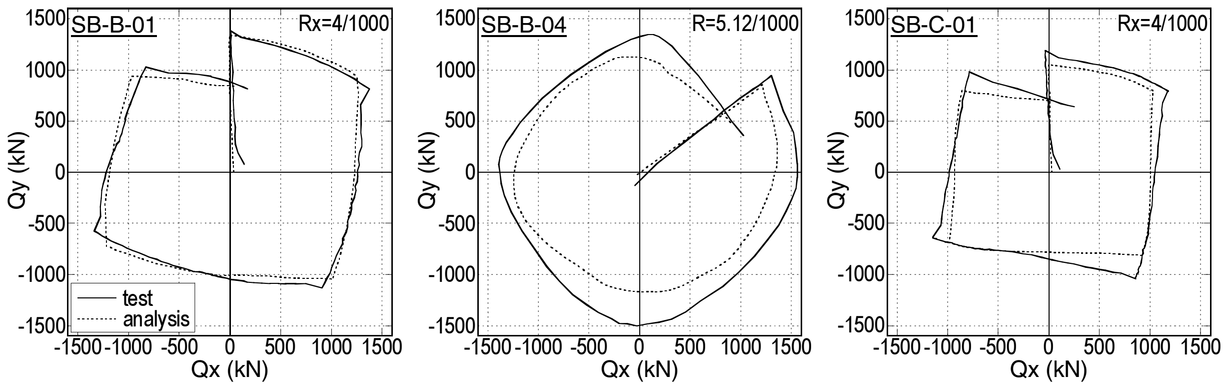

Fig.15 Comparison of Shear Force Orbit

CONCLUSIONS

The two directional horizontal loading test was conducted to understand the elasto-plastic characteristics of an RC seismic shear wall as a part of “Model tests of multi-axes loading on RC shear walls” project. From the results of this test, the following conclusions are derived:

(1) According to the test results, irrespective of loading patterns, resultant shear force - total deformation angle relationship under two-directional loading is analogous to that under one-directional loading.

(2) The envelope curve for the resultant shear force and the total deformation angle would exhibit a similar tendency to the JEAG model that considered one-directional loading.

(3) Simulation analysis results by a computer program of elasto-plastic FEM, which has four way multi-directional active crack model, considerably well agreed with the test results.

ACKNOWLEDGMENTS

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