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The Influence of Vertical Input on the Horizontal Restoring Force Characteristics of Shear Wall

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ABSTRACT

This paper describes the test and the simulation analysis results of the simultaneous horizontal and vertical loading tests on RC box shear wall specimens, performed as a part of the project entitled “Model Tests of Multi-Axis Loading on RC Shear Walls” [1]. In the test, varying vertical load was applied to two box shear wall specimens during cyclic loading in a horizontal direction. Through this test, we confirmed that the variation of the axial load affected the horizontal restoring force characteristics.

The simulation analysis was carried out using a computer program of elasto-plastic FEM with concrete constitutive laws. The merit of this FEM program is in the installation of four way multi-directional active crack model [2] [3]. The purpose of the analysis was to confirm whether or not the program could estimate the effect of the axial load variation. The analytical results considerably well agreed with the test results.

In order to confirm whether or not the above effect can stand under the dynamic loading condition, we have carried out a dynamic inelastic analysis of box shear wall model using the computer program by applying vertical motion together with horizontal motion. With the purpose of evaluating the effect of vertical motion to the horizontal restoring force characteristics, the same dynamic inelastic analysis was also carried out without vertical motion.

KEY WORDS: shear wall, multi-axis loading, model test, vertical input, restoring force characteristics

INTRODUCTION

In the current seismic design of nuclear power plant (NPP) buildings in Japan, seismic design loads in horizontal two directions are obtained independently and the load in the vertical direction is evaluated statically, whereas actual seismic forces simultaneously jolt the buildings in the three directions. Therefore in order to evaluate the seismic margin properly, it is important to grasp the seismic response characteristics of an NPP building for three-dimensional earthquake excitation up to the ultimate state. Nuclear Power Engineering Corporation (NUPEC), Japan, has been conducting a project entitled “Model Tests of Multi-Axis Loading on RC Shear Walls” to clarify the elasto-plastic characteristics of the RC seismic shear wall, and to study a method of evaluating restoring force characteristics under multi-directional seismic loading conditions. The objective of this part of the study is to evaluate the influence of vertical input on the horizontal restoring force characteristics of shear wall by the model tests and the simulation analysis.

STATIC TEST LOADED SIMULTANEOUSLY IN THE HORIZONTAL AND VERTICAL DIRECTIONS

Description of the test

The static loading tests are conducted using two RC box specimens consisting of four face shear walls with stiff top and base slabs. The specimens have the same configurations and dimensions with those used in the horizontal loading test [1] performed as a part of the project, "Model Test of Multi-Axis Loading on RC Shear Walls." Figure 1 shows a drawing of the specimen. The wall has a thickness of 75mm and the approximate reinforcement ratio of 1.2%. Table 1 shows the property of the concrete and the rebar used.

These specimens are loaded horizontally with reverse cyclic pattern to the top slab while varying vertical load is applied. The vertical load is varied in the range of ±1g (gravity force) from the ordinal axial stress of 1.47 MPa to a typical shear wall in NPP buildings.

Figure 2 shows the loading setup for the test. Two jacks give varying vertical load to the specimen, while the other four jacks keep the constant vertical load of 1.47 MPa.

Figure 3 shows the process of the combination of horizontal and vertical loads. The specimen “SM01” is given three cycles of vertical loading during a cycle of horizontal

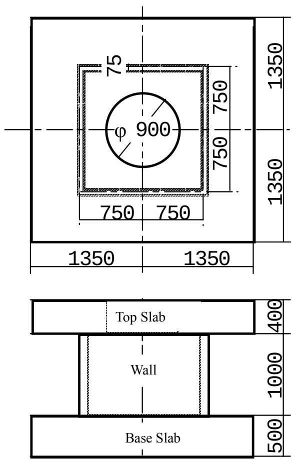


Fig. 1 Specimen

loading. On the other hand the specimen "SM02" is given eight cycles of vertical loading during a cycle of horizontal loading. The vertical load is not changed in the cycles where the total deformation angle is larger than 6×10^{-3}.

Table 1 Material Property

Concrete

Item	Unit	Specimen	
		SM01	SM02
Young's Modulus	GPa	28.5	28.4
Compressive Strength	MPa	36.0	35.9
Poisson's Ratio		0.20	0.20
Strain at Peak Strength	$\times10^{-6}$	1964	2027

Rebar

Item	Unit	D6(at wall)
Young's Modulus	GPa	176
Yield Strength	MPa	374
Tensile Strength	MPa	470
Strain at Peak Strength	%	28

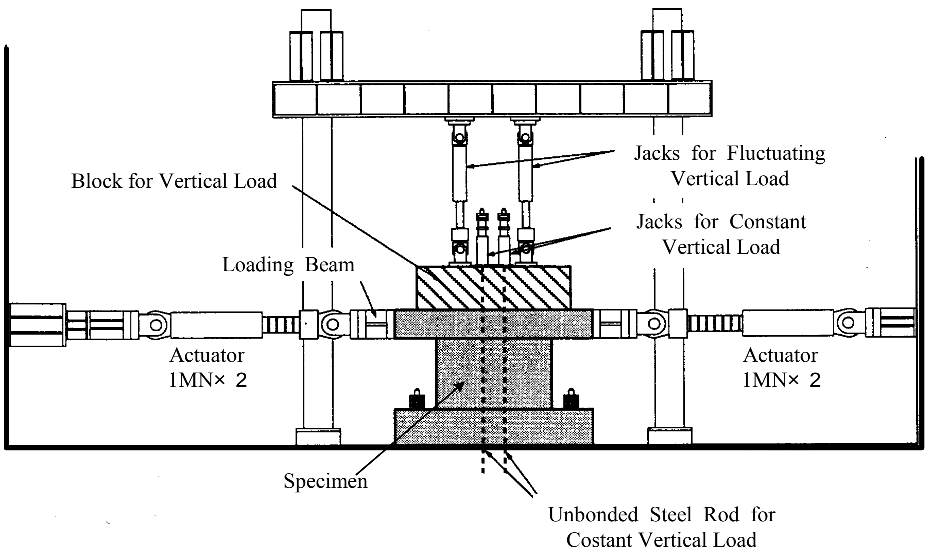


Fig. 2 Loading Setup

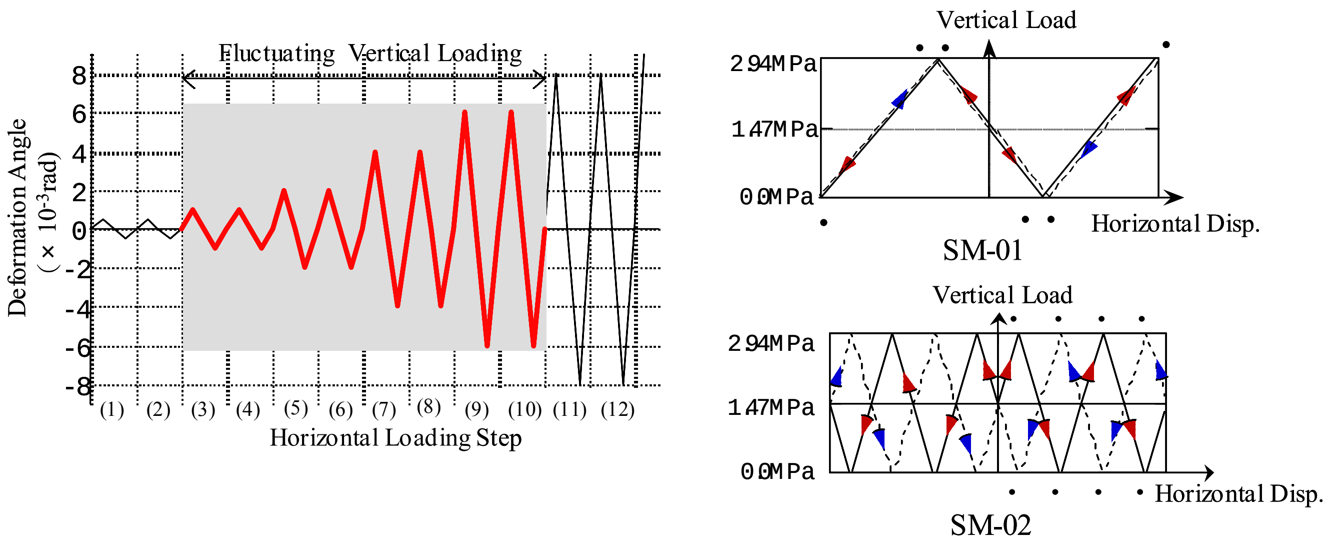


Fig. 3 Loading Patterns

Test Results

The relationships between shear force and total deformation angle of the specimens SM01 and SM02 are shown respectively in Fig. 4. In order to make the relationship clear, the cycle of the total deformation angle of 6×10^{-3} (the cycle of the maximum force) is extracted from Fig. 4 and shown in Fig. 5. In each case of SM01 and SM02, the shear force increases when the vertical force increases; it decreases when the vertical force decreases.

Figure 6 shows the test results plotted in the plane of shear force and the total deformation angle together with the skeleton curve calculated using the equation described in the Japanese technical guidelines for seismic design (JEAG) of NPPs [4]. The value of compression stress of 0 MPa, 1.47 MPa, or 2.94 MPa is substituted in the equation for each of varying vertical loads of –1g, 0g, and +1g respectively. The relationship of the shear force and total deformation angle of the test results is almost equal to the calculated result with the JEAG equation where the vertical load is kept constant at any of the three values. Thus it is confirmed that the relationship between horizontal shear force and displacement under varying axial force is estimated by substituting a constant axial force, equal to the varying force at the moment, to the JEAG equation.

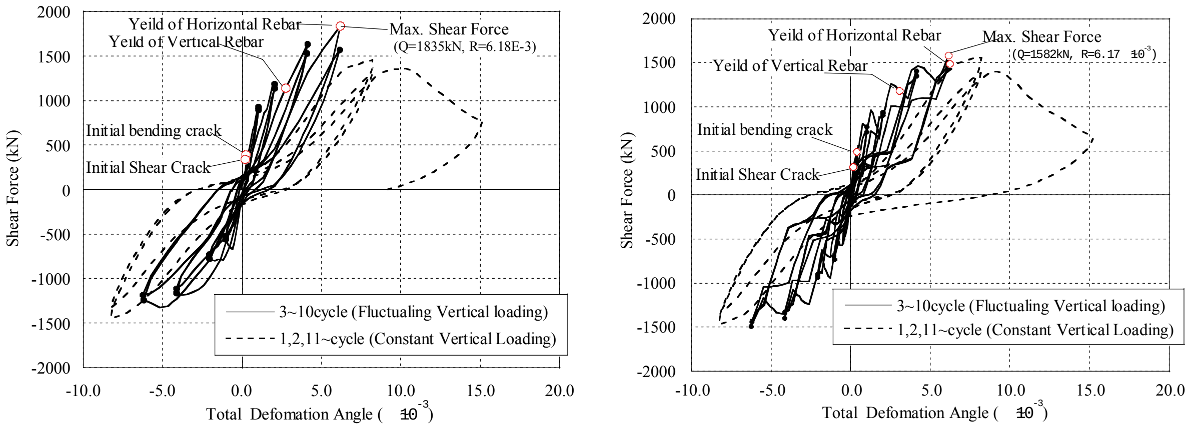


Fig. 4 Test Results (Relationship between Shear Force and Total Deformation Angle)

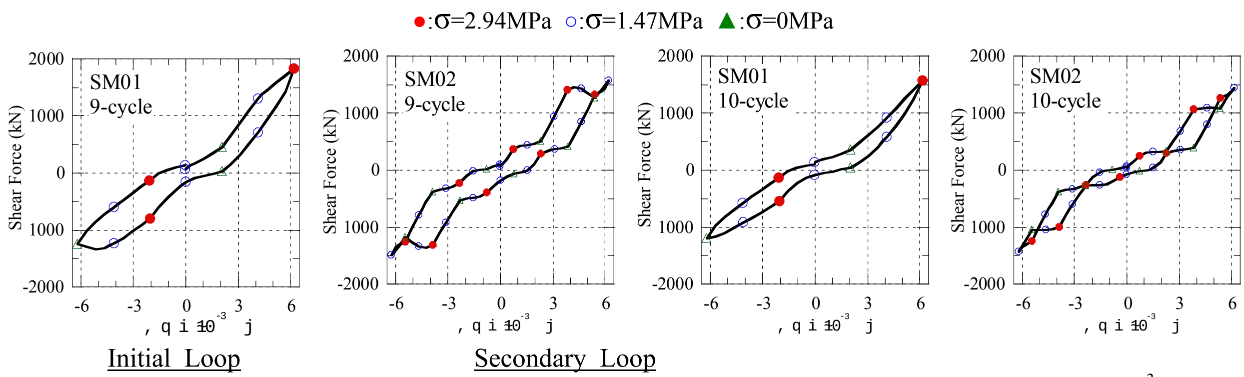


Fig. 5 Test Results (Shear Force - Total Deformation Angle, total deformation angle range of 6×10^{-3})

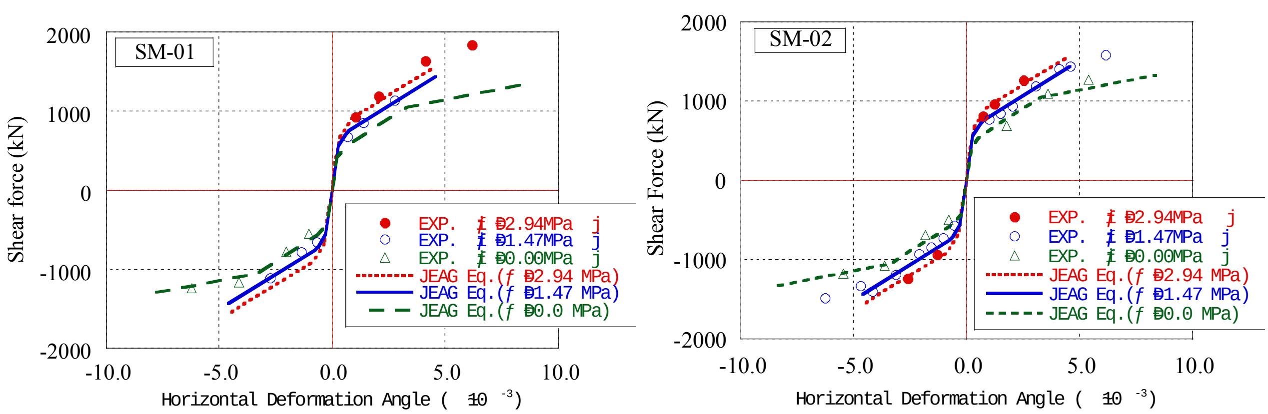


Fig. 6 Comparison of Test Results and JEAG skeleton curves calculated with constant axial force

ANALYTICAL STUDY ON THE HORIZONTAL AND VERTICAL SIMULTANEOUS LOADING TEST

The simulation analysis was carried out for the static simultaneous horizontal and vertical loading test result together with the horizontal two directional loading test results [5], using the FEM computer program with the concrete constitutive laws employing the four way multi-directional active crack model developed by Fukuura and Maekawa [2] [3]. A three dimensional FEM model used in the simulation analysis is shown in Fig. 7. The wall and the top slab are modeled with layered shell elements, and a half of the specimen is modeled because of its symmetrical characteristics. Deformation for the horizontal loading is given to the center of the top slab, which is colored in gray in Fig. 7, and vertical load is distributed uniformly on the top slab.

Figure 8 shows the relationship between shear force and deformation angle, where the test results (solid line) and analytical result (doted line) are both plotted. The analytical results agree well with the test results. The results show that the program can accurately simulate non-linear characteristics of shear wall when varying horizontal and vertical loads are applied simultaneously.

The relationship between the vertical displacement at the top center of the specimen and the total deformation angle in horizontal direction is shown in Fig. 9, where test and analytical results are compared with each other. Both in the test and analysis, as the deformation angle in horizontal direction increases, vertical deformation increases. When it experiences loading history where the horizontal total deformation angle is larger than 5×10^{-3}, vertical residual deformation (vertical deformation at total deformation angle of zero) increases drastically.

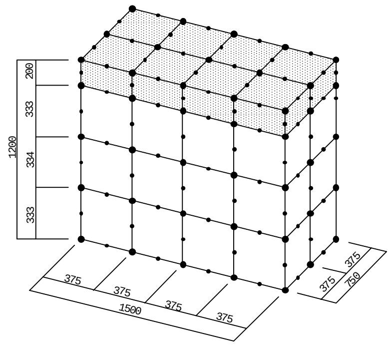
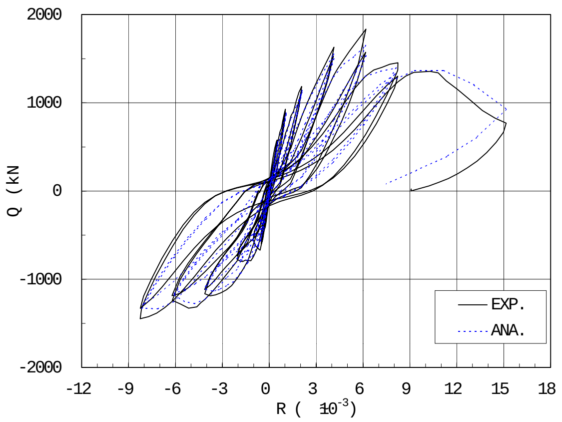
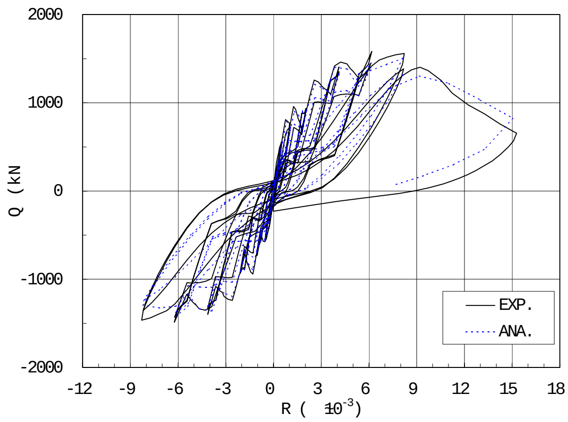


Fig.7 Analytical Model

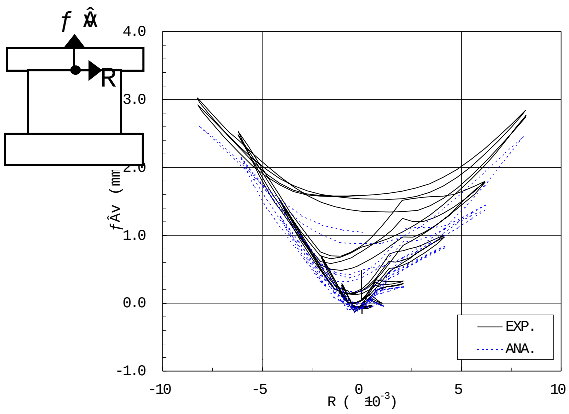


SM01

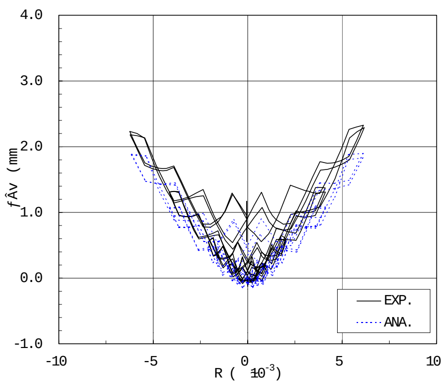


SM02

Fig. 8 Comparison between Test and Analytical Results (Shear force – Total Deformation Angle Relation)



SM01



SM02

Fig. 9 Comparison between Test and Analytical Results (Vertical Displacement vs. Total deformation angle)

ANALYTICAL STUDY ON THE EFFECTS OF VERTICAL MOTION ON DYNAMIC NON-LINEAR RESPONSE BEHAVIOR IN THE HORIZONTAL DIRECTION

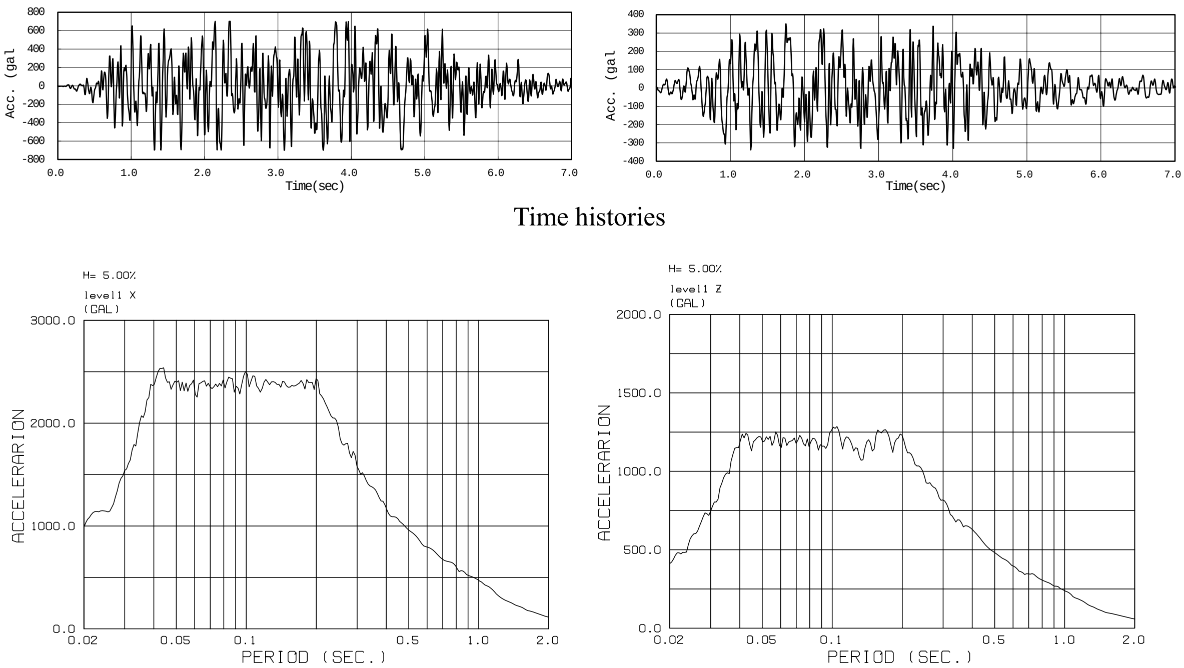
In the previous section, it is demonstrated that the FEM analysis program with the concrete constitutive equations employing the four way multi-directional active crack model can simulate properly the results of the horizontal and vertical simultaneous loading test. Therefore we have tried to use the program to study the effect of vertical input motion on restoring force characteristics in the horizontal direction by performing the dynamic analysis of box-type shear wall specimens model. For this analysis we have applied simultaneous horizontal and vertical input motions.

Input motions

A couple of the artificial earthquake motions used for "Shaking Table Test" in the project of "Multi-axis Loading Tests on RC Shear Walls" is used for the input motions, which are generated according to the following conditions:

- Horizontal and vertical motions are generated by fitting the same target response spectrum.
- The maximum amplitude of the vertical motion is half as large as that of the horizontal motion,
- Independent uniform random number sets are used for phase angles of each wave of both horizontal and vertical input motions.
- The maximum accelerations of horizontal and vertical motions are not generated at the same time.
- The duration of the motions are seven seconds.

Figure 10 shows spectra and acceleration time histories of the generated motions.



Time histories

Response Spectra

Horizontal input

Vertical input

Fig. 10 The spectra and time histories of the input motions (level 1)

Models and cases of analysis

The analysis model is an RC box shear wall, which has the same configuration, material properties, and rebar ratio with the specimen described in section 2, the specimen of the horizontal and vertical simultaneous loading test. The model size is, however, four times as large as the specimen to put the natural period on the peak period region of the spectrum of the input motion. The weight of the top slab is set to make the vertical stress of the wall 1.47 MPa, which is same with that of the static test in the section 2. Total of four cases of analyses are carried out, consisted of the combinations of two levels of input motion and the presence of vertical motions as shown in Table 2.

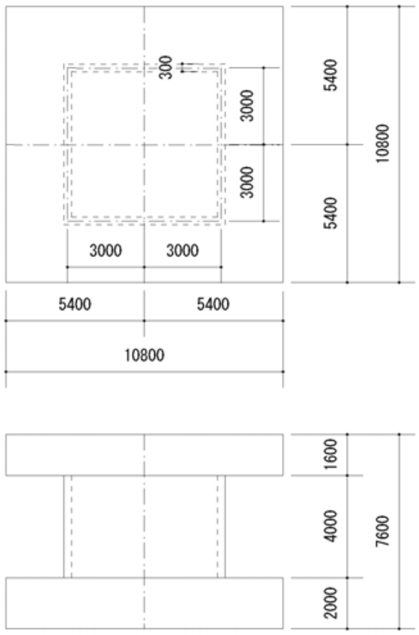
The magnitude of the input motion of level 2 is determined so as to reach the maximum load carrying capacity of the shear wall, and that of level 1 is determined so as to reach the half of the deformation of the level 2.

Dimensions of the RC shear wall used for the analyses are shown in Fig. 11, and a drawing of the analytical model is shown in Fig. 12.

Table 2 Analysis parameters

Cases		Horizontal input	Vertical input
level 1	With vertical input	700gal	350gal
	Without vertical input	700gal	N/A
level 2	With vertical input	1100gal	550gal
	Without vertical input	1100ga	N/A

Analytical results



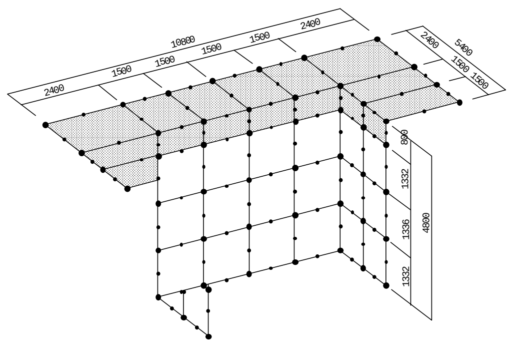


Fig. 11 Shear wall for the analysis

Fig. 12 Analysis model

(1) Eigenvalue analysis

Table 3 shows the primary natural period of the RC box shear wall model. It is empirically expected that the stiffness at the maximum shear force decreases to about one fifth and the natural period increases to 2.2 times. Thus, according to the response spectrum of the input motion and the natural period of the specimen under the maximum shear force, the response of the specimen is expected to remain in the plateau of the response spectrum.

Table 3 Eigen frequency (natural period) of the primary mode

Horizontal	Vertical
12.8 Hz (0.078 sec)	28.3 Hz (0.035 sec)

(2) Response analysis results

Figure 13 shows time histories of input motion and acceleration response at the center of the top of the wall for the level 2 cases with the vertical input motion. As can be seen in the figure, the amplification ratio of the vertical response to the vertical input motion is larger than that of the horizontal response to the horizontal input motion.

Figure 14 shows the comparison of acceleration time histories at the top of the specimen for the cases with and without vertical input motion. The horizontal response with the vertical input motion does not have conspicuous difference from that without the vertical input motion. Therefore we cannot say that the vertical response with the vertical input motion is larger than that without the vertical input motion, although the vertical input motion makes the response slightly different from the response without vertical motion.

Figure 15 shows Fourier spectra of acceleration response of each case. The Fourier spectra are calculated to study why the amplification ratio of the vertical response to the input motion is large and furthermore why the large amplification occurs without vertical input motion. In Fig. 15, it is found that the vertical response has peaks at double and fourfold frequency points of the horizontal peaks regardless of the presence of vertical input motion. It is therefore inferred that the horizontal response generates the peaks in the vertical response.

As can be seen in Fig. 9, where horizontal and vertical displacements during the horizontal and vertical simultaneous loading are shown, larger horizontal displacement develops larger upward displacement whose frequency is even-number-fold of horizontal one. Thus the vertical response peaks are generated irrelevant to eigen frequencies in the vertical direction when non-linearity in horizontal direction is considerably strong. That is to say, vertical motion develops much more with the horizontal response, independently of the presence of vertical input motion, than with vertical input.

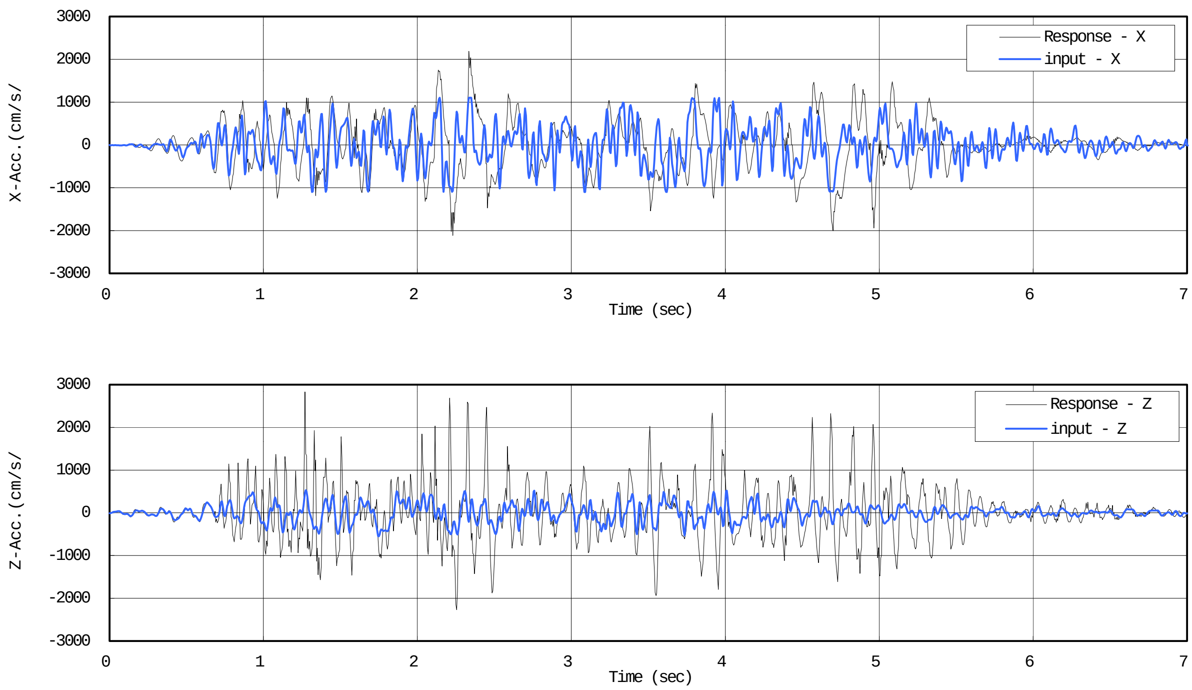


Fig. 13 Time histories of input motion and response acceleration (level 2 with vertical input motion)

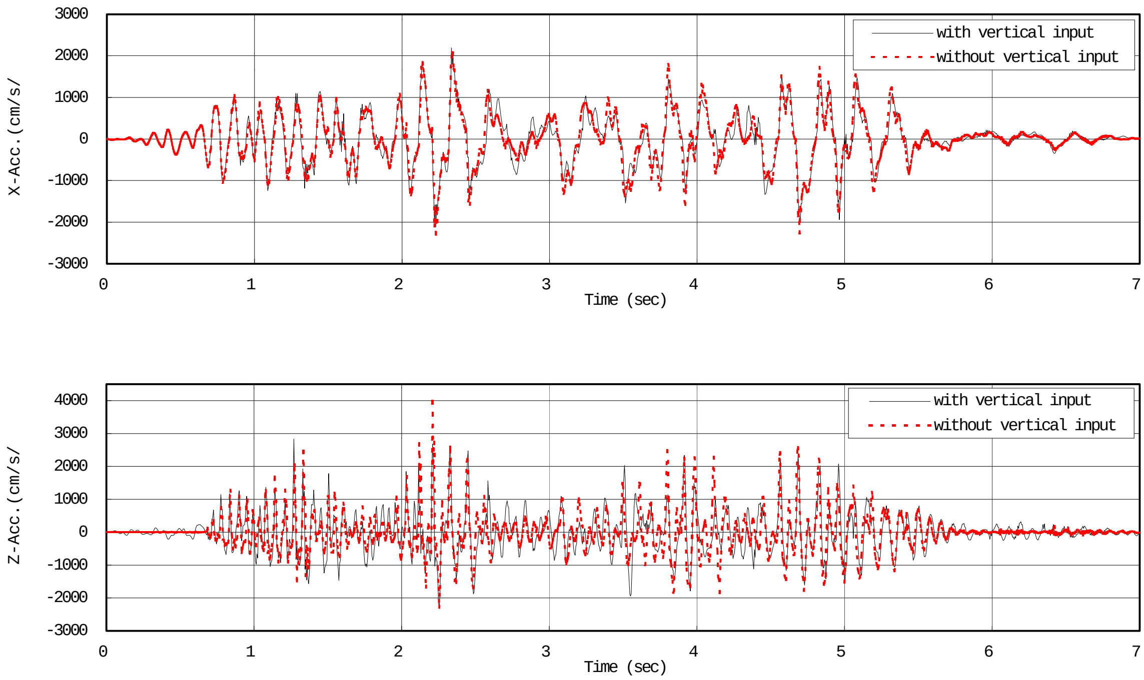
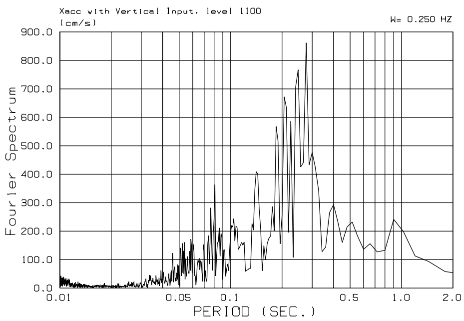
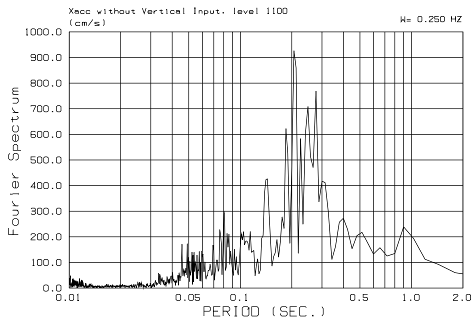


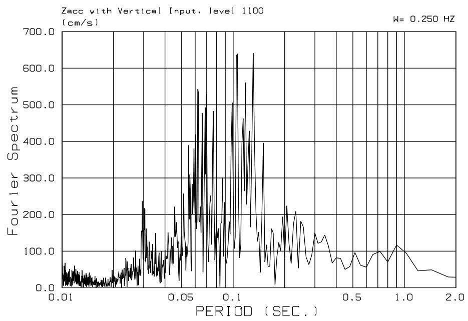
Fig. 14 Comparison of response time histories between the cases of with and without vertical input motion

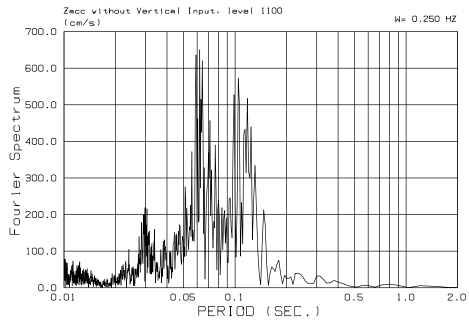




with vertical input motion without vertical input motion

horizontal direction





with vertical input motion without vertical input motion

vertical direction

Fig. 15 Fourier Spectrum of Acceleration Response at the center on the top of the wall

CONCLUSIONS

(1) The relationship of horizontal shear force and displacement under varying axial force is similar to that with constant axial force with which the varying axial force is replaced, and the influence of damage caused by varying axial force is relatively small in case the varying range is less than ±1g (gravity force).

(2) The non-linear FEM analysis with the computer program employing the four way multi-directional active crack model can simulate non-linear behavior of an RC shear wall when varying forces are applied simultaneously in the horizontal and vertical directions.

(3) The vertical response of an RC shear wall under simultaneous dynamic loading in the horizontal and vertical directions is, within the conditions of the study, mainly dependent on the horizontal response and not much on the excitation by vertical input motion. Thus vertical input motion has only slight effect on the hysteresis characteristics in the horizontal direction.

ACKNOWLEDGMENTS

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