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Model test and inelastic analysis on dynamic response of RC shear walls

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ABSTRACT : Two identical I-shaped reinforced concrete shear wall models were tested dynamically using a large high-performance shaking table in order to determine the dynamic performance of shear walls both in an elastic range and in a plastic range up to failure. An analysis using a lumped mass-spring model was carried out and compared with the test results. The analysis simulated the test result.

1 INTRODUCTION

In the seismic design of nuclear reactor buildings, inelastic response analyses are made to assess the seismic safety of the buildings. As reinforced concrete(RC) shear walls work as major earthquake resisting members in reactor buildings, the properties of shear walls dominate the seismic response of the buildings. Therefore, it is essentially important both to clarify the seismic behavior of shear walls and to evaluate appropriately the dynamic properties of shear walls. In order to determine the dynamic response behavior of shear walls both in an elastic range and in a plastic range up to failure and to examine the appropriateness of inelastic dynamic response analysis methods of shear walls, a shaking table test on models of a shear wall was carried out. Analytical results were compared with the test results.

2 SHAKING TABLE TEST OF SHEAR WALL

2.1 *Test specimens*

Two specimens (U-1 and U-2), with an identical design specification, were prepared and tested by using the same artificial input motion at similar input levels in order to ascertain the reproducibility of the test. Fig.1 shows the scale and geometry of a specimen. The specimen had a I-shaped section wall with a web wall of 75mm thickness, 3000mm length and flange walls of 100mm thickness, 2980mm length. The clear height of the wall was 2020mm. The shear span ratio was 0.8.

The wall reinforcement ratio, ps was 1.2% and D6 (deformed bar with a nominal diameter of 6.35mm) bars with spacing 70mm were used in double layers for the vertical and horizontal reinforcement of the web and flange walls. The tensile yield strength of the D6 bars was 3910kgf/cm². Normal concrete with coarse aggregate having a nominal maximum grain size of 10mm was used for the web and flange walls. The compressive strengths of the wall concrete were 292kgf/cm² (U-1) and 300kgf/cm² (U-2), respectively.

Additional lead weights were attached at upper and lower surface of the top slab, respectively. The total additional weight was 92.9 tonf and.the total weight including top slab was 122.0tonf.

2.2 *Test procedures*

NUPEC's large-scale, high-performance shaking table at the Tadotsu Engineering Laboratory was used for the test. Photo.1 shows the specimen set on the shaking table. The specimens were subjected to excitations in the X-direction. Five test runs ,which were sequentially performed as RUN-1 to RUN-5, were set corresponding to the following series of five target response levels, (1) small-amplitude level in elastic range (RUN-1), (2) strain level at shear crack initiation, shear deformation angle of about 0.24/1000rad.(RUN-2), (3) strain level at 3 times the RUN-2, shear deformation angle of about 0.72/1000rad.(RUN-3), (4) shear deformation angle of about 2/1000rad. (RUN-4), and (5) vicinity of ultimate strength, shear deformation angle of about 4/1000 rad.(RUN-5), as shown in Fig.2.

2.3 *Test results*

Two specimens were tested under the same input wave at similar input levels.

Maximum Response Values : Table 1 shows the maximum values for the horizontal input acceleration at the base slab, response acceleration and displacement of the top slab, horizontal rebar strain of the web and of vertical rebar strain of the flange walls at each test run. Fig.3 shows the relationships between the maximum inertial force and the maximum horizontal displacement at each test run. It can be seen from this figure that the test results of the U-1 and U-2 specimens were almost similar and the good reproducibility of the test was obtained.

Failure Mode : The final cracking pattern of the specimen U-1 is shown in Fig.4. Initial shear cracking at mid portion of the web wall was observed after RUN-2' and horizontal cracking of the flange walls after RUN-4. At RUN-5, shear sliding failure occurred at the bottom of the web wall, and the concrete fell out. The U-2 specimen also indicated similar crack patterns and failure mode.

Time Histories : The time histories of response acceleration of the specimen U-1 are shown in Fig.7.

Load-displacement Relationships : Load (inertial force)-displacement relationships are shown in Fig.5. The specimen reached the maximum strength during RUN-5 and significant strength loss occurred due to shear sliding failure of the web wall.

Dynamic Characteristics of Specimens : The natural frequency f_o and the equivalent damping ratio h_{eq} were determined from the transfer function calculated from the horizontal accelerations of the base slab and that of the top slab, which were monitored during small amplitude vibration test performed immediately before each test run. Table 2 shows that as the response level and the degree of damage in specimen increased, the natural frequency f_o decreased from about 13Hz (monitored before RUN-1) to 7-8Hz (monitored before RUN-5). The equivalent damping ratio h_{eq} increased from slightly more than 1% to approximately 4%.

3 INELASTIC DYNAMIC ANALYSIS

3.1 *Analytical method*

A lumped mass-spring model with 2 degrees of freedom, considering horizontal and rotational displacements of a mass, was used. The springs consist of shear and flexural components. For restoring-force characteristics for shear component of the spring in an analytical model, peak-oriented model as shown in Fig.6 was adopted. The figures of each point on the skeleton curve of the restoring-force characteristics were determined based on empirical formulae. The first point corresponding to shear cracking and the second one were determined by using formulae proposed by Dr. Tanaka et.al.[1987] and the third point corresponding to the maximum shear strength were determined by Dr.Suzuki's formulae[1988].Flexural stiffness were assumed as elastic throughout the analysis because no flexural crack could be expected from a beam-theory analysis.

Viscous damping proportional to initial stiffness was assumed.Viscous damping proportional to tangent stiffness was also adopted for the analyses of RUN-4 and RUN-5. The damping ratio was estimated from the test results shown in Table 2. The damping ratio of 1% for RUN-1 and RUN-2, 2% for RUN-2' and RUN-3, 3% for RUN-4, and 5% for RUN-5 were assumed, respectively.

3.2 *Analytical results and comparison with test results*

Maximum Response : The Maximum response values obtained from the analysis are shown in Table 3 together with the test results. When compared with the test results, the analytical results for RUN1～RUN2' agreed well with the test results. The analysis simulated well the test results of RUN-3 although the analysis somewhat overestimated the response displacement. It could be because the shear cracking strength of restoring-force characteristics in the analytical-model was somewhat underestimated.For RUN-4, the analytical results also simulated the test results when viscous damping proportional to tangent stiffness with a damping ratio of 3% was adopted, although the response displacement was overestimated.When viscous damping proportional to initial stiffness with a damping ratio of 3% was assumed, the analysis simulated the response displacement, but underestimated the response acceleration. For RUN-5, the analysis did not simulate the test results because of numerical unconvergence.

Time-History : The analytical results on time histories of response acceleration are shown in Fig.7, together with the test results. The analysis shows good simulation for RUN-2～RUN-4. The analyses did not simulate well RUN-1 because the analytical stiffness somewhat overestimated the stiffness evaluated from the test results.

Transfer Function : The analytical results are also compares with the test results in terms of transfer functions. As shown in Fig.8. The analytical results agreed well with the test results for RUN-1～4.

4 CONCLUSIONS

Two identical I-shaped reinforced concrete shear wall models were shaken in a range from elastic up to failure in order to determine the dynamic performance of shear walls, and inelastic dynamic response analysis was carried out by using a lumped mass-spring model. Based on the test and analytical results, the following conclusions are drawn.

1) The two specimens exhibited almost similar dynamic performance and showed shear sliding failure mode. A good reproducibility of the test was achieved.

2) The natural frequency of the specimens decreased from about 13Hz to 7～8Hz. The equivalent damping ratio increased from slightly greater than 1% to approximately 4%.

3) The analysis using lumped mass-spring model simulated the test results in a elastic range and in a range of deformation angle up to about 0.2% (RUN-1～RUN-4). The empirical formulae used for the estimation of the restoring-force characteristics of spring in the analytical model were appropriate enough to simulate the test results.

4) To simulate the test results, the damping ratio was changed from 1% for elastic range to 5% for ultimate stage, based on the test results. The damping ratio should be estimated appropriately with consideration of restoring-force characteristics used in analyses.

5) The analytical results did not simulate the failure of the test models(RUN-5). Further improvement for the analytical method are needed.

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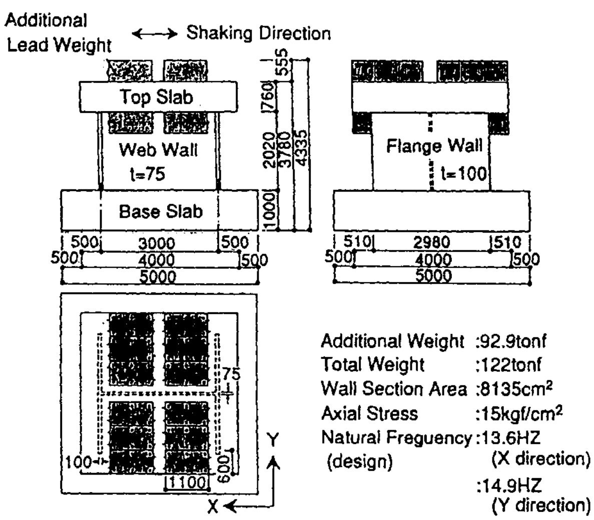

Fig.1 Outline of Specimen

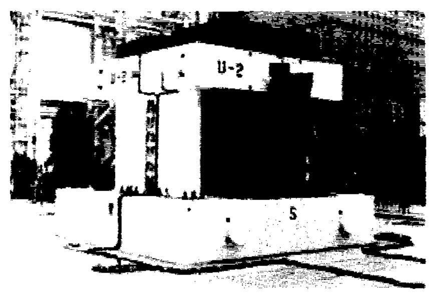

Photo.1 Specimen on Shaking Table

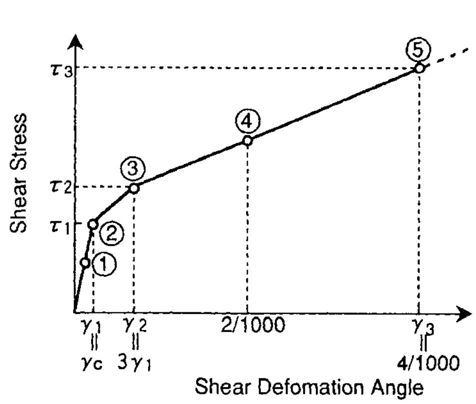

Fig.2 Target Response Level

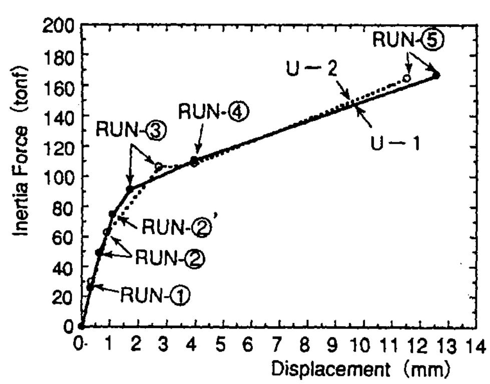

Fig.3 Inertia Force - Displacement Relationships (Max. Response)

Table 1 Test Results

Specimen	Run No.	Input Horizontal acceleration of the base slab at upper surface (cm/s²)	Top slab horizontal response acceleration & inertial force		Top slab horizontal response displacement & deformation angle		Horizontal rebar strain of web wall (10^{-6})	Vertical rebar strain of flange wall (10^{-6})	
			cm/s²	tonf	mm	1/1000 rad.		Left flange	Right flange
U-1	RUN-1	58	208	25.8	0.30	0.15	-10	45	-38
	RUN-2	122	399	49.5	0.61	0.30	-22	-93	-72
	RUN-2'	317	602	74.6	1.09	0.54	448	-159	-124
	RUN-3	361	738	91.5	1.71	0.85	686	-205	139
	RUN-4	583	895	111.	3.93	1.94	942	1075	891
	RUN-5	1256	1347	167.	>20.0 (12.5)*1	>10.0 (6.19)*1	>5000	2615	2822
U-2	RUN-1	75	241	29.9	0.35	0.17	-11	-46	-44
	RUN-2	237	507	62.9	0.89	0.44	1059	-114	-99
	RUN-3	371	858	106.	2.68	1.33	1301	661	-262
	RUN-4	450	875	109.	3.92	1.94	1150	783	707
	RUN-5	1030	1330	165.	14.7 (11.5)*1	7.23 (5.69)*1	1865	2013	1996

*1: Maximum response displacement & deformation angle at maximum horizontal response acceleration

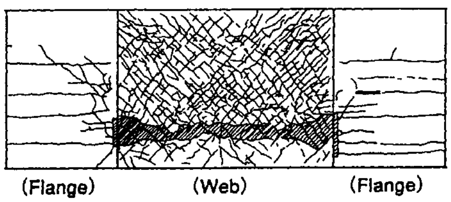

Fig.4 Final Appearance after Test

Table 2 Change of Frequency and Equivalent Damping Ratio

	U−1		U−2	
	f o (Hz)	heq (%)	f o (Hz)	heq (%)
Before RUN-①	13.2	1.1	13.1	1.2
Before RUN-③	11.3	2.5	11.3	2.6
Before RUN-④	9.9	3.0	8.3	4.2
Before RUN-⑤	7.7	4.0	7.1	4.2

Table 3 Comparison of the Test and Analysis (U-1)

	Test (max.value)			Analysis (max.value)	
	Input Acc. (gal)	Response Acc. (gal)	Response Disp. (mm)	Response Acc. (gal)	Response Disp. (mm)
RUN-1	58	208	0.30	187	0.25
RUN-2	122	399	0.61	463	0.77
RUN-2'	317	602	1.09	506	1.06
RUN-3	361	738	1.71	736	2.93
RUN-4	583	895	3.93	784 [884	3.32 4.74]*1
RUN-5	1256	1347	>20.5	1235 [1400	6.75 >9.58]*1

*1 Damping proportional to tangent stiffness was adopted.

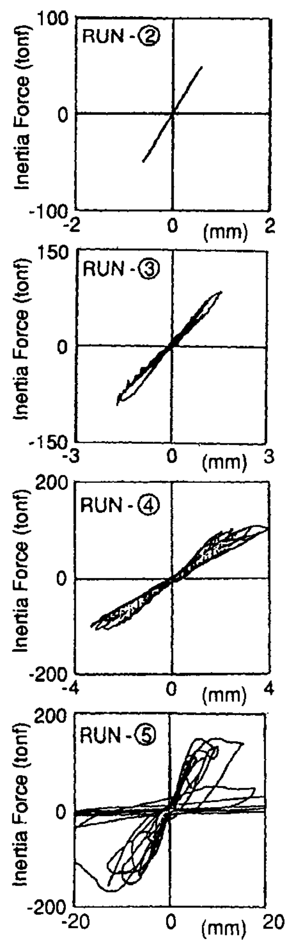

Fig.5 Inertia Force-Wall Displacement Relationships (U-1)

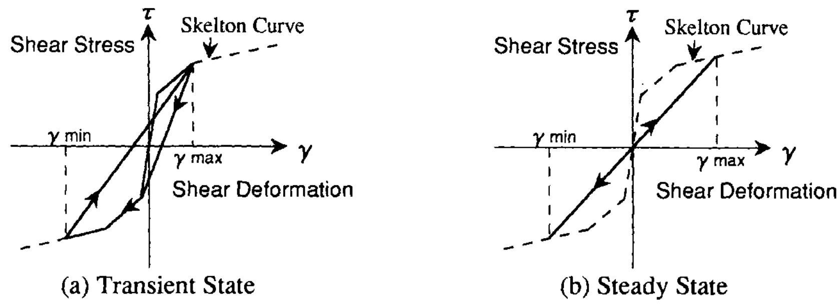

Fig.6 Analytical Model of Shear Restoring Force Characteristics

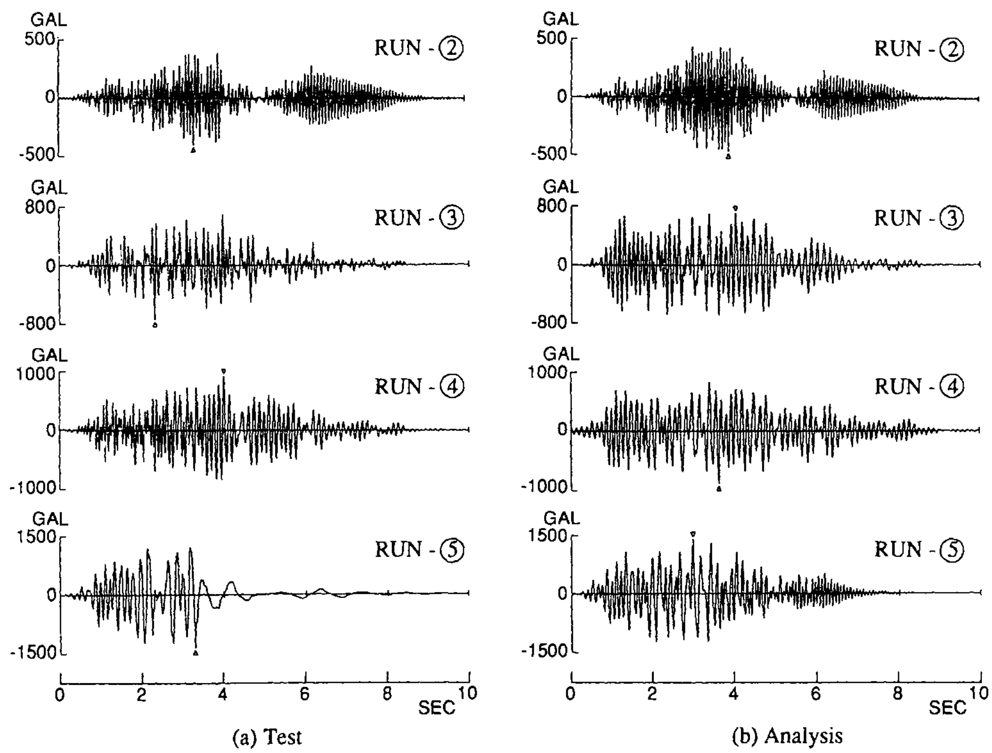

Fig.7 Comparison of Analysis and Test on Response Acceleration (U-1)

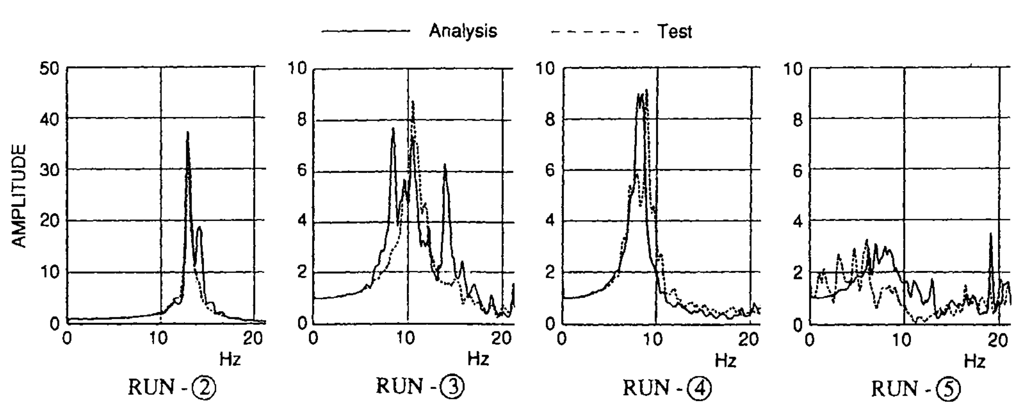

Fig.8 Comparison of Analysis and Test Result on Transfer Function (U-1)