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ULTIMATE STRENGTH OF RC SHEAR WALLS UNDER MULTI-AXES SEISMIC LOADS

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ABSTRACT

"The Model test on Multi-axes Loading on RC Shear Walls" had been carried out as for the 10years project aiming at comprehension of the earthquake response behavior of three dimensional (3-D) reinforced concrete (RC) shear walls under the 3-D of multi-axes earthquake loading condition. The motivation of the project building-up is that the current seismic design of nuclear power plant building is carried out by applying one dimensional (1-D) dynamic earthquake load to a building model in each direction independently whereas actual earthquake jolts the building in the three directions simultaneously. Therefore some experts have been pointing out that some testing is needed to confirm whether or not the current seismic design methodology is reliable for the input motions exceeding the design earthquake ground motion moreover for the input motions of the 3-D. The project had completed with various valuable outcomes that can reply to the concerns of the experts. Moreover the outcomes will play an important role in evaluating seismic margins of important structures in a nuclear power plant. In this paper, the author describes a review of the whole testing and summarizes the major outcomes extracted by the test project.

Keywords: Seismic shear wall, reinforced concrete, shaking table test, static loading test, and multi-axes loading test.

1. 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 grasp the seismic response characteristics of an NPP building for the 3-D earthquake excitation up to the ultimate state of the building to evaluate the seismic margin properly.

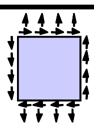
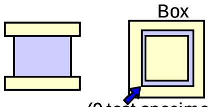
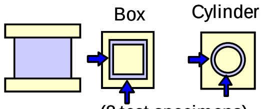
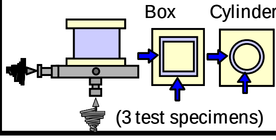
Japan Nuclear Energy Safety Organization (JNES) had therefore conducted a project entitled "Model Tests of Multi-axes Loading on RC Shear Walls" succeeding from Nuclear Power Engineering Corporation (NUPEC) to clarify the effects of multi-directional forces on the ultimate strength of reinforced concrete (RC) shear walls under multi-directional seismic loading conditions. The project had performed with a subsidy of the Ministry of Economy, Trade and Industry (METI) of Japan. In the test, we firstly accumulate the static and dynamic test data by performing the multi-directional loading test, and secondly we develop the evaluation methodology of restoring force characteristics of RC shear walls subjected to the multi-directional seismic (dynamic) loads.

In this paper, the author describes a review of the whole testing and summarizes the major outcomes extracted by the test project.

2. PROGRESS OF THE TEST PROJECT

Table 1 summarizes the progress of the whole test project being performed for ten years. Two kinds of static and dynamic loading tests were performed in the project. The static loading test was performed to study basic characteristics of RC shear wall behavior under the multi-axes loading condition by applying the static loads using oil-jacks. For this test category, we have performed the element test using RC plate specimens, the diagonal loading test using box-type RC shear wall specimens, the simultaneous horizontal and vertical loading test using box-type RC shear wall specimens, and the simultaneous cross directional loading test using box-type and cylindrical RC specimens. The dynamic loading test was performed to confirm whether or not the various characteristics of RC shear wall behavior found under the multi-axes static loading condition can also stand under the dynamic loading condition. The dynamic loading test was performed using a 3-D shaking table apparatus.

Table 1 Outline and the schedule of the tests

Execution items			FY(Japan)	94	95	96	97	98	99	00	01	02	03
Planning and Check & Review of The Test Results Comprehensive Evaluation of The Test Results				■	■	■	■	■	■	■	■	■	■
	Tests	Item to be studied	Outline of Test										
Static test	Element test	Shear transfer mechanism of cracked RC plate under multi-axis loads	 Plate (12 test specimens)		■	■	■						
Static test	Diagonal loading test	Restoring force characteristics of RC seismic shear wall under diagonal load	 Box (9 test specimens)		■	■	■						
Static test	Multi-directional simultaneous loading test	Restoring force characteristics of RC seismic shear wall under multi-axis loads	 Box Cylinder (8 test specimens)		■ (simultaneous horizontal and vertical loading)	■	■	■	■ (simultaneous horizontal two-axis loading)	■	■	■	
Dynamic test	Shaking table test	Verification of restoring force and FEM analytical model under multi-axis dynamic loads	 Box Cylinder (3 test specimens)							■	■	■	■

3. OUTLINE OF THE TEST PROJECT

In this section, outline of each test performed as an item of the whole test described in Table 1 is introduced with a photograph of the test situation.

3.1 Element Test

Figure 1 shows a snap shot of the element test under testing. A specimen had a 1.2m×1.2m in span and a 20cm in thickness. The specimen was designed by taking into account a typical seismic RC shear wall of a reactor building in a nuclear power plant, which has a dimension of a 6.0m×6.0m in span and a 1.0m in thickness. Twelve specimens taking into account the reinforcement ratios and axial forces as for the test parameters were tested.

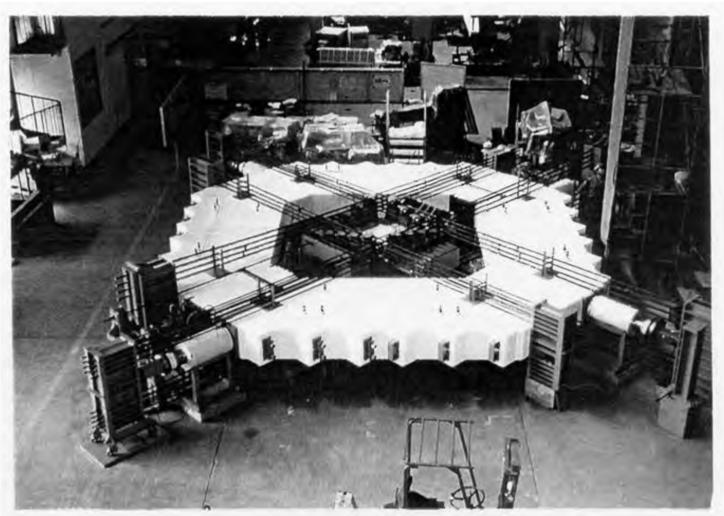


Fig. 1 A snap shot of the element test

3.2 Diagonal Loading Test

Figure 2 shows a snap shot of a diagonal loading test of a box-type RC shear walls consists of four faces of plate RC shear walls. Static loads are applied to box type specimen typically in each of three horizontal directions of 0.0, 26.6, and 45.0 degrees. Nine specimens were tested. The test parameters for the specimens are three kinds of shear span ratios of 1.0, 0.8 and 0.6. Typical specimen of shear span ratio of 0.8 has a dimension of a 1.5m in width 1.0m in height and 7.5cm in thickness. The RC specimen has the reinforcement ratio of 1.2% and has the concrete compression strength of 35MPa.

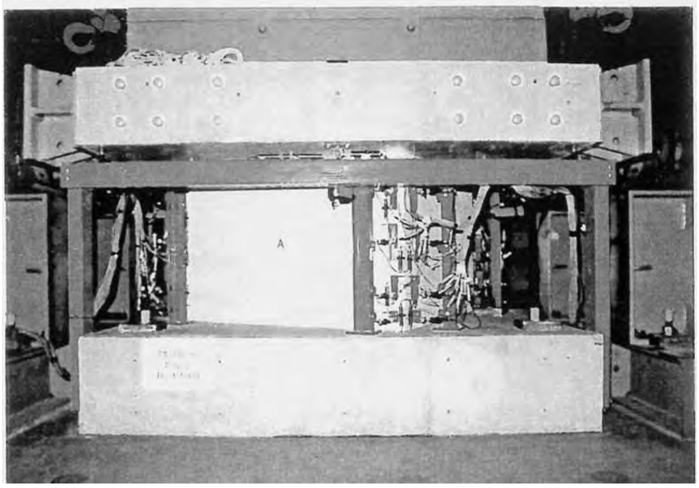


Fig. 2 A snap shot of the diagonal loading test

3.3 Simultaneous Horizontal and Vertical Loading Test

Figure 3 shows a snap shot of a multi-directional loading test of a box-type RC shear walls. In this test, static loads were applied both in a horizontal and in vertical directions simultaneously. The shear span ratios of the specimens are designed to be 0.8. The dimension, reinforcement ratio, and concrete compression strength of the specimen are the same with those specimens for the diagonal loading test that have the same shear span ratio of 0.8. The vertical loads are applied by two jacks attached at the top of the specimen and the horizontal loads are applied by jacks attached to the loading RC slab placed on the top of the shear wall part. In this test, two specimens were tested by taking loading speed of vertical load as for the test parameter.

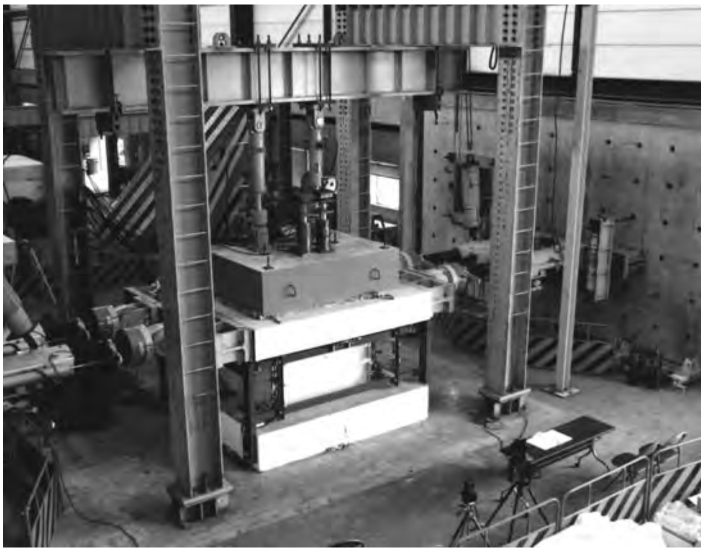


Fig. 3 A snap shot of the simultaneous Horizontal and Vertical loading test

3.4 Simultaneous Horizontal and Vertical Loading Test

Figure 4 shows a snap shot of a multi-directional loading test of a box-type RC shear walls. In this test, static load was applied in the horizontal two directions simultaneously. The shear span ratios of the specimens are designed to be 0.8. The dimension, reinforcement ratio, and concrete compression strength of the specimen are the same with those specimens for the diagonal loading test that have the same shear span ratio of 0.8. Six specimens (four are box type and two are cylinder type specimens) were tested by taking loading pattern as for test parameters. The figure shows a loading test at the final stage (to be collapsed) of a specimen that had been performed in the presence of many invited experts in this field in Japan.

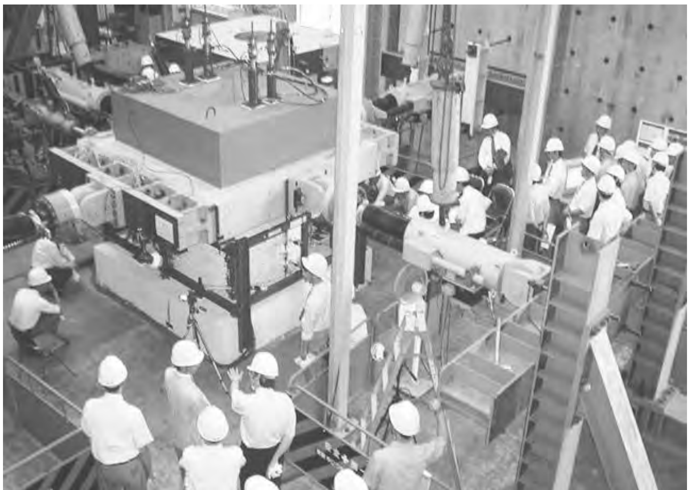


Fig. 4 A snap shot of the simultaneous Horizontal two directional loading test

3.5 Dynamic Loading Test

Figure 5 shows a snap shot of the dynamic loading test of a box-type RC shear wall at the test preparation condition. Figure 6 shows a snap shot at the loading testing. A three dimensional shaking table that has six degree of freedom in control was used. In this test, three specimen (two were box types and one was a cylinder type) were tested. This test was a highlight of the whole test project and had various important test data.

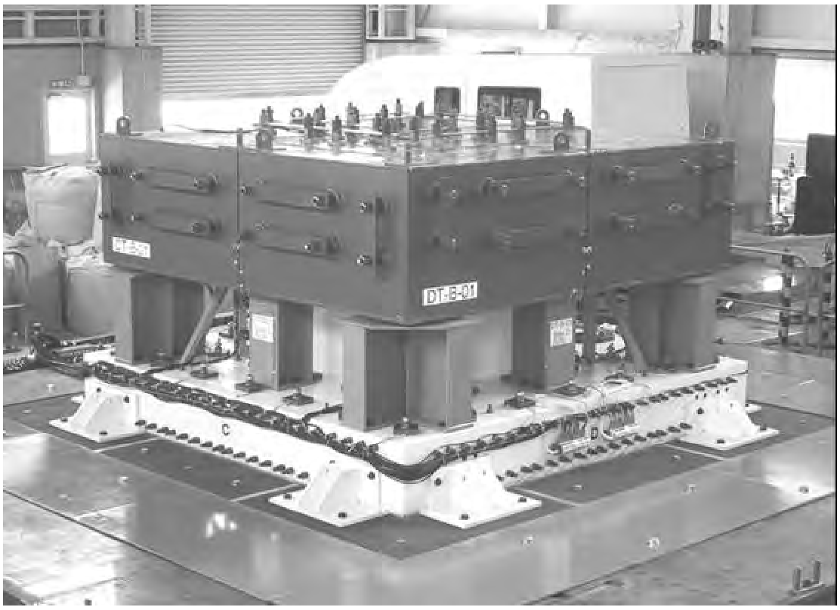


Fig. 5 A snap shot of the dynamic loading test

Fig. 6 A snap shot of the dynamic loading test

4. RESULT OF THE TEST PROJECT

The major results of this test project are summarized and shown in Table 2. We have classified and summarized the findings obtained by analyzing the test data with regard to (1) capacity and deformation characteristics, (2) skeleton curve, (3) dynamic behavior and (4) analytical methodologies as follows:

Table 2. The major results of this test project

<table>
<tr><td rowspan="4">Static Test</td><td>Element Test</td><td>A shear transfer constitutive model was developed and proposed as a function of both shear and axial stresses. [1]</td></tr>
<tr><td>Diagonal Loading Test</td><td>The maximum load and overall deformation at the maximum load are affected by loading angle. The data of all specimens being applied the load in the directions of 26.6° and/or 45° indicate that the maximum load and the overall deformation at the maximum load were larger than those of 0° whereas the maximum load itself was unchanged. [2]</td></tr>
<tr><td>Simultaneous Horizontal & Vertical Loading Test</td><td>The relationship between horizontal shear force and displacement under varying vertical load was changing but it can be evaluated by replacing the vertical load term of the equation recommended in the current technical standard of JEAG-4601 [3] with the corresponding vertical load value. [4]

The vertical response of an RC shear wall under simultaneous dynamic loading in the horizontal and vertical directions is, within the conditions that the varying range is less than ±1g (gravity force), mainly dependent on the horizontal response and not much on the excitation by vertical input motion. Thus the vertical input motion has only a slight effect on the hysteretic characteristics in the horizontal direction. [4]</td></tr>
<tr><td>Simultaneous Horizontal Two Directional Loading Test</td><td>The test results showed, irrespective of the loading patterns, that the relationship between shear force and total deformation angle under horizontal two-directional loading is analogous to that under one-directional loading. [5]

The envelope curve of the shear force - total deformation angle relationship is similar to that defined in JEAG-4601 for one-directional loading in the range of the deformation angle smaller than 1/2000. [5]

The non-linear FEM analysis with the computer program employing the four way multi-directional active crack models is a powerful tool for the analysis to simulate non-linear behavior of an RC shear wall under multi-axes simultaneous loading conditions. [6], [7]</td></tr>
<tr><td colspan="2">Dynamic Loading Test [8], [9]</td><td>The skeleton curve of shear force (Q) - shear deformation angle (γ) relationship derived from one directional static loading tests data is also effective for the dynamic loading condition, if horizontal response data are evaluated as vectors consist of the two directional components then plotted on the Q- γ plane.

It is also confirmed that the values of equivalent viscous damping derived in trial estimation are close to those derived in one-directional loading tests.</td></tr>
</table>

4.1 Capacity and Deformation Characteristics

(1) The stiffness in the vertical direction of an RC shear wall was decreased under the fluctuating vertical load in the range of ±1g. The decrement was mainly caused by plasticization of the RC shear wall by the horizontal load and the influence of the vertical load fluctuation to the stiffness in the horizontal direction is

small.

(2) The seismic loading capacities of the box-type and the cylinder type RC shear walls under horizontal two directional loading condition is distributed on the outer (safety) side of the circular capacity curve drawn with the calculated maximum capacities based on the current technical standard (JEAG-4601).

(3) The test results showed that the shear deformation angles of the RC shear wall specimen at the ultimate states exceeded 4/1000 both in the horizontal two directions.

(4) The restoring forth characteristics of an RC shear wall specimen in a direction in concern tends to decreases due to the damage in the shear walls perpendicular to the direction. However, when the damage is not severe as not to reach a concrete compression failure, the effects of the damage on the RC shear wall capacity in concern is negligibly small.

4.2 Skeleton Curve

(1) It is possible to express the influence of the fluctuation of vertical load on the skeleton curve and the restoring force characteristics in the horizontal direction. That is achieved by substituting a fluctuating vertical load into the vertical load term in the skeleton curve calculation formula recommended in the current technical standard for seismic design of NPP in Japan (JEAG-4601). However, the result of the analytical study, performed by applying both horizontal and vertical loads simultaneously to an analytical model of the specimen, indicates that the influence of the non-linear behavior of the specimen in the horizontal direction is negligibly small.

(2) If we take vector skeleton curve by taking into account the vector shear force and the vector deformation angle consists of horizontal two directional components, the skeleton curve become nearly the same with that recommended in the JEAG-4601 defined based on one directional loading test data.

4.3 Dynamic Behaviors

(1) All three specimens had been collapsed with circumference shear-slip failure at the wall leg part. In particular, the cylinder wall specimen had many shear cracks in the middle height part just before the collapse. The situation had been also observed in the specimen of the static loading test.

(2) All three specimen reached the deformation angle of 6/1000 before collapse. The deformation angle of the cylinder type specimen was almost the same with those of box type specimens far smaller than those observed in the static loading test for the cylinder type specimen. One reason can be pointed out for the smaller value that the specimen of the dynamic loading test have damages of through cracks with shear slip at the boundary between cylinder wall and it’s base slab as the result of repetitive loading.

(3) It is confirmed when we plot a vector shear force with the corresponding vector deformation angle on a shear force-deformation angle plane from the beginning of dynamic loading, the envelop curve becomes nearly the same with the Skeleton Curve recommended in the JEAG-4601 when the vertical load fluctuation is within ±1g. The tendency is the same with that observed in the static loading test results.

(4) Because of randomness of the motion applied, the shape of hysteretic loop of the restoring force became disorder and complex. However, we have obtained nearly the same hysteretic loop analytically by introducing an equivalent damping to the area of each step-by-step hysteretic loop to the analytical model.

5. ANALYTICAL METHODOLOGIES

(1) In the range of the shear deformation angle is equal to or less than 2×10^{-3}, the influence of the earthquake load in the direction perpendicular to the direction in concern is negligibly small. Therefore an analytical methodology using lumped mass model recommended in JEAG-4601, which applies the dynamic load in one direction, can be applied continuously. But, it should be noted that the method tends to give a large earthquake response because of smaller damping evaluation due to the smaller evaluation of energy absorption in the strong nonlinear range of the shear deformation angle exceeding the value of 2×10^{-3}. Furthermore in this range, seismic capacity of the specimen decreased explicitly due to an effect of simultaneous multi-axes loading. Therefore the analysis should be done by taking into account the multi-axes loading and peer review is needed to check whether or not the results according to the purposes are obtained.

(2) The non-linear response of an RC structure as well as its hysteretic curve for the restoring force to the multi-axes loading can be evaluated with satisfactory reliability if we apply FEM (finite element method) analysis technique together with four-way crack model. However, because it takes huge time to modeling the structure and to the analysis under current circumstances of both software and hardware, it is difficult to apply the technique immediately to an actual structure. However it is promising to apply the technique to the

actual structure in the near future because recent progresses of the computer technology in the software and the hardware are enormous.

6. CONCLUDING REMARKS

We had completed the 10-years project of "The Model test on Multi-axes Loading on RC Shear Walls". Through the test project we have had a series of various test data together with many findings relating to the behaviors of RC shear walls up to collapse under the multi-axes loading conditions. Based on these data and findings, we have confirmed the validity of the analytical methodology using FEM technology to evaluate the behavior of the RC structures up to collapse under the multi-axes loading condition. If the soil structure interaction phenomena for nuclear power plant structures could keep in linear response up to the collapse of the building, we could have established the analytical methodology to evaluate earthquake response behaviors of NPP RC structures by applying the 3-D earthquake ground motions simultaneously.

ACKNOWLEDGEMENTS

The most part of this work was performed by NUPEC as a part of the "Model Tests of Multi-axis Loading on RC Shear Walls" project under the commission of the Ministry of Economy, Trade and Industry (METI) of Japan. In the middle of the final year of the project, it was succeeded to JNES and performed the work of wrapping up the project as subsidy from METI. Technical issues had been discussed in the advisory committee on the project established within NUPEC (Chairperson: Professor Dr. T. Nishikawa). The author wishes to express his thanks to all the members of committee for their valuable suggestions and cooperation.

REFERENCES

[1]. Habasaki A., Kitada Y., Nishikawa T., Maekawa K., Umeki K., Yamada M., and Kamimura K.; "Shear Transfer mechanism of Pre-cracked RC Plates", Proc. of the 12 World Conference on Earthquake Engineering, Paper no. 1493, 2000.

[2]. Habasaki A., Kitada Y., Nishikawa T., Takiguchi K. and Torita H. "Multi-Directional Loading Test for RC Seismic Shear Walls.", Proc. of the 12 World Conference on Earthquake Engineering, Paper no. 454, 2000.

[3]. Japan Electric Association: "Technical Guidelines for Aseismic Design of Nuclear Power Plants.", JEAG-4601-1991 Supplement, 1991. (in Japanese)

[4]. Ono H., Maekawa K., Kitada Y., and Mitsugi S.: "The Influence of Vertical Input on the Horizontal Restoring Force Characteristics of Shear Wall", Proc. SMiRT-17, Paper # H03-4, 2003.

[5]. Kitada Y. Maekawa Koich et al.: "Restoring Force Characteristics of Shear Wall Subjected to Horizontal Two Directional Loading", Proc. of the 13 World Conference on Earthquake Engineering, Paper no.2423, 2004.

[6]. Ono H., Yoshimura M., Maekawa K., KITADA Y., and Oguro E.: "Pretest Analysis of Shear Walls Subjected to Horizontal Two-directional Loading", Proc. SMiRT-16, Paper # 1339, 2001.

[7]. Maekawa K., Pimanmas A., and Okamura H.: "NONLINEAR MECHANICS OF REINFORCED CONCRETE", Spon Press, 2003.

[8]. Kitada Y., Kusama K., Nishikawa T. et al.: "Shaking Table Test of RC Box-type Shear Wall in Multi-axes Loading", Proc. of the 13 World Conference on Earthquake Engineering, Paper no.1854, 2004.

[9]. Oguri S., Takiguchi K., Kitada Y. et al.: "Simulation Analysis of Shaking Table Test for RC Shear Wall in Multi-Axes Loading Tests", Proc. of the 13 World Conference on Earthquake Engineering, Paper no.2511, 2004.

