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Experimental studies on the collapse of RC columns during strong earthquake motions

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ABSTRACT: The RC column damage pattern differences between static cyclic loading tests and dynamic shaking table tests were observed. In this study, the spacing of shear inforcement bars in columns were variable. Four types of spacings of shear inforcement bar are used. As results of the tests, it was verified that the dynamic maximum horizontal strengths and the dynamic deformation capacities were almost agreed with the static ones. However, the damage patterns were changed with the shear inforcement bar spacings, and also with testing method differences between statics and dynamics.

1 INTRODUCTION

Many studies concerning about the ultimate horizontal strengths of columns were already conducted. However, most of these studies were carried out by the static cyclic loadings of one column, or psuedo-dynamic loadings. In this investigation, realistic dynamic loadings which would simulate earthquake responses of structures, were done by the use of a shaking table, and the dynamic damage characteristics of columns were observed. A small test structure of one story and one bay had four columns. These columns were made by RC. Four kind of spacings of shear inforcement bars were used. In addition to the shaking table test, static cyclic loading test had been done on behalf of the comparisons. The time variations of damage patterns, the ultimate strength and the story deformations were observed.

2 TEST METHODS

One story×one bay test structure was assembled on the shaking table. Four columns had the section of 13cm×13cm, and the height of85cm. The diameters of four main steel bars were 16mm. The columns were fixed in steel roof girder and steel base frames with bolts. The roof of test structure was made by steel frame. On the roof, three concrete mass weightwere fixed. Total weight of roof was 27.8ton. The spans of this test structure were 2m in loading direction, and 2m in perpendicular direction. In order to mitigate the shock loads of falling roofs in the shaking table during damage excitations, the roof support frame was installed inside of the test structure. Therefore, the roof of 27.8ton fell about 15cm in damage excitation. The four types of columns with the shear inforcement bar spacings of

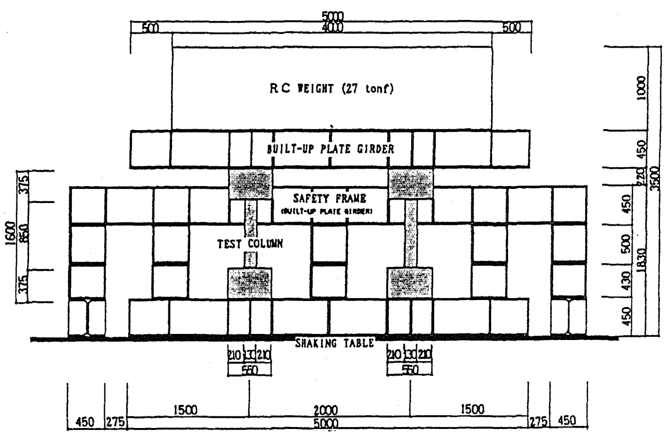

Figure 1. General view of the test structure

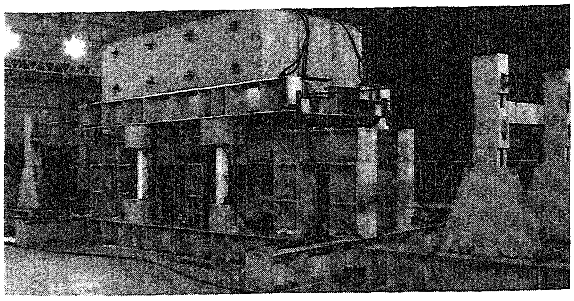

Figure 2. Set up of static loading test

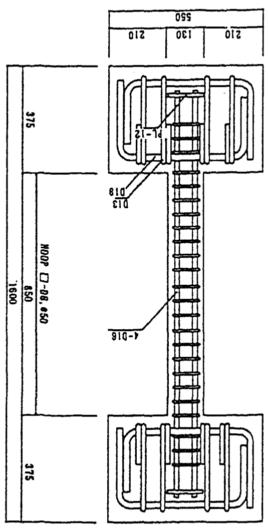

Figure 3. Dimension of specimen of CT4

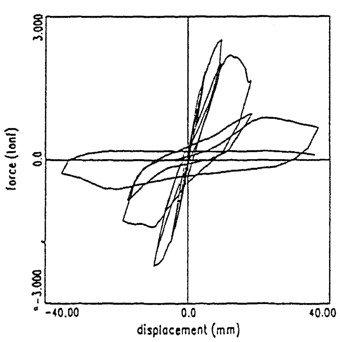

Figure 4. hysteresis loop of CT1
by static loading test

50mm, 110mm, 170mm, and 285mm were tested in the shaking table. The outline of the test structure are shown in Figure 1, 2. The details of columns are shown in Figure 3, and the material and physical properties of columns are listed in Table 1, 2, 3. In a static cyclic

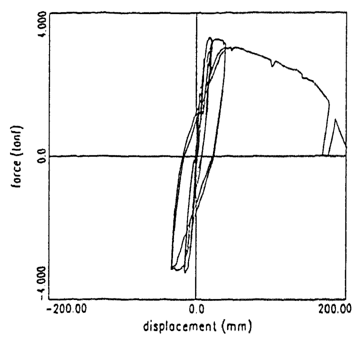

Figure 5. hysteresis loop of CT4
by static loading test

loading test, the pull type oil jacks which were connected in the roof frame, were used. Two jacks were set in right side, the others were set in leftside. Cyclic loading level were 1/1000, 1/200, 1/100, 1/50, 1/20 in story deformation angles. After cyclic test, loads increased gradually until column collapses.

The one dimensional shaking table of National Research Institute for Earth Science Disaster Prevention was used in this test. The dimension of shaking table is 12m by 12m. The table weight is 180ton. The maximum power is 360tons. The maximum velocity and displacement are 75cm/s and 24cm. The test structure was excited horizontally with 1968 Tokachi-oki Hachinohe E-W which was modified by FFT high pass filter of 0.4Hz. The time scale was 1. The acceleration of these tests were 0.5G and the velocity were 70cm/s approximately. Collapse responses of test columns were observed by video records, and measured by various sensors.

3 STATIC TEST RESULTS

Two kinds of columns were tested. In the static cyclic loading test of column CT1, the shear cracks appeared in the region between about 1.0D(13cm) and 3.0D from two column ends at the cyclic loading of deformation angle 1/100. At the cyclic loading of 1/50, the shear cracks increased diagonally, and, the main

TABLE 1. Table of specimen.

SPECIMEN TYPE	DIMENSION (cm)	HEIGHT (cm)	COVER THICKNESS (cm)	LONGITUDINAL STEEL	TIE	SPACING OF TIE (cm)	VOLUMETRIC RATIO OF T	AXIAL COMPRESSIVE STRESS OF SECTION (kgf/cm2)
CT1	13x13	85	1.7	4-D16	D6	28.5	0.0017	41.1
CT2	13x13	85	1.7	4-D16	D6	17.0	0.0029	41.1
CT3	13x13	85	1.7	4-D16	D6	11.0	0.0045	41.1
CT4	13x13	85	1.7	4-D16	D6	5.0	0.0098	41.1

TABLE 2. Material properties of steel bar.

	As (cm2)	σy (kgf/cm2)	σmax (kgf/cm2)
D16	1.92	3622	5360

TABLE 3. Material properties of concrete.

		compressive strength (kgf/cm2)	elastic modulus (kgf/cm2)
STATIC	CT1	232	2.01x10E5
	CT2	280	2.03x10E5
DYNAMIC	CT1	270	2.05x10E5
	CT2	258	2.15x10E5
	CT3	289	2.08x10E5
	CT4	299	2.08x10E5

TABLE 4. Results of tests.

	STATIC LOADING TEST		SHAKING TABLE TEST			
SPECIMEN TYPE	CT1	CT4	CT1	CT2	CT3	CT4
tQmax(tonf)	2.52	3.32	2.47	3.50	4.00	4.21
cQsu(tonf)	3.02	4.25	3.19	3.35	3.72	4.34
cQmy(tonf)	2.90	2.93	2.92	2.91	2.93	2.94
cQbou(tonf)	3.02	3.30	3.24	3.16	3.35	3.40
tQxmax(tonf)	0.69	1.07	0.7	1.3	1.4	1.2
tXmax(mm)	37	185	46	55	108	166
tXy(mm)	9.6	16.4	-	-	-	-
cXmy(mm)	9.1	9.3	13.3	12.8	14.1	14.4
tFreq(Hz)	-	-	4.71	4.85	4.62	4.58
cFreq(Hz)	5.60	5.63	5.65	5.79	5.70	5.70

tQmax: maximum horizontal force in test
cQsu: maximum shear strength of column (calculated)
cQmy: shear strength at the bending yeild of column ends (calculated)
cQbou: maximum bond strength (calculated)
tQxmax: horizontal force when maximum displacement occured
tXmax: maximum displacement in test
cXmy: horizontal displacement when the both column ends yielded (calculated)
tFreq: dominant frequency before yield in dynamic test
cFreq: dominant frequency before yield (calculated)

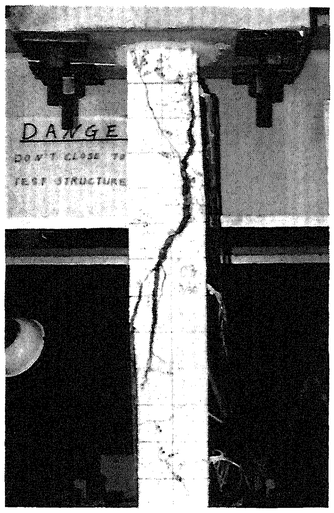

Figure 6. Crack pattern of CT1 at 1/50

Figure 7 Collaps shape of CT1

steel bars of two columns in a frame were buckled at the middle height, with the separation of concrete and main steel bars, at last the roof fell down.

In the static cyclic loading test of column CT4, the bending cracks concentrated in the area from two column ends till 1.0D or 2.0D positions at cyclic loading of 1/50 and 1/25. At cyclic loading of 1/5, the compressive crushes of two column ends began to grow immediately. At last, the concrete of two column ends were crushed completely, and the main steel bars were buckled. The Load-Displacement hysteresis loops of these two static cyclic loading tests are shown in Figure 4 and 5. The crack sketches of these loadings are shown in Figure 6-8.

Figure 8. Collaps shape of CT4

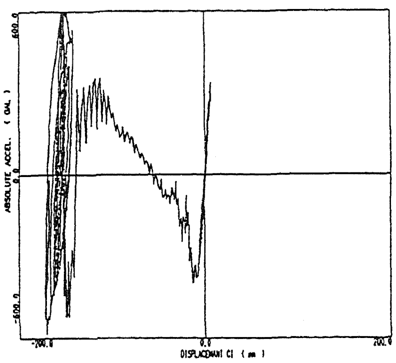

Figure 9. Absolute acc.-Story disp.hysteresis loop of CT1 by shaking table test

4 DYNAMIC TEST RESULTS

Four kinds of columns were tested in the shaking table. The natural frequencies of the elastic regions of each test structure was 4.5Hz approximately. The damping ratios before yield was estimated about 5% by AR model analysis. Distinct differences between the fre quencies and the damping ratios of four types were not found. The plastic region dominant frequencies of each test structure was about 3Hz at the time just before collapse. Four test structures collapsed at the beginning of principal shocks. Acceleration-Story Displacement Hysteresis Loops of four shaking table tests are shown in Figure 9-12. Damaged

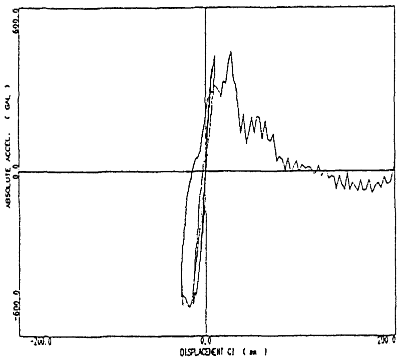

Figure 10. Absolute acc.-Story disp.hysteresis loop of CT2 by shaking table test

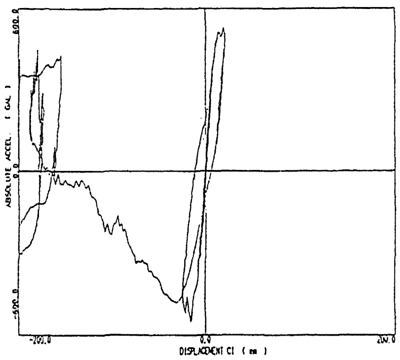

Figure 11. Absolute acc.-Story disp.hysteresis loop of CT3 by shaking table test

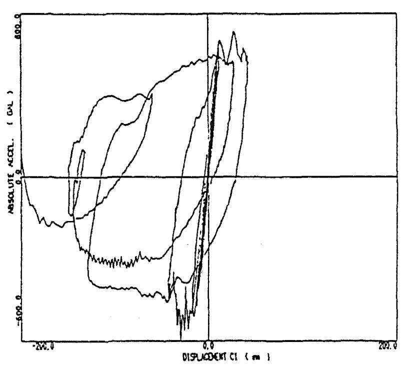

Figure 12. Absolute acc.-Story disp.hysteresis loop of CT4 by shaking table test

columns are shown in Figure 13 - 16. Table 4. indicates the estimated maximum deformations, maximum strengths, and so on, including static test results and design values.

In the shaking table test of CT1, initial shear cracks grew immediately, and three columns were cut near column caps, the other

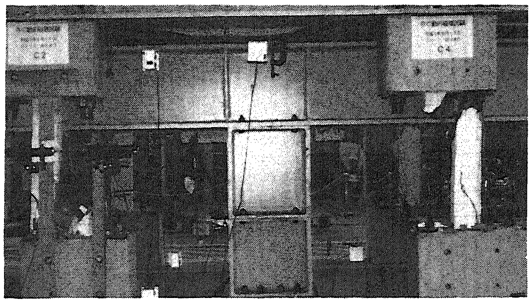

Figure 13. Collapse shape of CT1
by shaking table test

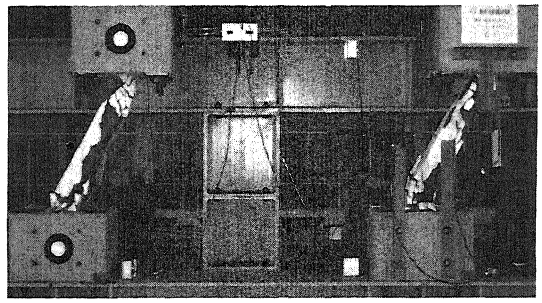

Figure 15. Collapse shape of CT3
by shaking table test

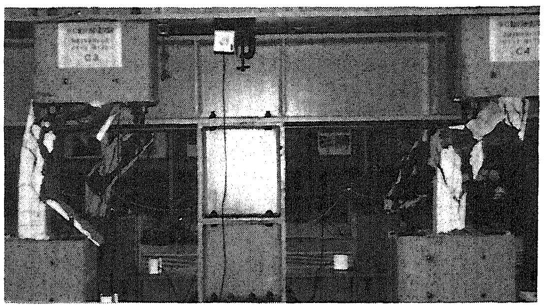

Figure 14. Collapse shape of CT2
by shaking table test

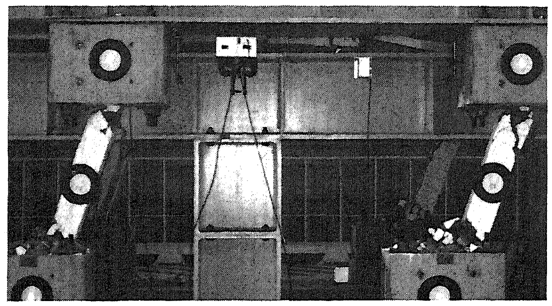

Figure 16. Collapse shape of CT4
by shaking table test

one was cut near a column bottom. The main steel bars buckled.

In the test of CT2, the initial crack types were same to CT1 test case. However, the columns collapsed in next opposite acceleration with the separation of concretes and steel bars, and with the crush of core concretes.

In the test of CT3, the shear bending cracks were appeared near two column ends. These cracks increased and collapsed with the separation of concretes, and with buckling of main steel bars of compressive zone.

In the test of CT4, the initial shear bending cracks appeared in two column ends. These cracks grew gradually(0.5D~0.75D~1.5D), and the compressive concretes crushed with main steel bar buckling. The damaged area of columns were limited in column ends.

5 CONCLUSION

The dynamic maximum horizontal strengths and the dynamic deformation capacities were almost agreed with the static ones. However, the damage patterns were changed with the shear in forcement bar spacings, and also with testing method differences between statics and dynamics.

ACKNOWLEDGMENT

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