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Shaking Table Test of a RC Box Shear Wall under Uni-directional Input Motion

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ABSTRACT

Shaking table tests of RC box shear walls subjected to uni- or multi-directional input motions have been conducted in this research series. This paper describes the result of an uni-directional horizontal input shaking table test carried out as the first step of this research series. The employed specimens referred to the models of previous static loading tests by Nuclear Power Engineering Corporation of Japan. The main objective of this study is to grasp dynamic behaviour of RC shear walls.

From the result of the shaking table test, inelastic behaviour of a RC box shear wall under uni-directional horizontal input was grasped. The final failure mode was shear slip failure at the wall bottom after flexural yielding. The obtained envelope curve was compared with a result of a past static loading test.

Generally, in case of shaking table tests with the conventional control technique, there is a problem that the fidelity of input waves gets worse when structural characteristic of the specimen changes during shaking. This study employed a newly developed real-time compensation system to improve control accuracy during such nonlinear shaking. The test result verified that the shaking table was controlled with sufficient fidelity by this system.

KEY WORDS: shaking table test, RC, box, shear wall, dynamic behavior, fidelity, compensation.

INTRODUCTION

Reinforced concrete (RC) shear walls are main structural elements of nuclear reactor buildings. The fundamental characteristics of RC shear walls have been investigated by analytical studies and static loading tests. However, dynamic behavior subjected to multi-directional input motion is not well known, therefore investigation by shaking table tests and accumulation of test data are needed.

In this research series, shaking table tests of RC box shear walls subjected to uni- or multi-directional input motions have been conducted. The test parameters are input direction of earthquake motion, and with-or-without openings. A total of three specimens were prepared. As for two specimens, input direction of earthquake motions was the parameter to examine the influence of the multi-directional input. As for the third specimen, the wall openings were employed to induce the torsional vibration. Examination of the torsional behavior was also the purpose of this research series. This study used a tri-axial shaking table, and employed a real-time compensation system in order to improve the control accuracy of shaking table. This paper describes the result of the uni-directional horizontal input shaking table test, conducted as the first step of this research series.

TEST CONDITIONS

Test Specimen

The outline and general view of the specimen are shown in Fig.1 and Fig.2. The Specimen, which has a box shaped wall, refers to the models of previous static loading tests carried out by Nuclear Power Engineering Corporation (NUPEC) of Japan [1]. The specimen is reduced in size to 80% of the original one in consideration of the capacity of the employed shaking table. The shear wall thickness of the specimen is 60mm, and the span width of the shear wall is 1200mm. The clear span height of the wall is 760mm, and the height between the base slab upper surface and the top slab center-of-gravity is 960mm. So the shear span ratio M/QD of the specimen is 0.8, where the influence of the moment by rotation inertia of the top slab is ignored.

Table 1 shows the material properties of wall part of the specimen. The reinforcing bars of D6 (6mm in diameter) are employed for the vertical and horizontal bars of the walls, arranged with double-fold in 85mm pitch. The wall-reinforcement ratio of the specimen is approximately 1.25%. Concrete with coarse aggregate maximum size of 9mm is used for the wall part of the specimen.

The additional steel mass (241kN in weight) is installed in the upper and lower sides of the top slab. Thereby, the total weight of the specimen is 390kN. When the specimen is modelled as a single lumped mass system, the top weight is 333kN. The axial stress of the wall is 1.14N/mm^2.

In addition, various wet tiling finishes were constructed to the area of about 3/4 of the surface of the box wall. The examination about the earthquake resistance of tiling methods of construction was also carried out [2].

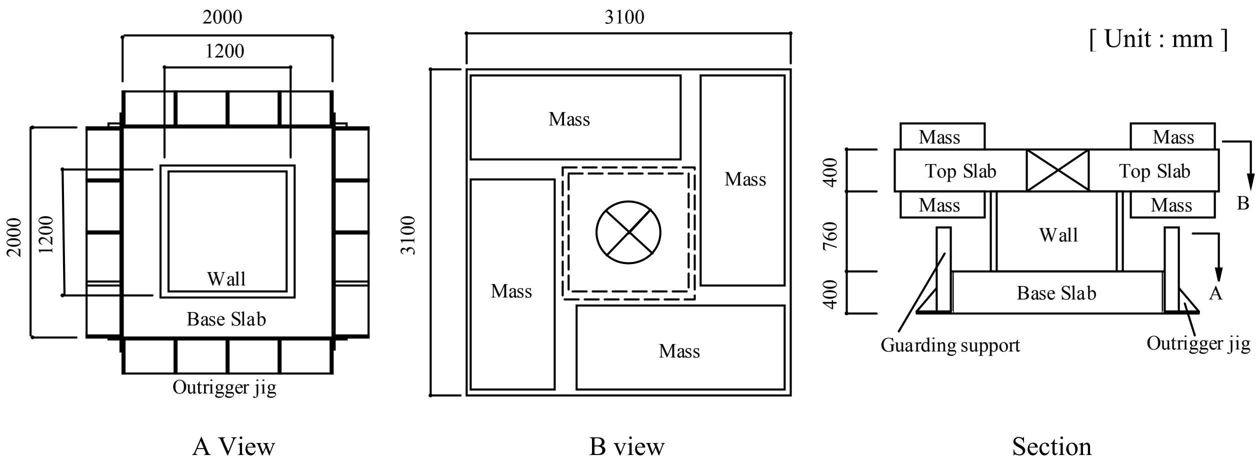

Fig.1 Outline of specimen

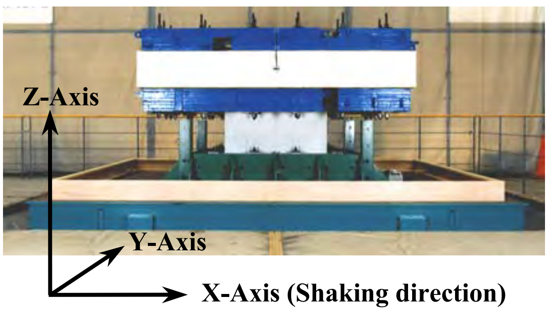

Fig.2 General view of specimen

Table 1 Material properties of wall

Material	Property	Value
Concrete (Test day)	Compressive strength	33.8 N/mm^2
	Peak strain	2828x10^{-6}
	Young's modulus	2.41x10^4 N/mm^2
	Poisson's ratio	0.180
	Tensile strength	2.26 N/mm^2
Rebar (D6)	Yeild strength	369 N/mm^2
	Young's modulus	1.98x10^5 N/mm^2

Shaking Table

The outline of the shaking table used in this study is shown in Fig.3, and the capacity of the shaking table is shown in Table 2.

Generally, in shaking table tests, the motion of the table is generated by not only drive force from actuators but also reaction force from the specimen. The reaction force acts as a disturbance to the shaking table control. As a result, the fidelity of shaking waves gets worse. Therefore, it is necessary to carry out a certain compensation.

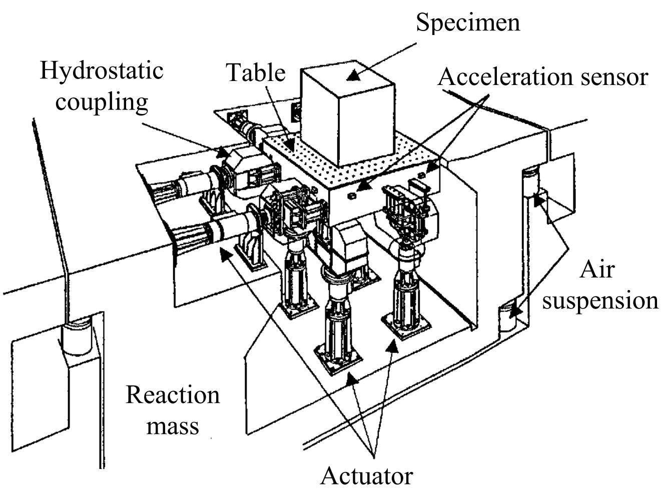

Fig.3 Tri-axial shaking table

Table 2 Capacity of shaking table

Maximum payload	490 kN		
Table size	5m x 5m		
Axis	X	Y	Z
Maximum displacement	60cm	30cm	20cm
Maximum velocity	200cm/s	130 cm/s	100 cm/s
Maximum acceleration	3G	2G	1G
Frequency	DC - 50Hz		

Input Compensation

Input compensation [3] is one of the techniques used widely now in order to improve the control accuracy of shaking tables. The block diagram of input compensation in the control system of this shaking table is shown in Fig.4.

In the case of input compensation, the transfer function of a over-all system of the shaking table and the specimen is obtained in advance. Next, using the inverse of the transfer function, the command signal is adjusted by the tuning shaking. Finally, the influence of the specimen is reduced, and the characteristics of the shaking table are improved.

This technique is satisfactory when the specimen is linear, that is, vibration characteristics do not change during shaking, even if the shaking level changes from the level of the tuning shaking. However, when the damage on the specimen proceeds and the vibration characteristic of specimen changes, the control accuracy gets worse.

Adaptive Filter

Like this test, where the natural frequency of the specimen is comparatively high (elastic natural frequency of this specimen is about 30Hz), feed forward type compensation is effective. Then, in this test, in order to improve the control accuracy of the shaking table, a newly developed real-time control system with “adaptive filter [4]” was used together with the conventional input compensation technique.

The adaptive filter is the system with a variable filter installed in the input part of the shaking table control system. The filtering characteristic of the variable filter is changed so that the influence of specimens at every moment can be removed.

As shown in Fig.5, the adaptive filter consists of two modules, the variable filter module mentioned before, and an identification module. In the identification module, the measured wave of the shaking table is compared with the target wave (reference signal), and the influence of the specimen is grasped. This identification is carried out over about 0.1 seconds in consideration of the stability of the control system. When the characteristic of the specimen changes and the measured wave of the shaking table differs from the target wave for a while, the filter reacts to fit the measured wave to the target wave. The frequency range of application of the adaptive filter of this shaking table is 10-35Hz, aiming at high frequency specimens.

The preliminary test using steel frame specimens with bi-linear restoring force characteristic had been conducted in advance. This preliminary test result shows that the compensation effects improved when the adaptive filter and input compensation are used together, compared to the case where only input compensation is used.

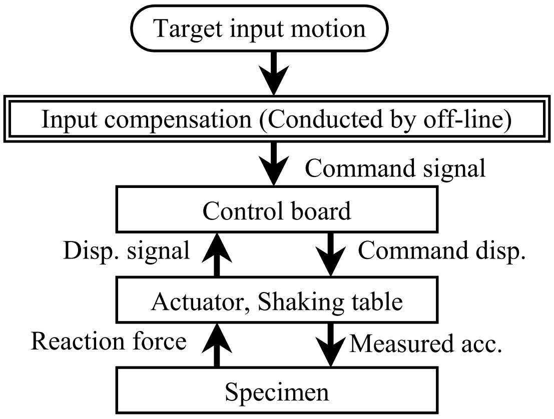

Fig.4 Block diagram of input compensation

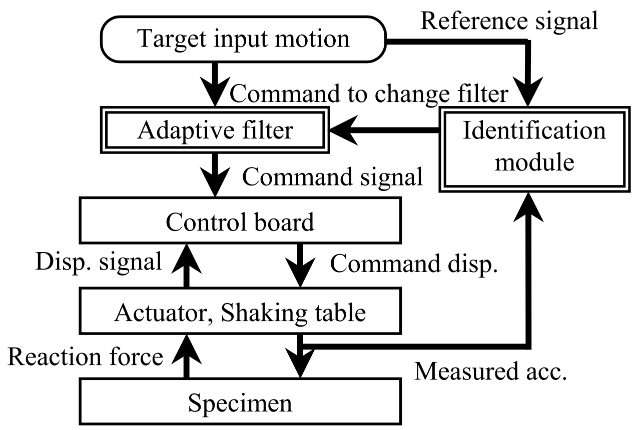

Fig.5 Block diagram of adaptive filter

Input Motion

The acceleration time history of the standard input earthquake motion used in this test is shown in Fig.6, and acceleration response spectrum is shown in Fig.7. A total of 11 runs were conducted to collapse the specimen. The input magnifications of the standard input earthquake motion were gradually increased for every Run. The simulated seismic wave was created so that the acceleration response spectrum might suit the target spectrum. The target spectrum has constant acceleration response spectrum within about 15- 33Hz, and in a low frequency domain velocity response spectrum is constant. The phase characteristic was given with the random number, and the time history envelope function was the Jennings type.

It was expected that the equivalent period of the specimen would become longer gradually when the specimen was damaged. Therefore, the time axis of input waves was suitably extended 1.0 - 2.44 times, so that the input waves might have large power to the specimen in each Run.

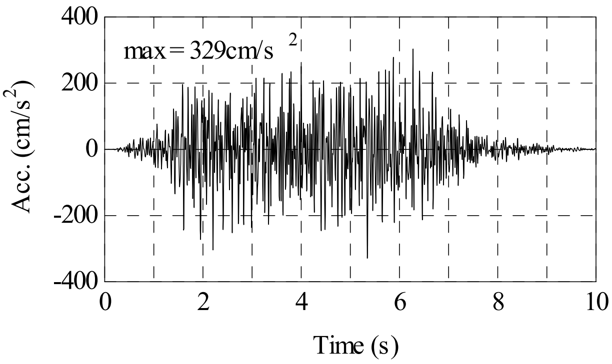

Fig.6 Acceleration time history of standard input motion

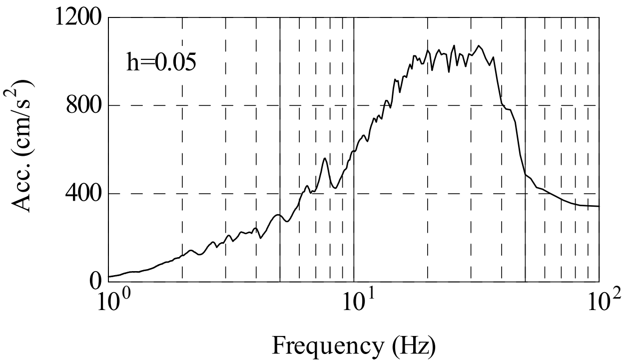

Fig.7 Acceleration response spectrum of standard input motion

Test RESULTS

Maximum Response

The maximum response values of test results are shown in Table 3. The inertia force was calculated by multiplying the top mass by acceleration response at the center-of-gravity of the top slab. The shear stress was calculated by dividing the inertia force by the section area of the web walls. The displacement response was total relative deformation between the upper surface of the base slab and the lower surface of the top slab (measurement height 760mm). The deformation angle was calculated by dividing the displacement response by the measurement height.

After each Run, the crack patterns were observed. In Run8 shear cracks were found. On the other hand, maximum value of horizontal rebar strain was greatly increased in Run3. It is guessed that shear cracks were actually generated in Run3. Since the area of tiling finisher portion is large and cracks were closed after shaking, finding of shear cracks was delayed.

Table 3 Maximum response

Run	Time ratio*)	Acc. at shaking table (cm/s^2)	Maximum response				Strain of rebar (D6)		Notes
			Inertia force (kN)	Shear stress (N/mm^2)	Disp. (mm)	Deformation angle ($x10^{-3}$ rad)	Vertical ($x10^{-6}$)	Horizontal ($x10^{-6}$)	
1	1	153	64	0.44	0.09	0.12	64	5	
2	1	335	149	1.03	0.13	0.17	166	17	
3	1.11	1035	374	2.60	0.40	0.53	1001	416	Bending crack
4	1.47	1109	465	3.23	0.97	1.28	1191	576	
5	1.47	1629	640	4.44	1.55	2.04	1593	1294	
6	1.9	1807	691	4.80	2.43	3.20	2200	1495	Yielding of vertical rebar
7	2.1	1792	685	4.76	2.38	3.13	2094	1527	
8	2.1	1821	769	5.34	2.99	3.93	2450	1680	Shear crack
9	2.2	2210	924	6.42	3.86	5.08	2680	1848	
10	2.44	2720	1032	7.17	4.61	6.07	2740	2230	
11	2.44	3050	1011	7.02	>15.0	>19.7	4920	2440	Shear slip failure

* Time ratio : Multiplication factor of time axis

Response Behavior

From the test result, the time history of displacement response is shown in Fig.8, and the inertia force - displacement relationship (P-D loops) is shown in Fig.9. Run3 (bending crack was found) showed slight expansion of the P-D loops, and Run4 showed slip shape a little. In Run6, tensile yielding of vertical rebar was measured at the flange wall. Thus, the slip shape of the P-D loops became remarkable with proceeding of damages on the specimen. Run11 (shear slip failure at wall bottom occurred) showed the P-D loops with softening after the maximum strength.