Pretest Analysis of Shear Walls Subjected to Horizontal Two-directional Loading

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ABSTRACT

This paper shows the results of pretest analyses for the behavior of RC shear walls subjected to horizontal two-directional loading. The objective of the study is to carry out the nonlinear FEM analyses on the probable loading patterns, and to investigate how the differences in crack models affect on the results of analysis. The shape and dimension of specimens are box-type and cylindrical. Various loading patterns on X-Y plane are adopted in the analyses. In order to examine the effects of differences in crack models on the analysis, pretest analysis was performed using two types of crack model. The one is a non-orthogonal cracking model up to 4-way directions and the other is a bi-directional cracking model. The analyses of box wall subjected to one-directional reverse cyclic loading were performed using two programs to verify the accuracy of codes. Then, the analyses in horizontal two-directional loading were performed. Effects of two-directional loading on non-linear behavior as compared with one-directional loading are remarkable in rectangular loading pattern which produces a rectangular response orbit on X-Y displacement plane. There are differences in the analytical results by both programs. By the two-directional fixed crack model, it is difficult to simulate the cracks that are expected to generate on the wall surface subjected to two-directional loading. The loading tests were carried out recently. Then, the comparison of the results by tests and analyses were performed. The analytical results by the 4-way cracking model are in agreement well with the test results.

1 INTRODUCTION

Horizontal two-directional simultaneous loading test of shear wall is a part of "Model Tests of Multi-Axis Loading on RC Shear Walls", which has been conducted by Nuclear Power Engineering Corporation (NUPEC). This project have been carrying out aiming at advancement of the seismic safety evaluation methodology in the design of reactor building for nuclear power plant. Plan and test results are presented in the other report of SMiRT-16 [1] .

The objective of pretest analysis is to execute a nonlinear FEM analysis on the probable loading patterns, which will be adopted in the tests, then, to identify the characteristics of nonlinear behaviors corresponding to each loading pattern, and to investigate the effects of differences in crack models on the results of analysis. A matter of great interest is how accurately the test results can be predicted by the analysis.

2 PROGRAMS USED IN ANALYSES

In order to examine the effects of differences in crack models and constitutive equations for the shear transfer of cracked concrete on the results of analysis, a pretest analysis will be performed using two types of codes, the differences of crack models between both programs are shown in Fig.1, and Table 1 shows the characteristics of programs. By collating the findings with the test results, factors necessary for analyzing a seismic behavior of wall subjected to multi-directional inputs will be evaluated.

2.1 Introduction of the Constitutive Equation for the Shear Transfer of Cracked Concrete in "Program I"

As the result of "Element Tests" [2] which is a series of "Model Tests of Multi-Axis Loading on RC Shear Walls", conducted in fiscal 1998, it has been suggested to adopt the constitutive equation for the shear transfer of cracked concrete that assumes in the shear stress state after a horizontal direction crack generated. (See Fig. 2) Horizontal two-directional loading analyses were performed by Program I into which this constitutive equation was introduced. In order to verify the constitutive equation adopted, the simulations of Element Tests was carried out. It is found that the shear stiffness after cracking is almost in agreement with the test results.

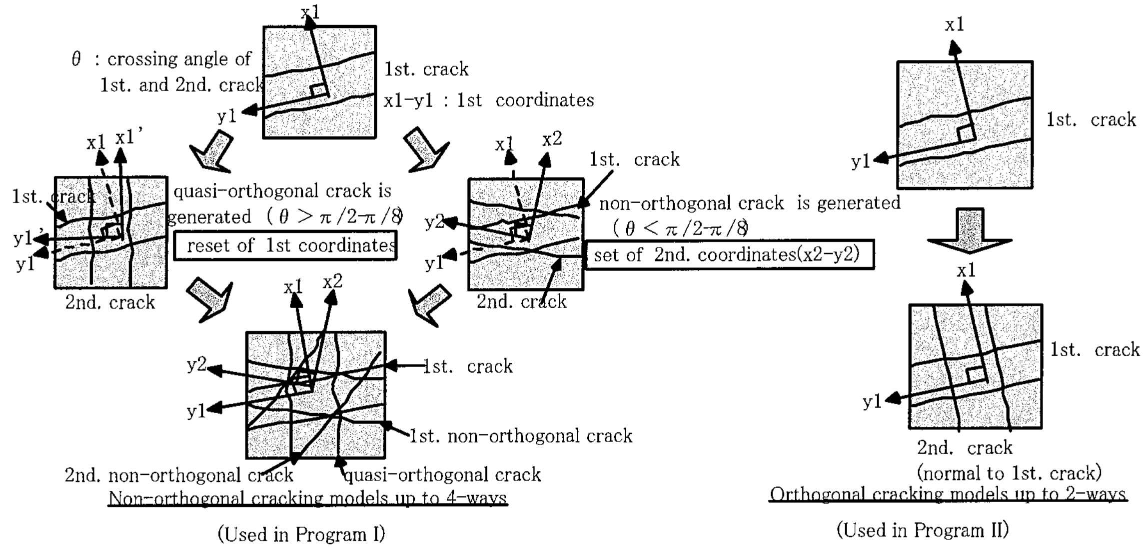


Fig. 1 Crack Models

Table 1 Programs Used in Analysis

Program	Characteristics of Program (mainly, according to crack models)
Program I	**Element :** 8-node quadrilateral isoparametric layered shell element **Nonlinear Solution :** The stress are obtained by computing directly from total strains through the stress-strain relations **Concrete Model :** Elasto-plastic and fracture model by Maekawa and Okamura **Crack Models:** 4 way multi-directional active crack model by Fukuura and Maekawa [3] (Non-orthogonal cracking models up to 4-way directions that contain two orthogonal coordinates corresponding to quasi-orthogonal bi-directional cracking) - Stress is determined by coordinates corresponding to active cracks (wider cracks to be transferred in proportion to stress change). - A constitutive equation for the shear transfer of cracked concrete that can be derived as the result of Element Tests is incorporated.
Program II	**Element :** 4-node quadrilateral isoparametric layered shell element **Nonlinear Solution :** The stress are obtained by the conventional step-by-step integration of the tangential stiffness **Concrete Model :** Elasto-plastic Model **Crack Models :** - Bi-directional crack model (The angle of a crack, once generated, will not change. A second crack will be at right angles to the first one if the first one is open and it will take any direction if the first one is closed. Stress on the wider crack will be determined.) - A constitutive equation for the shear transfer of cracked concrete is a model that takes into consideration aggregate interlock action and dowel action in the bi-linear form.

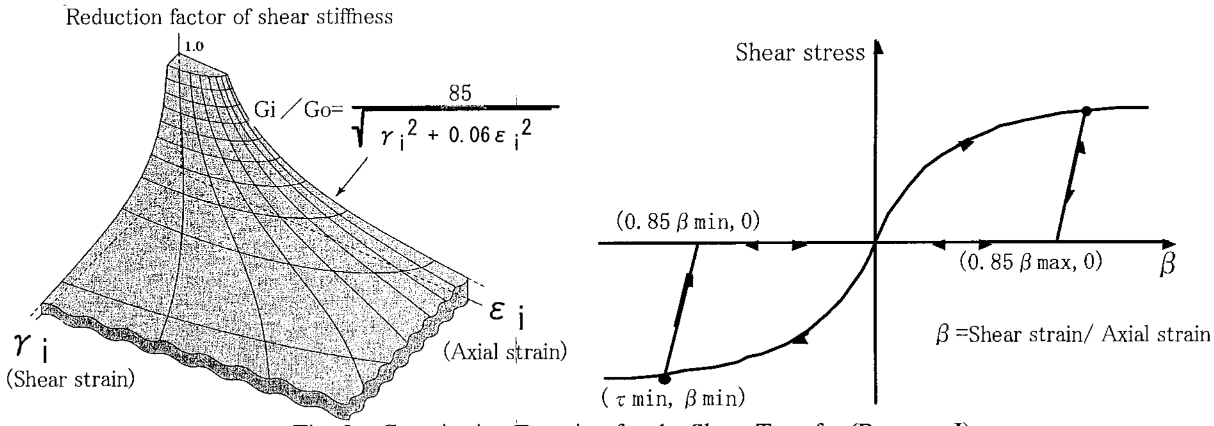


Fig. 2 Constitutive Equation for the Shear Transfer (Program I)

3 ANALYTICAL MODELS

3.1 Material Characteristics

- Concrete: A target compression strength in horizontal two-directional tests was set at 35MPa, which is the actual level attained in Diagonal Loading Tests, a part of "Multi-axial Loading Test for RC Wall". Therefore, material test results, obtained in Diagonal Loading Tests [4] , were used for the concrete stress-strain relationship in the analysis. Moreover, cracking stress is determined based on cracking stress observed in Element Tests.

- Reinforcement: The stress-strain relationship of reinforcing bars (D6), which were used in a wall, was determined based on the results of material tests. The characteristics of materials used in the analysis are shown in Table 2.

Table 2 Material Property

Material	Properties	Assumed Value
Concrete (Wall&Slab)	Young's Modulus	26.3Mpa
	Compressive Strength	34.9Mpa
	Peak Strain	2230μ
	Poisson's Ratio	0.21
	Tensile Strength (estimated value)	1.57Mpa
Rebar (D6)	Young's Modulus	200Gpa
	Yield Strength	375Mpa
	Tensile Strength	493Mpa

3.2 Modeling of Specimen

Configuration and size of box-shape specimen is shown in Fig. 3. The analytical models is the three-dimensional FEM models in which the wall and upper slab are modeled with layered shell elements. Wall cross sections take two shapes: box-shape and cylindrical. The reinforcement ratio is 1.2% both in vertical and horizontal. Reinforcing bar elements were placed in the prescribed position of a wall cross section. For the boundary condition of the model, the wall was fixed at upper surface of base slab. The analytical model of box type is shown in Fig. 4.

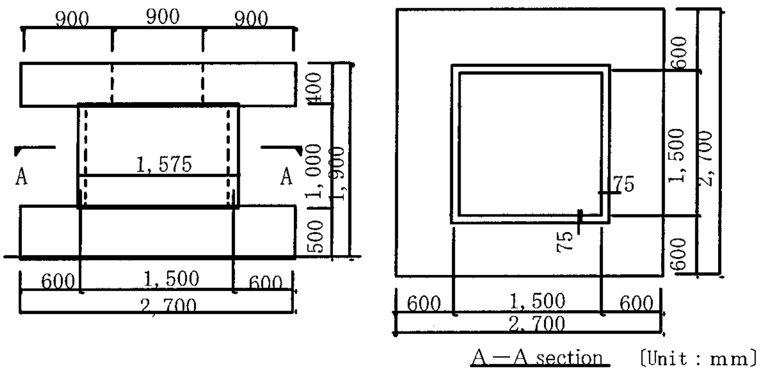


Fig.3 Test Specimen (Box type)

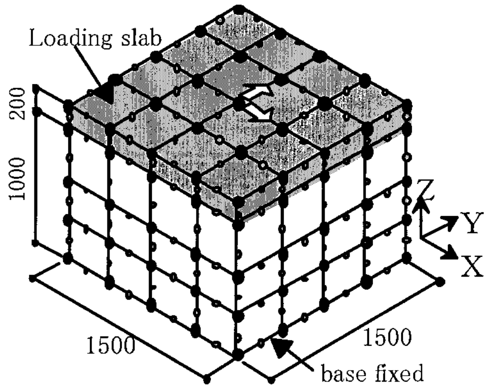


Fig.4 Analysis Model (Box type)

4 LOADING PATTERN

A three-dimensional seismic response analysis of reactor building was conducted in our study. Consequently, the stress response orbit in the horizontal two-directions at wall is, roughly speaking, the combined shape of a radial orbit and a circular or elliptic orbit. Cross loading pattern represents a simplified pattern of a radial orbit and rectangular loading pattern represents a simplified pattern of a circular or elliptic orbit. Accordingly, these two pattern were adopted as basic loading patterns for the test. The rectangular pattern produces a rectangular response orbit, and it enables the examination of not only the damages due to the orthogonal loading but also the influence of the orthogonal deformation. Meanwhile, the cross pattern is a radial loading response, which enables the identification of the influence of damages due to the orthogonal loading. The peak deformation ratio of Y direction to X direction shall be 0.8 for all loading patterns so as to grasp the influence on the hysteresis due to several level of orthogonal deformation and damage. Fig.5 shows the loading patterns adopted in the analysis.

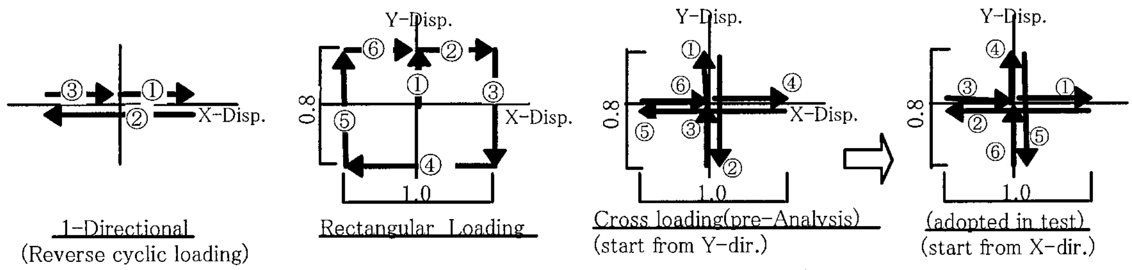


Fig. 5 Loading Pattern Adopted in the Analyses

5 RESULTS OF ANALYSES

5.1 Comparison of One Directional Loading with the Past Test Results

Fig.6 compares the results of one-directional loading shear force-total displacement relationship using Program I and II with the past tests results of "Diagonal loading Test" [4] in which the same properties of specimen and loading patters were adopted. There are some differences in the results of both programs, but they are found to almost agree with the test results both in terms of an envelope curve and the shape of hysteresis loops. Therefore, the analytical models of both programs are verified as for one-dimensional reverse cyclic loading.

5.2 Differences of the Analytical Results in Two-Directional Loading using Program I and Program II

Fig.7 shows the results of shear force - total displacement relationship of box-type wall subjected to rectangular loading and cross loading using Program I and Program II. Shear strength in X or Y direction by both programs subjected to rectangular loading is expected to be smaller than that in one directional loading. By Program II, on the positive side of X-direction, shear force reduces due to Y-direction displacement, but it does not in the negative direction. Moreover, on the negative side of X-direction, hysteresis loops do not swell significantly, indicating the origin-oriented hysteresis properties. By Program I, shapes of hysteresis loops are symmetry in both directions and swell compared with the one-directional loading.

For cross loading by Program II, the Y-direction shear force-total displacement relationship is almost the same as that in one-directional loading. The X-direction shear force-total displacement relationship does not take a positive-negative symmetrical pattern. In a low displacement region, stiffness is larger than in one-directional loading. By comparison, there are slight differences for shear strength and loop shapes in Program I, as compared with that in one-directional loading.

These properties obtained by Program II are different from those by Program I. The reason may be a difference in crack models adopted. Then, the applicability is verified to check whether the stiffness reduction due to propagation of cracks can properly be represented.

As an example of analytical results, Fig. 8 shows the results obtained on a loading pattern that simulates the situation where cyclic shear forces are applied after horizontal cracks have generated due to vertical tension.

Under Program II, after horizontal cracks have generated due to vertical tension, the second crack generates due to positive-direction shear force and cracking occurs any more, so that the shear stiffness in the negative direction becomes larger than that in the positive direction.

Therefore, Program II cannot represent three or more cracking in rectangular loading or cross loading on the box wall, so that the different results may be produced between the positive and negative loading patterns, or shear stiffness may be larger than in horizontal one-directional loading.

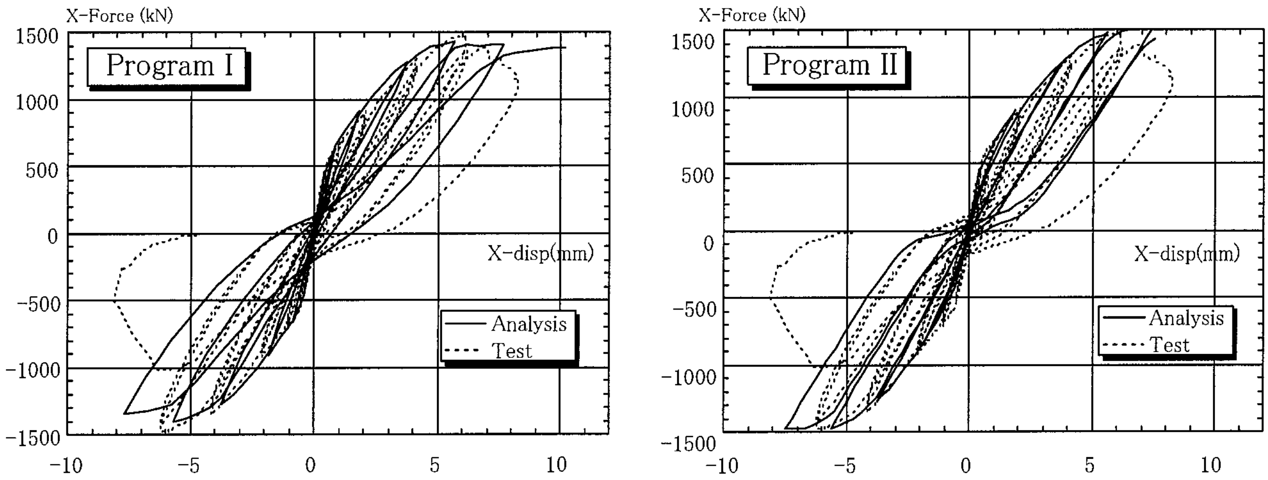


Fig. 6 Comparison of Shear Force - Disp. Relations Subjected to One-Directional Loading - Test and Analysis-

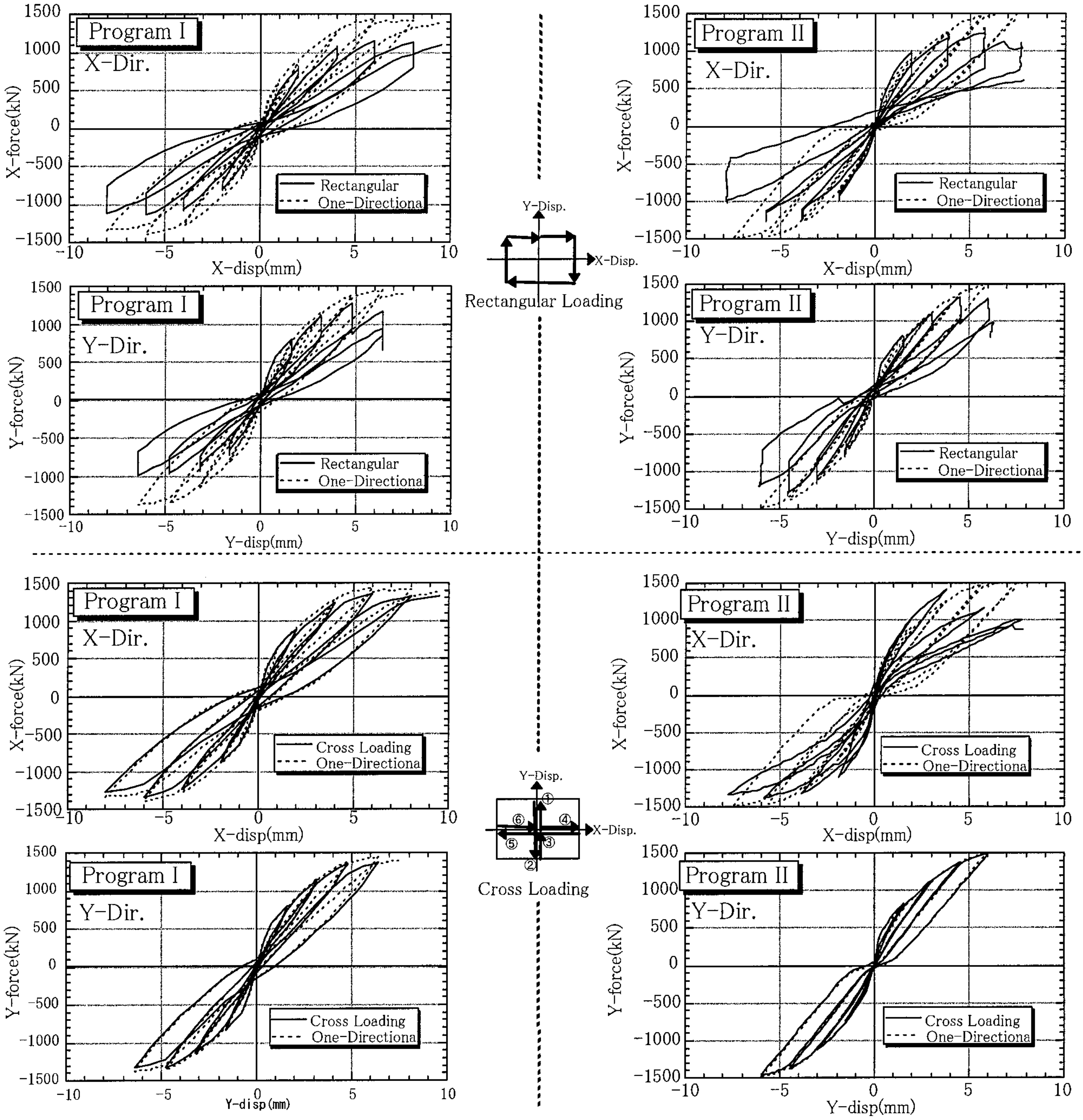
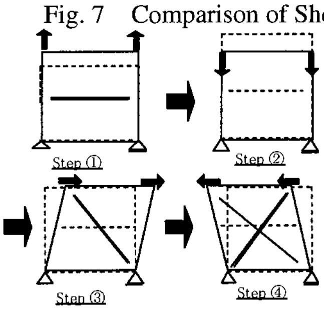


Fig. 7 Comparison of Shear force – Disp. Relations Subjected to Two- directional Loading



Loading Process of RC Element

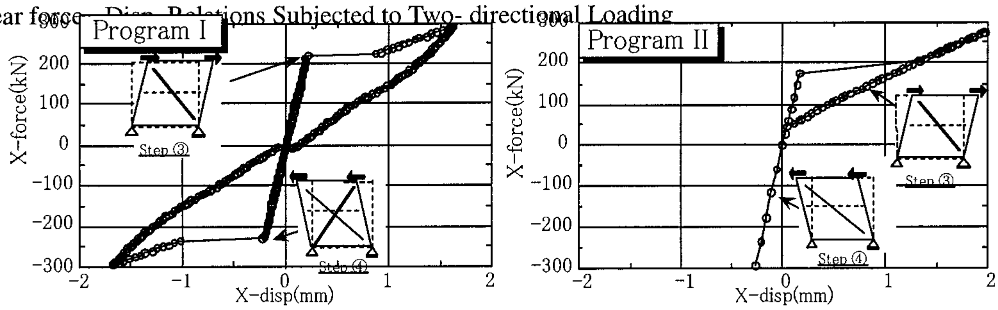


Fig.8 One Element Test Analyses

6 COMPARISON OF PRETEST ANALYSIS RESULTS TO TEST DATA

6.1 Reanalysis

Two-dimensional loading tests of 4 specimens were carried out. The details of test procedure and results are presented in Ref. 1. The comparison of these test results and analytical results using Program I are shown below. The analytical conditions changed from the previous chapter about following three items.

1) The results of concrete material tests performed just before the loading tests were adopted.

2) The loading cycles of the analysis are determined from those of the test.

3) Regarding cross loading on a box wall, almost no difference was observed to one-directional loading. One of the reasons is the loading patterns. This loading pattern lets Y-direction loading first in the X-Y ratio of 1:0.8. When this pattern applies, the past empirical orthogonal loading level is always lower than that of the target direction when displacement is renewed, so that the effects of damage due to a significant displacement cannot be considered.

Accordingly, X-direction loading was allowed to take place first as an improvement. Applying this pattern, the orthogonal empirical displacement will be larger than the target displacement when Y-direction loading is applied.

The analytical results of load - horizontal displacement relations in X and Y - direction and orbit of shear force in X-Y plane are compared with the test results. Fig.9~11 show the results of shear force - total displacement relationships , Table 3 compares the maximum load with tests and analyses and Fig.12 shows the orbits of shear force in X-Y plane.

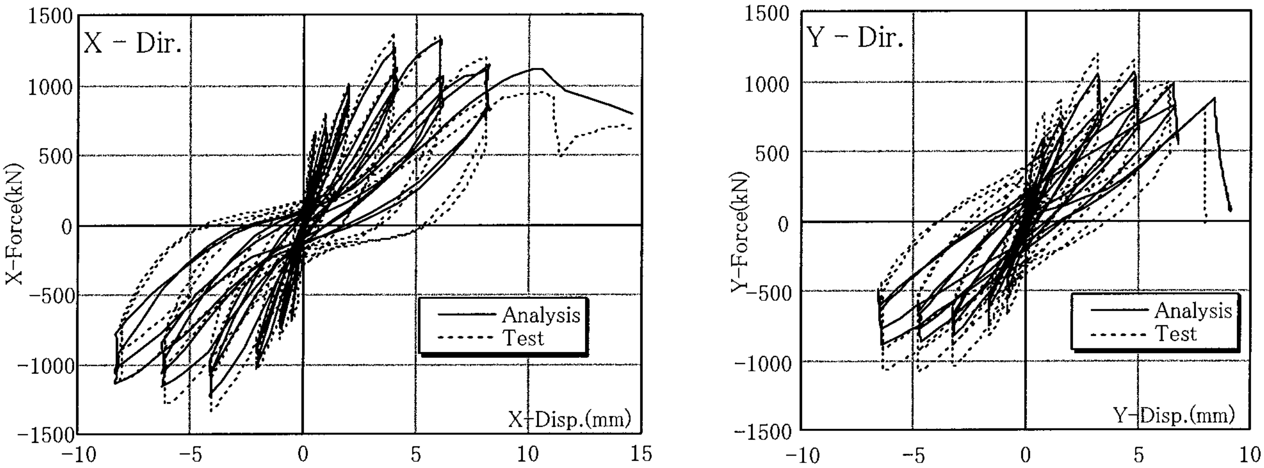


Fig. 9 Comparison of Shear Force - Displacement Relations with Test and Analysis (Box-type Wall Rectangular Loading)

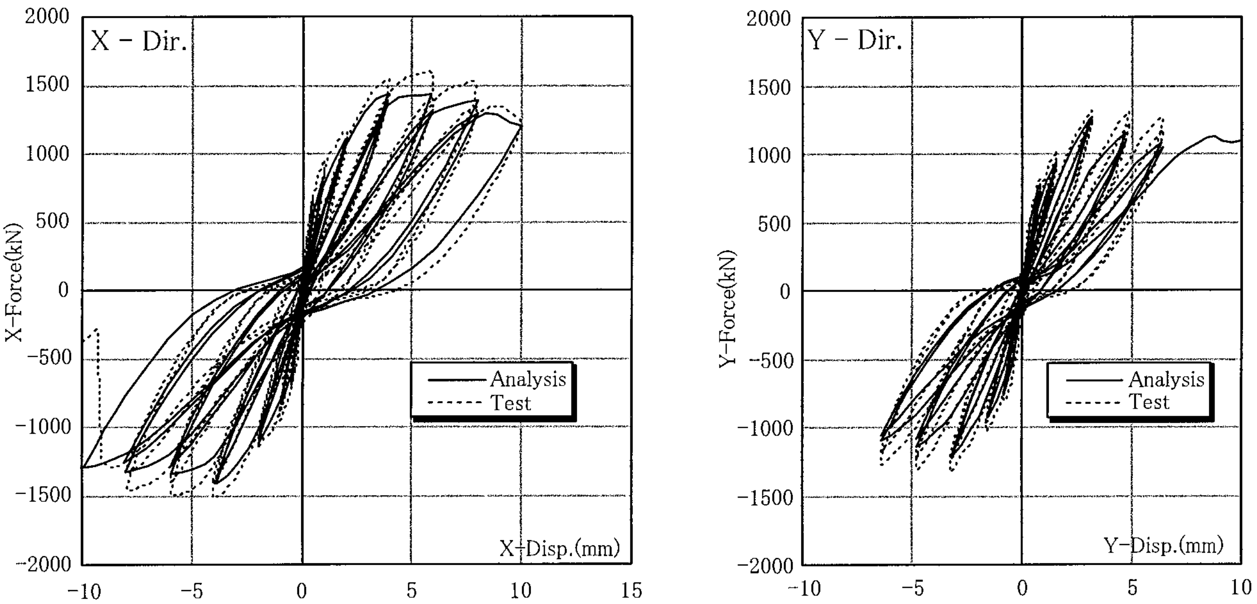


Fig. 10 Comparison of Shear Force - Displacement Relations with Test and Analysis (Box-type Wall Cross Loading)

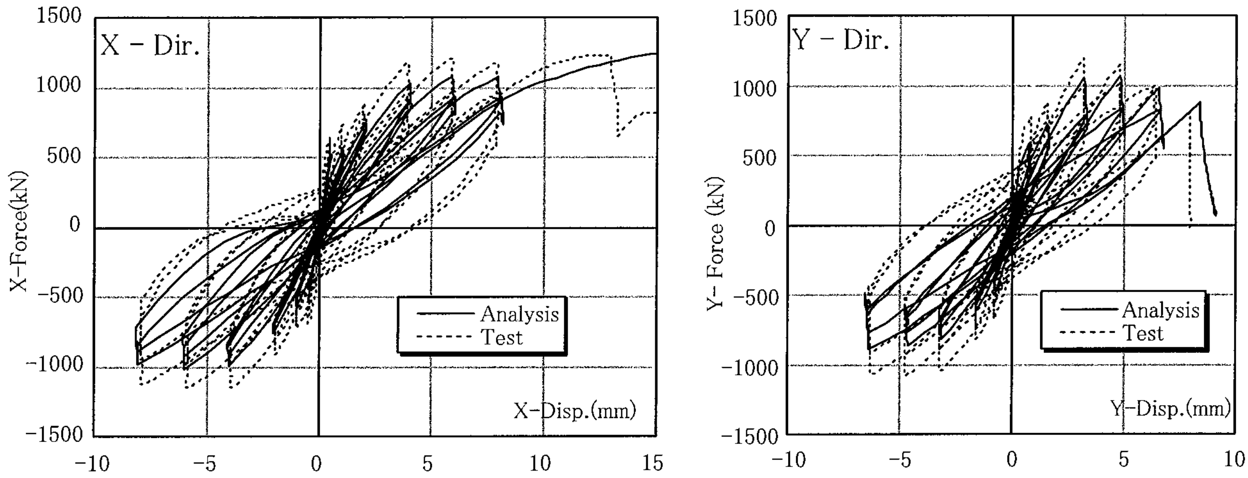


Fig. 11 Comparison of Shear Force - Displacement Relations with Test and Analysis (Cylindrical Wall Rectangular Loading)

Table 3 Comparison of Maximum Load with Tests and Analyses

	X - Direction			Y - Direction			Combined force		
	Test(kN)	Analysis(kN)	Test / Analysis	Test(kN)	Analysis(kN)	Test / Analysis	Test(kN)	Analysis(kN)	Test / Analysis
Box Wall - Rectangular Loading	1376	1321	1.04	1381	1341	1.03	1600	1586	1.01
Box Wall - Cross Loading	1596	1432	1.11	1325	1255	1.06			
Cylindrical - Rectangular Loading	1233	1315	0.94	1189	1064	1.12	1440	1435	1.00

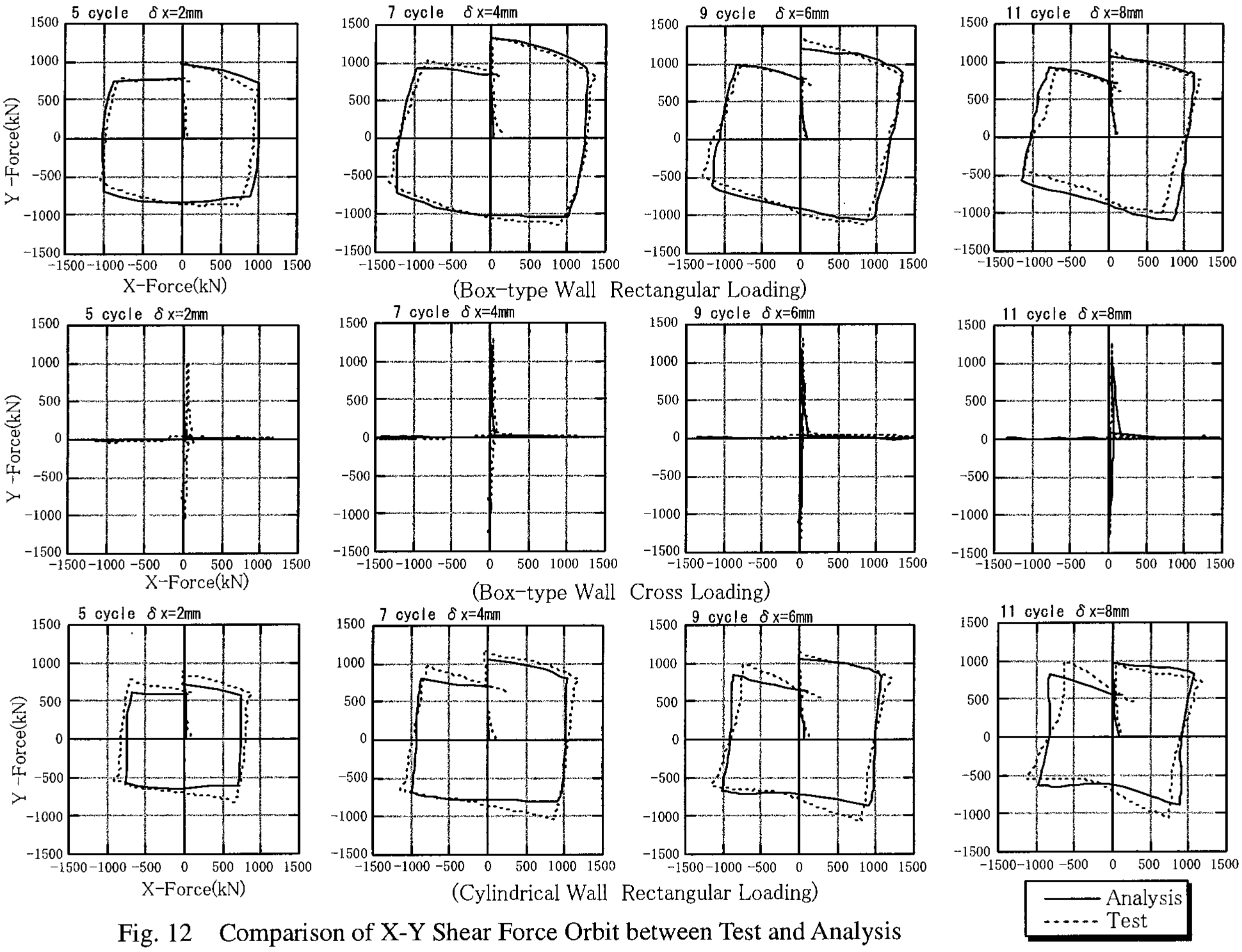


Fig. 12 Comparison of X-Y Shear Force Orbit between Test and Analysis

6.2 Comparison of Analytical Results to Test Data

(1) Comparison of maximum load

The maximum load of the analysis in each case agrees well with the test results, and the difference is less than 10%. By calculating the combined load, analytical results are good agreement with the test results.

(2) Shape of hysteresis loops

Rectangular Loading of box wall : In load - displacement relations, the maximum load of each displacement level is approximately equal to the test value, and hysteresis loop shapes in loading are well fitted with the test results. But the loop shapes in unloading is slender comparing with the tests.

Cross Loading of box wall : In load - displacement relations, maximum load of each displacement level is 10% smaller than that of test. Hysteresis loop shapes in loading and unloading show little difference to the test results.

Rectangular Loading of cylindrical wall : The maximum load of each displacement level is somewhat smaller than the test results. In the same manner as rectangular loading of box wall, the loop shapes in unloading is slender comparing with the tests.

(3) X-Y shear force orbit

In rectangular loading case of both box and cylindrical wall, there are little difference between test and analysis on the shape of X-Y shear force orbit when the displacement level is small. But when the displacement is 8mm, the clock-wise tilt of rectangular orbit in the analysis is smaller than that of the tests.

7 CONCLUSIONS

(1) Effects of differences in crack models on the analytical results on an elastoplastic behavior

Program I and Program II make it possible to simulate the elastplastic behavior of one-directional cyclic loading in spite of using different crack models. There are differences in the analytical results of two-directional loading. By Program II, the properties peculiar to two-directional loading in terms of the shear force - total displacement relationship or cracking patterns cannot be sufficiently simulated. This may be because, by the two-directional fixed crack model used in Program II, it is difficult to properly represent the cracks that are expected to generate on the wall surface subjected to two-directional loading.

(2) Comparison of Analytical Results (Program I) to Test Data

The analytical results on maximum load,loop shapes and X-Y shear force orbit in two-directional loading are well fitted with the test results. But in the rectangular loading, the loop shapes in unloading is slender comparing with the tests. Using Program I, maximum load and hysteresis loops of the seismic wall subjected to horizontal two-directional loading can be predicted with sufficient accuracy.

8 ACKNOWLEDGMENTS

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