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SHAKING TABLE TESTS OF REINFORCED CONCRETE STRUCTURES UNDER BIDIRECTIONAL EARTHQUAKE MOTIONS

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ABSTRACT

Shaking table tests were conducted to investigate the dynamic nonlinear behavior of the reinforced concrete (R/C) structure under bidirectional horizontal input motions. Two identical single story structures composed of five R/C columns whose top were connected to a thick and heavy steel plate were tested with special attentions to the strict control of shaking table as well as to the accurate measurement of structures. One test structure was subjected to bidirectional artificial earthquake motions while the other was unidirectional for comparison. Test program varied in input acceleration from low to high levels. Before and after the shaking, free vibration tests were also conducted. The nonlinear responses of the test structure under bidirectional motions were all different from those under unidirectional motion. For example, the bidirectional load bearing capacity of columns was lost after 0.35g input acceleration while unidirectional ones withstood 0.48g acceleration. Computer analyses were then conducted to explain the test results by constructing a 3-D structural model, where sectional component of R/C column was divided into several fibers having each stress strain relationship. The simulation was fairly well agreed with the test up to the strong nonlinear response range resulting in the confirmation of validity of developed analytical method.

KEYWORDS

Shaking table test; Bidirectional input motions; Reinforced concrete column; Nonlinear response; Simulation analysis; Fiber model; Earthquake response analysis

OBJECTIVE

Numerous experimental studies on R/C structures under bidirectional horizontal loads have been made. Most of those studies using R/C column specimens were, however, performed under the static condition. The shaking table tests of R/C structures under bidirectional earthquake motions have been scarcely conducted, to the author's knowledge, due to payload limit of shaking table as well as difficulties in measurement during the shaking. The authors recently introduced an advanced shaking table with elaborated control and a data acquisition system. The objective of this study is to investigate the dynamic nonlinear response characteristics of the R/C structures under the bidirectional input motions by means of the shaking table tests and to verify the analytical method developed.

SHAKING TABLE TESTS

Test Structures, Input Earthquake Motions and Test Program

The shaking table tests were carried out using the two identical structures composed of five R/C columns connected by steel tendons to the steel plate as shown in Fig.1, which represented a single story structure. It was expected that the axial force of the column at the center of the structure would be nearly constant and the axial force of the other columns would vary during the tests. The cross-section of the each R/C column was 100mm by 100mm with a height of 600mm. Four longitudinal bars (D6: deformed bar with 6mm diameter) and 10mm intervals' hoop wires (ϕ 3.1: steel wire with 3.1mm diameter) were used for reinforcement. These columns were designed so that bending failure would precede shear failure. Ready mixed concrete of which maximum size of the aggregate was 5mm was used. The material properties of the concrete and the steels are shown in Table 1.

A lot of acceleration and displacement sensors were installed in two directions for each of the test structures, although only major sensors are shown in Fig.1. Dynamic strain gages were also glued to several specific locations of the column reinforcements. Besides, the acting forces on the each column, such as shear forces, bending moments and an axial force were measured by the load cell connected by high strength bolts between the column bottom and a steel block which was connected to the table. The load cells were specially manufactured using steel boxes equipped with three dimensional arrangement of strain gages.

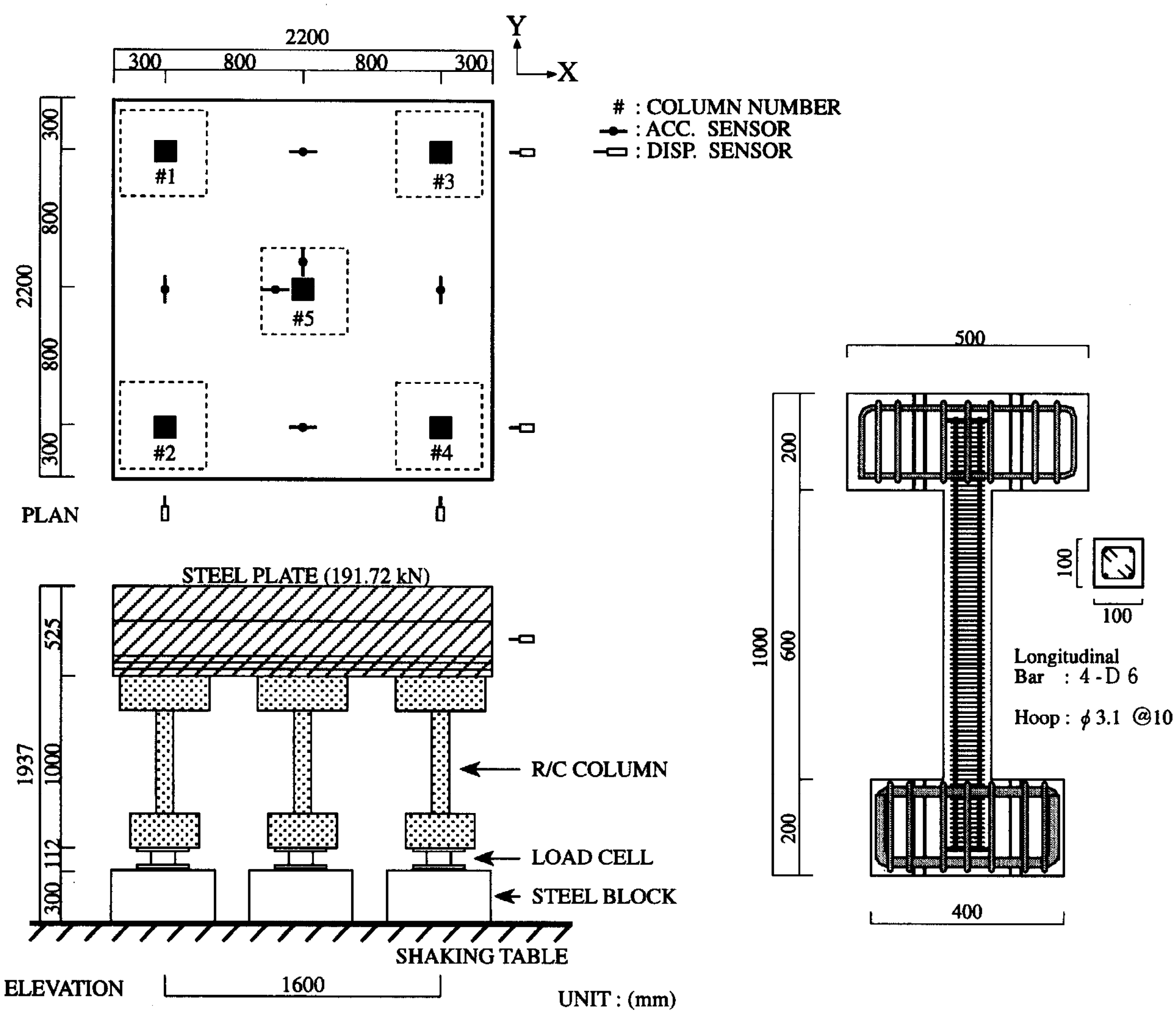

Fig. 1 Setup of Test Structure and Detail of R/C column

In order to investigate the dynamic response of the test structures from a linear to a strong nonlinear range, the target maximum acceleration level of input waves was adjusted according to the test program as shown in Table 2. Those input levels were determined from the results of analyses conducted before the test, predicting and defining for the unidirectional structure (denominated as X) as follows; 1) Run1: elastic level, 2) Run2: crack level, 3) Run3: reinforcement yield level, 4) Run4: failure level. For the test of bidirectional structure (also denominated as XY), the same three levels from Run1 to Run3 were applied but Run4 level could not be applied because of the failure at Run3. Before and after the each test, the free vibration tests by the wire cutting method were conducted to monitor the change of a natural frequency and a damping factor of the test structures.

As for input earthquake motions, artificial earthquake motions with 10 seconds duration were used. Since the fundamental natural frequency of the structure in a linear range predicted was 4 Hz, the artificial motions were synthesized so that the spectral values from 1 to 4 Hz were almost equal. Difference between the table motions in x and y directions was mainly attributed to the phase differences. For the unidirectional structure X, only x-directional wave was applied. Figure 2 shows a pair of the acceleration time histories of the input motions with orbit measured on the shaking table and response spectra of the table motions for Run1 to Run3. Although the time histories in Fig.2 are for Run3, the response spectra indicate that the x-directional input motion for XY was almost the same as that for X at each Run. It was intended that the test results of XY could be compared with X at the same input level in one direction.

Table 1. Physical Properties of Materials

Concrete	Compressive Strength	: 29.3MPa
Steel D6	Yield Strength	: 383.4MPa
Steel ϕ 3.1	Yield Strength	: 224.8MPa

Table 2. Test Program

No.	Content
1	Free Vibration
2	Run 1 (Target input level : 100 Gal)
3	Free Vibration
4	Run 2 (Target input level : 200 Gal)
5	Free Vibration
6	Run 3 (Target input level : 390 Gal)
7	Free Vibration
8	Run 4 (Target input level : 510 Gal)
9	Free Vibration

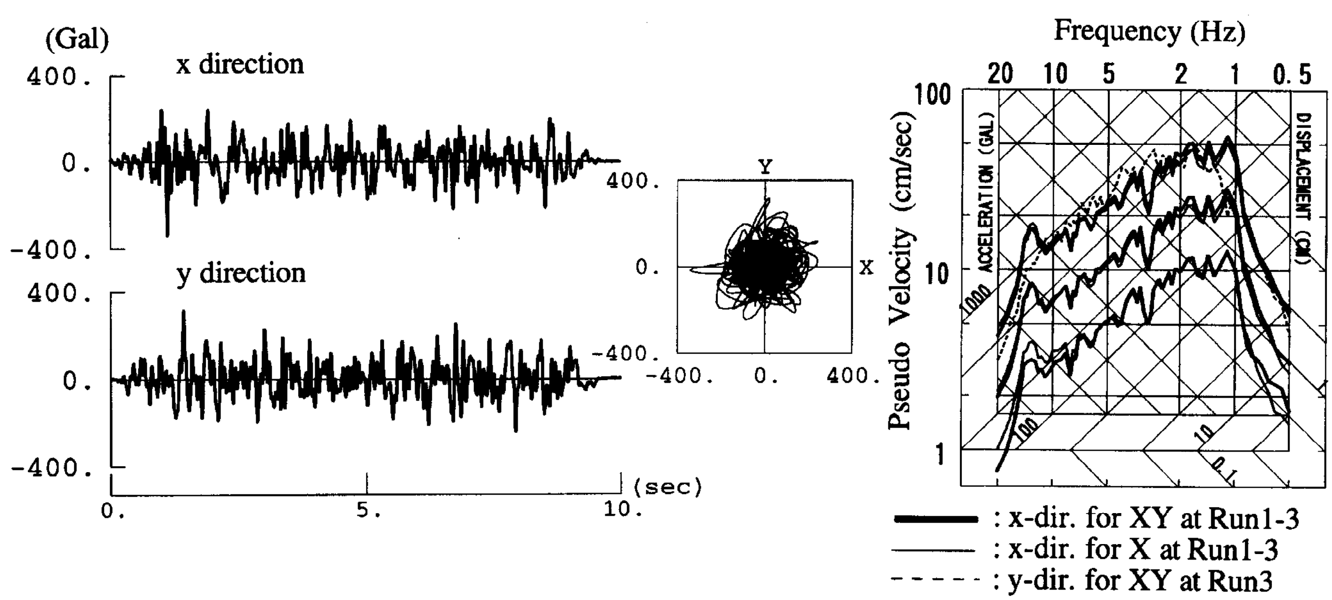

Fig. 2 Input Acceleration observed on Shaking Table and its Response Spectra

Test Results

The change of the natural frequency of the test structures obtained from the free vibration tests are shown in Fig.3. Before Run2, the natural frequency of XY was almost the same as that of X. After Run2, the natural frequencies of both x and y directions of XY remarkably decreased and became much smaller than those of X. In case of X, that was exposed only the x-directional input motion, the natural frequency in y direction was also decreased. This indicates that, even in unidirectional excitation, the structure would be damaged not only in the excited direction but also in the perpendicular direction.

Maximum response values obtained from the tests are summarized in Table 3. These values are the overall response of the test structures. The listed story shear force is an inertia force calculated by multiplying the mass of the steel plate with an acceleration at the center of the steel plate. Sum of the shear forces of columns obtained by the load cells was agreed well with the story shear force above. Therefore, it was suggested that the response of the each column could be examined in detail using the data by the load cell.

Figure 4 shows, as an example of test results, the response displacements of XY with comparison of X at Run3. The orbits of them are also illustrated in the figure. The x-directional displacement of both XY and X were almost the same from the beginning of excitation until 1.4 seconds. After that, however, the waveforms became different with each other, where the displacement value of XY was larger than that of X. A residual displacement was observed after about 5 seconds only in XY.

Figure 5 shows the relationship of the story shear force and displacement at the center of the steel plate both in x direction. In Run2, both the X and XY structures entered into an inelastic range. Small cracks at the both ends of all columns were recognized after Run2. The reinforcements of the column at the center of XY reached the yield point although those of X were within a linear range in Run2. Therefore, the stiffness of XY was a little lower than that of X. During Run3, both the strength and stiffness of XY remarkably reduced due to extended and deepened cracks accompanied with spalling of the cover concrete and became much smaller than those of X. The damages of the columns of XY during and after Run3 with the maximum 0.35g acceleration were so severer than those of X during Run4 with 0.48g that the excitation of Run4 for XY was impossible.

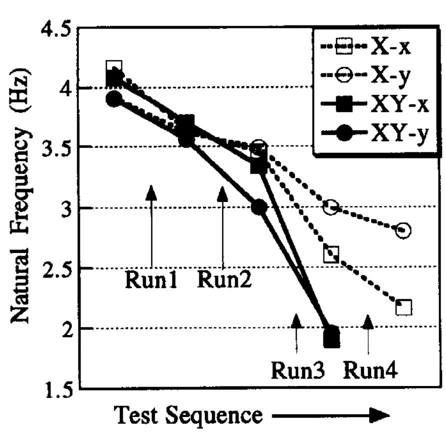

Fig. 3 Change of Natural Frequency of the Test Structures

Table 3. Maximum Response Values

Test No.		Run 1		Run 2		Run 3		Run 4	
Structure Type		X	XY	X	XY	X	XY	X	XY
Acc. of Shaking Table	x	78	64	171	163	354	344	484	*
(cm/sec^2)	y	----	62	----	151	----	319	----	*
Acc. of Steel Plate	x	145	184	227	229	306	228	264	*
(cm/sec^2)	y	82	127	82	267	67	276	67	*
Disp. of Steel Plate	x	3.5	3.9	5.8	9.1	14.5	27.0	32.3	*
(mm)	y	1.8	3.2	2.2	12.4	1.4	20.5	2.9	*
Story Shear Force	x	28.4	36.1	44.4	44.7	59.8	44.5	51.6	*
(kN)	y	16.0	24.8	16.0	52.3	13.0	54.1	13.1	*

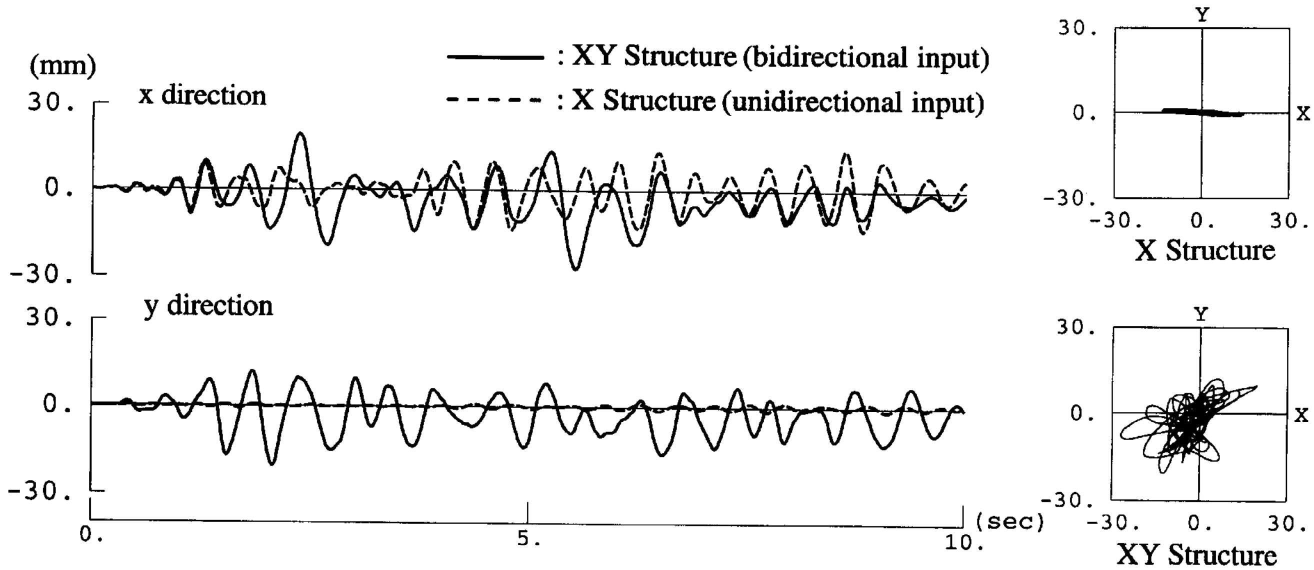

Fig. 4 Response Displacement Time History and Orbit of Steel Plate at Run3

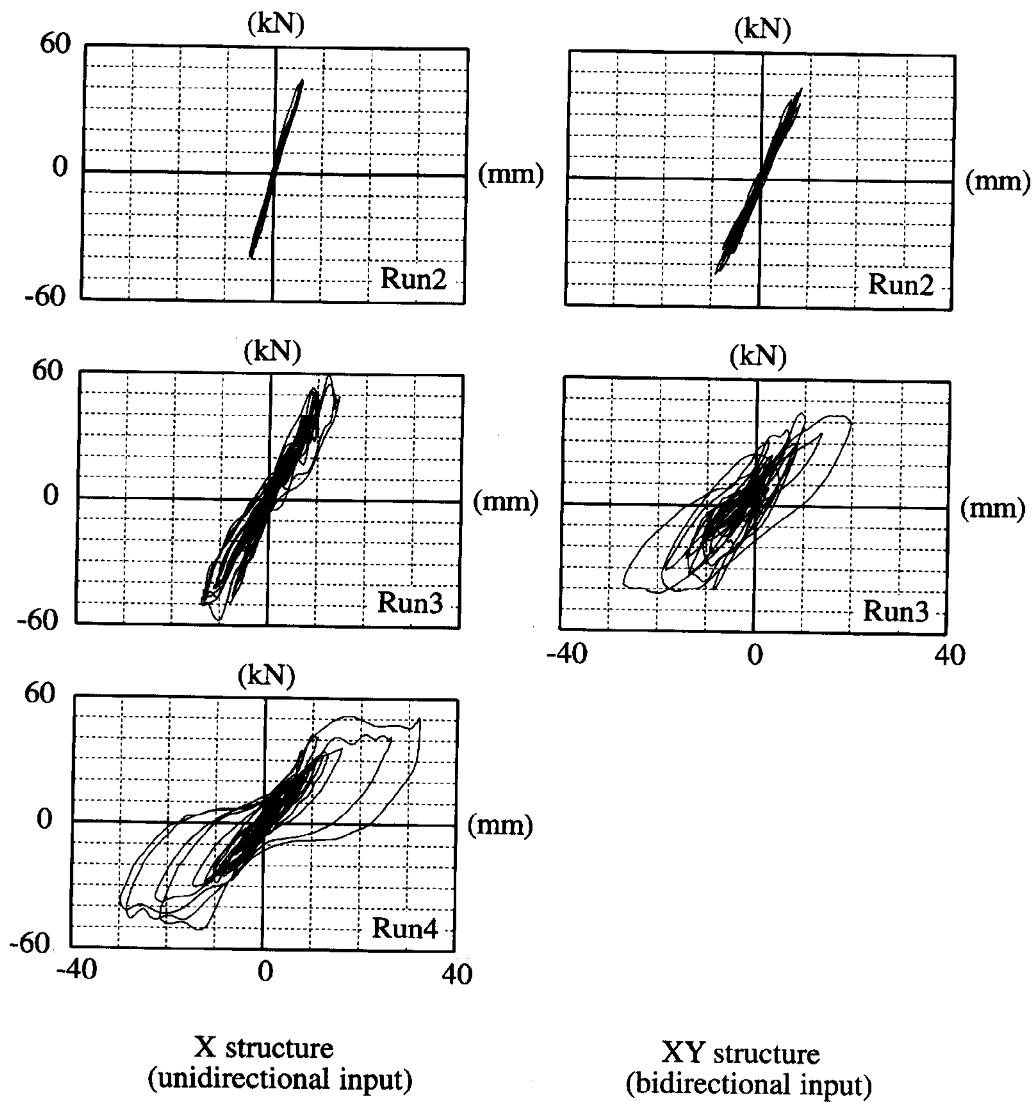

Fig. 5 Story Shear Force and Displacement Relationship in x direction

SIMULATION ANALYSIS

Analytical Method

Figure 6 shows the three dimensional analytical model of the test structure. The steel plate was replaced by rigid truss components while weight of the steel plate and the column heads were replaced as upper and lower masses respectively. The columns were also replaced as rod members where sectional components of top and bottom portions were divided into several fibers having each stress strain relationship. The stress and strain relationship of the concrete and the reinforcement for the each fiber was idealized as shown in Fig.7. In all the rod members, bending and axial deformations in linear and nonlinear ranges were considered as well as shear deformation in linear range. The each load cell beneath the column base was represented as a rotational and a shearing spring in both x and y horizontal directions.

As for input ground motions to the analytical model, the acceleration time histories measured on the shaking table were adopted. The simulation analyses on the test from Run1 to Run3 were carried out based on the same successive conditions as the tests in order to take into account of the effect of experienced hysteretic behaviors. Viscous damping proportional to the initial stiffness of the test structure was assumed, whose value was decided referring to the result of the free vibration test.

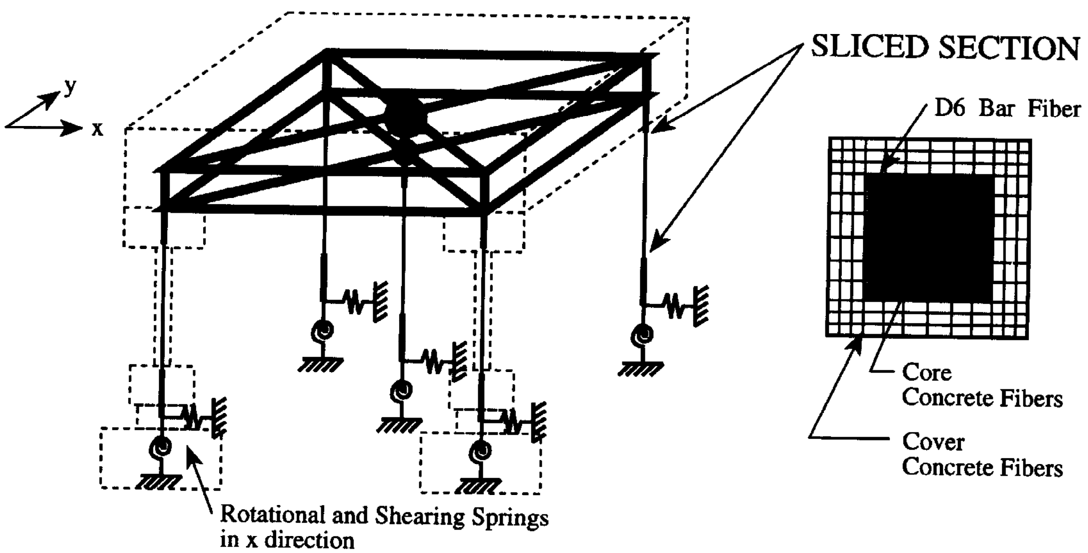

Fig. 6 Analytical Model and Discretization of Column Section

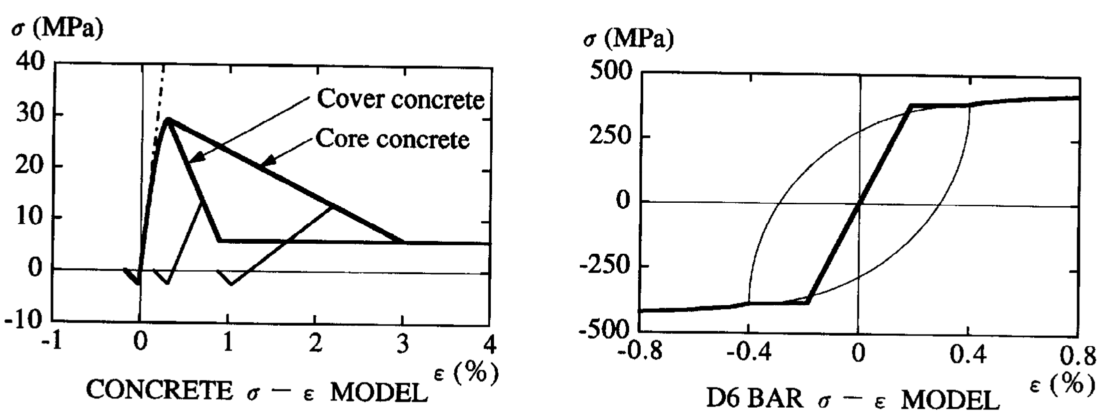

Fig. 7 Idealized Stress and Strain Relationship of Concrete and Reinforcement

Comparison of Analytical and Test Results

Figure 8 shows the acceleration time history and the orbit of XY during Run3. The solid line for the analytical result is well tracing the broken line for the test result except in a small intermediate portion of the time history. The two orbits are almost identical. In Fig.9, the story shear force and displacement relationships are also compared. Although the displacement of analysis for Run3 was a little smaller than that of test, the overall tendencies of analytical results were sufficient to explain the test results even in the strong nonlinear response range.

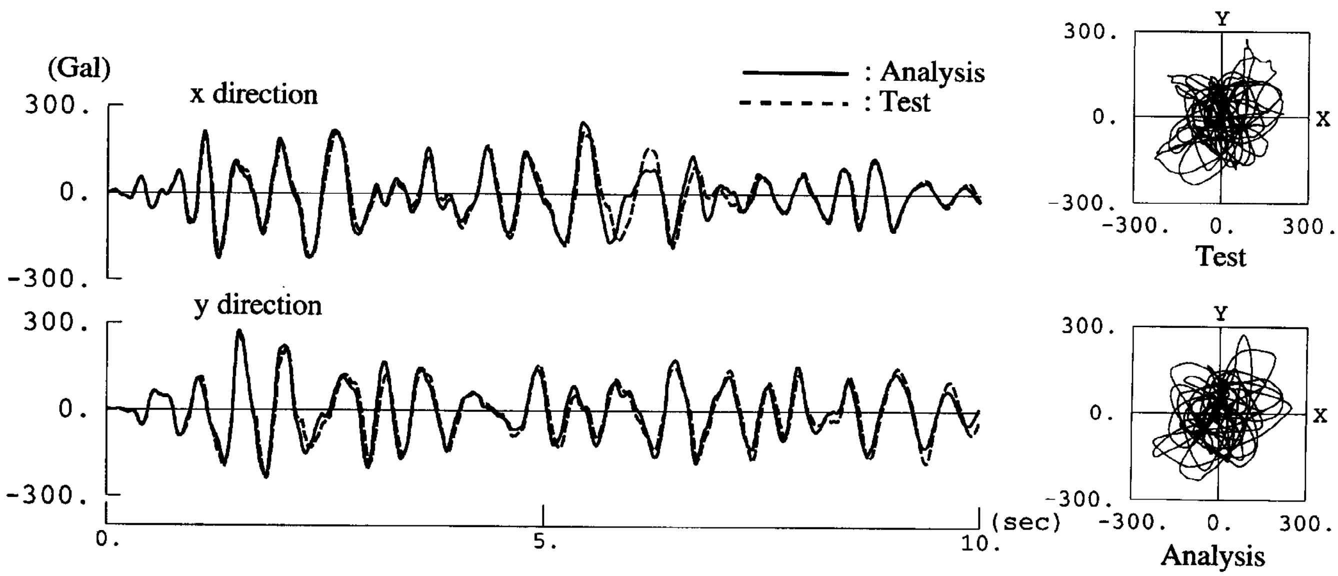

Fig. 8 Comparison of Analytical and Test Results at Run3
(Acceleration Time History and Orbit)

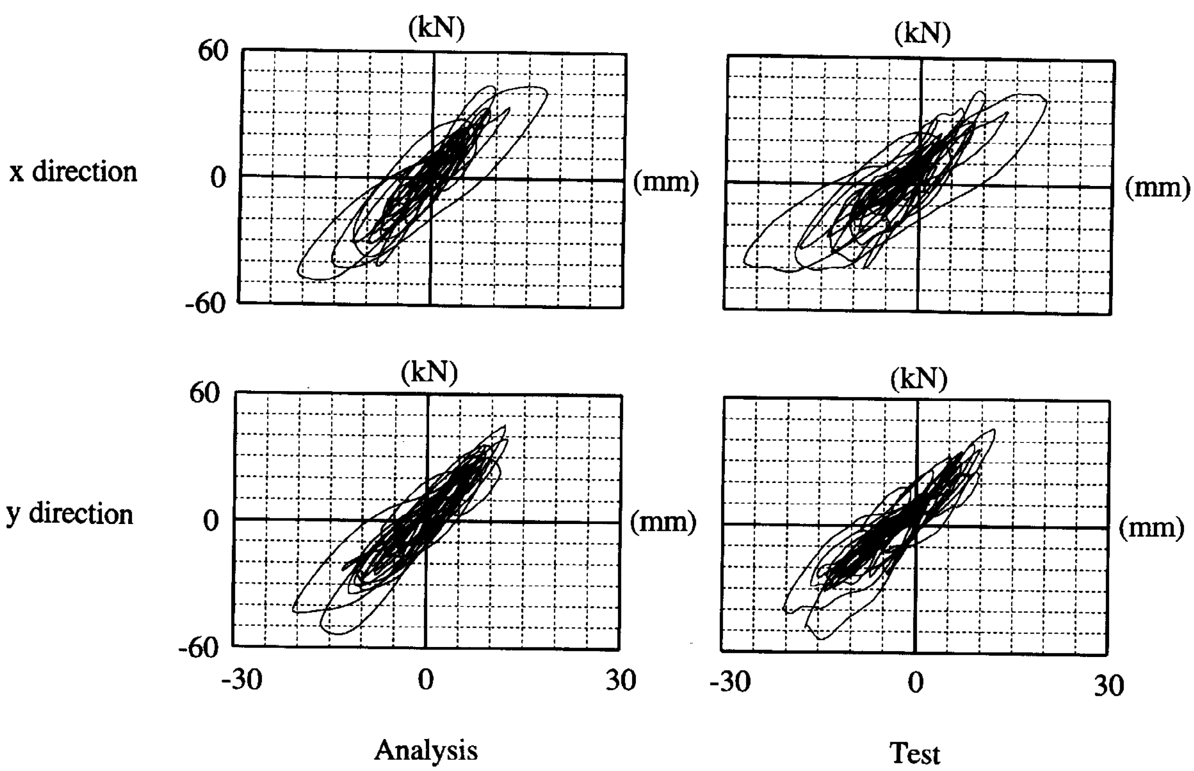

Fig. 9 Comparison of Analytical and Test Results at Run3
(Story Shear Force and Displacement Relationship)

CONCLUSIONS

The bidirectional shaking table tests on the R/C structure were conducted together with the unidirectional tests on the other identical structure using the advanced testing system. Through the shaking table tests accompanied with the free vibration tests, it was successful in clarifying and quantifying that the nonlinear response characteristics of the structure subjected to the bidirectional input motions were largely different from those to the unidirectional input motion. Strength reduction and stiffness degradation of the structure under the bidirectional excitations were remarkable in contrast with that under the unidirectional one. Simulation analyses on the whole tests were also conducted by using the three dimensional discrete model in order to explain the responses of structures. The analytical results obtained in the form of response time histories and of relationships between the story shear force and displacement throughout the nonlinear range proved that the dynamic characteristics of the structures could be reproduced, which resulted in the confirmation of analytical validity.

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