A SIMULATION OF EARTHQUAKE RESPONSE OF REINFORCED CONCRETE BUILDING FRAMES TO BI-DIRECTIONAL GROUND MOTION BY IIS COMPUTER-ACTUATOR ON-LINE SYSTEM

by

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ABSTRACT

The non-linear earthquake response of reinforced concrete single story building frames to bi-directional ground motion was simulated by the improved IIS computer-actuator on-line system. The methodology, the test results and the comparison with analysis were described in this paper.

INTRODUCTION

The importance to consider the bi-directional effect of earthquake ground motion in seismic design of reinforced concrete buildings has been recognized recently. Analytical works on nonlinear response of building frames to bi-directional horizontal ground motion suggested that the response displacement would be amplified due to the coupling of two components of ground motion [1, 2,3]. Static test results on reinforced concrete columns subjected to bi-directional bending with or without shear force also showed a significant deterioration of strength and/or ductility would occur due to the bi-directional horizontal displacement history [4,5,6,7,8]. However, in order to develop a rational seismic design method considering the above mentioned behaviour, more studies to examine the real behaviour and to develop more realistic analytical models have been requested.

As the second phase of the project on "Earthquake Response of Reinforced Concrete Buildings to Bi-directional Ground Motion" granted to the authors by the Ministry of Education, Japanese Government during the period of 1975 - 1977, the simulation of earthquake response of reinforced concrete frames to bi-directional ground motion was carried out by the IIS Computer-Actuator On-line System.

The primary purpose of this paper is to describe the detail of the methodology as well as the results of the simulation.

IIS COMPUTER-ACTUATOR ON-LINE SYSTEM

<u>Principle:</u> A principle of the on-line simulation is to solve the nonlinear differential equation expressing the earthquake response of the structural system by the computer using the real restoring force characteristics obtained by the pseudo-dynamic loading test which is controlled by the computer and performed in parallel with the computer analysis. Therefore, it is a kind of the hybrid system of computer analysis and pseudo-dynamic loading test. Since the IIS On-line System was developed initially for the simulation of single degree-of-freedom structural system [9,10], it has been improved to be applied to two degrees-of-freedom system for this project.

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Vibration Equations and Numerical Integration: Assuming the one-mass structural model subjected to bi-directional ground motion, the vibration equations without viscous damping term at i-th time step are;

$$M \cdot \ddot{X}_1^i + F_1^i = -M \cdot \ddot{X}_{01}^i \qquad \cdots\cdots (1)$$

$$M \cdot \ddot{X}_2^i + F_2^i = -M \cdot \ddot{X}_{02}^i \qquad \cdots\cdots (2)$$

where, M : mass of the system

$\ddot{X}_j^i$: response relative acceleration of the system (to j-th direction)

F_j^i : restoring force of the system (to j-th direction)

$\ddot{X}_{0j}^i$: ground acceleration (to j-th direction)

In order to integrate the Eqs. 1 and 2 numerically, the central finite difference equations; Eqs. 3 and 4, are used,

$$\ddot{X}_1^i = \frac{1}{\Delta t^2} \cdot X_1^{i-1} - \frac{2}{\Delta t^2} \cdot X_1^i + \frac{1}{\Delta t^2} \cdot X_1^{i+1} \qquad \cdots\cdots (3)$$

$$\ddot{X}_2^i = \frac{1}{\Delta t^2} \cdot X_2^{i-1} - \frac{2}{\Delta t^2} \cdot X^i + \frac{1}{\Delta t^2} \cdot X_2^{i+1} \qquad \cdots\cdots (4)$$

where, Δt : time interval

$\ddot{X}_j^{i-1}$: response displacement at (i-1)-th step (to j-th direction)

$\ddot{X}_j^{i+1}$: response displacement at (i+1)-th step (to j-th direction)

Substituting the Eqs. 3 and 4 into Eqs. 1 and 2, respectively, the response displacement at (i+1)-st step are predicted by Eqs. 5 and 6.

$$X_1^{i+1} = -(\ddot{X}_{01}^i + F_1^i/M) \cdot \Delta t^2 - X_1^{i-1} + 2 \cdot X_1^i \qquad \cdots\cdots (5)$$

$$X_2^{i+1} = -(\ddot{X}_{02}^i + F_2^i/M) \cdot \Delta t^2 - X_2^{i-1} + 2 \cdot X_2^i \qquad \cdots\cdots (6)$$

The simulation is carried out by repeating the following procedure at each time step until the response of the system is terminated;

a) to predict the response displacements at (i+1) step; X_1^{i+1} and X_2^{i+1}, by Eqs. 5 and 6, respectively in the computer system. A coupling of the bi-directional components is considered in the terms of F_1^i and F_2^i.
b) to give the response displacements; X_1^{i+1} and X_2^{i+1}, to the test frame by the actuator system.
c) to measure the restoring forces; F_1^{i+1} and F_2^{i+1}.
d) to repeat the step a), b), and c) for the next step.

Since the central finite difference method is not self-starting, the linear acceleration method is used at the first step assuming the elastic stiffness of the system.

METHOD OF ON-LINE TEST

The simulation of earthquake response of single story reinforced concrete 1/3 scaled frames to uni-directional and bi-directional horizontal ground motion was carried out by the improved on-line system.

Frames and Test Specimens: Six frames of column yielding type; with strong beam and weak column, were tested as shown in Table 1. Test results of two other frames reported in the previous paper [11] are also referred in Table 1. Test variables were initial natural period, number of components of the ground motion and peak acceleration of the ground motion. The detail of the test column is shown in Fig. 2. Both the upper and lower columns represented the columns of the single story strong beam frame. The top and bottom of the specimen were fixed both to bending and shear, and bi-directional lateral forces were applied at the middle, so that the inflection points of the upper and lower columns were located at the mid-height. Longitudinal and lateral bars arrangement was designed according to the AIJ Building Code Requirement [12] so that shear failure did not occur prior to flexural yielding. The longitudinal bars were welded to the end steel plates.

Loading System: Test setup is shown in Fig. 3. Axial stress of $30kg/cm^2$ was applied by an actuator beginning of the test and kept constant during the test. Lateral forces were applied by other actuators driven by the command from the computer. The test specimen was fixed to bending and shear force at the top and the bottom. The vertical displacement at the bottom was not restrained to keep the axial force constant.

Ground Motion and Other Parameters: The NS and EW components of the 1968 Hachinohe acceleration record were used for the ground motion. The duration time was 12 seconds with zero data at the last 2 seconds. The amplitude of the acceleration was modified so that the ratio of the lateral strength of the frame in terms of the base shear coefficient (k_y) to the peak ground acceleration normalized by the acceleration of the gravity (k_g) became 0.9 - 1.0 for NS component and 1.1 - 1.25 for EW component. The lateral capacity of the frame was determined by the static test [6]. The time interval for numerical integration was 0.01 second, however, the real time to execute a step of the on-line simulation was expanded to about 8 seconds to make the observation of the behavior of the specimen easy. A viscous damping was not considered.

RESULTS OF ON-LINE TEST

Time History of Response Displacement: Examples of the time history of response displacements are shown in Fig. 4. Fig. 4(a) shows NS and EW components of response displacements to bi-directional ground motion, and Fig. 4(b) shows the response displacement subjected to NS or EW component of the ground motion independently. As far as the patterns of the response displacement time history are concerned, the effect of coupling of NS and EW components is not so signifficant, while some discrepancies between Fig. 4(a) and Fig. 4(b) are observed on the response period and the muximum displacement.

Response Displacement Trace: An example of the relationship between the NS and EW components of response displacement is shown in Fig. 5(a). The shape of the trace is very complicated due to the coupling of both components.

Maximum Response Displacements: The maximum response displacements obtained by the on-line test are shown in Fig. 6. The response displacements to bi-directional ground motion (mark●) were 10% - 120% greater than those to uni-directional ground motions (mark▲or■). In order to approximate the response displacement to bi-directional ground motion, the root sum square of each maximum response displacement to uni-directional ground motion (mark✦) were calculated. A good correlation between the mark ● and the mark ✦ is obtained.

Crack Pattern: Examples of crack pattern of the columns subjected to uni-directional ground motion and bi-directional ground motion are shown in Fig. 7. The crack pattern of the column subjected to the bi-directional ground motion was similar to the composition of each crack pattern of the column subjected to the uni-directional ground motion. However, as seen in Fig. 7, the grade of damage became severe due to the effect of bi-directional ground motion.

Analytical Study: In order to analize the on-line test results, the computer program; OS-2D, for fibre model analysis was developed. The program OS-2D is an extended version of the program OS-1D for uni-directional earthquake response [10] and the program OS-2S for bi-directional bending [6]. The results are shown in Figs. 4, 5(b), and 6. A good correlation between the on-line test results and the analytical results was observed.

SUMMARY

The results are summarized as follows:

1) It was verified that the computer-actuator on-line system is applicable to the simulation of earthquake response of the reinforced concrete frames to bi-directional ground motion,
2) The maximum response displacements were increased 1.1 - 2.2 times due to the bi-directional effect of ground motion, and
3) The computer program OS-2D approximated well the on-line test results.

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REFERENCES

[1] Okada, T. et al "Analysis of the Hachinohe Library Damaged by '68 Tokachi-Oki Earthquake" Bulletin of ERS, No. 3, Earthquake Resistant Structure Research Center, Institute of Industrial Science, University of Tokyo, 1969
[2] Takizawa, H. "Bi-axial and Gravity Effects in Modeling Strong Motion Response of R/C Structures" A paper presented to the VI-WCEE, New Delhi, India, 1977.
[3] Aktan, A.E. et al "Response of A Reinforced Concrete Section to two Dimensional Curvature Histories" ACI Journal, 1974.
[4] Okada, T. et al "Restoring Force Characteristics of R/C Columns subjected to Bi-directional Cyclic Eccentric Axial Load" A paper presented to the AIJ Annual Convention, 1970. (in Japanese)
[5] Yoshimura, M. et al "R/C Columns Subjected to Bi-axial Bending-Part 2 and 3" Papers presented to the AIJ Annual Convention, 1974. (in Japanese)
[6] Okada, T., Seki, M., and Asai, S., "Response of Reinforced Concrete Columns to Bi-directional Horizontal Force and Constant Axial Force" Bulletin of ERS, No.10, Earthquake Resistant Structure Research Center, Institue of Industrial Science, University of Tokyo, 1976

[7] Takiguchi, K. et at "Bi-axial Bending of R/C Columns" Transactions of AIJ, No. 229, 1975. (in Japanese)
[8] Otani, S. et al "Behavior of Reinforced Concrete Columns Under Simulated Bi-axial Earthquake Loads", Proceedings of International Symposium on Behavior of Building Systems and Components, Vanderbilt University, Nashville, U.S.A. 1979
[9] Takanashi, K. et al "Nonlinear Earthquake Response Analysis of Structures by A Computer-Actuator On-line System. Detail of the System" Bulletin of ERS No. 8, Institute of Industrial Science, Univ. of Tokyo, 1974
[10] Okada, T. and Seki, M., "A Simulation of Earthquake Response of Reinforced Concrete Buildings", A paper presented to the VI-WCEE, in New Delhi, India 1977
[11] Seki, M. and Okada, T., "Nonlinear Earthquake Response of Reinforced Concrete Building Frames by Computer-Actuator On-line System (Part 1 - part 5)", Transactions of AIJ, No.275, No.279, No.280, No.282, and No.284, 1979. (in Japanese)
[12] AIJ "Building Code Requirements of Reinforced Concrete Structures 1975", Architectural Institute of Japan, Tokyo (in Japanese)

Table 1 Identification of Frames, Input Ground Acceleration and Maximum Response Displacement

NO.	FRAME ID.	INITIAL PERIOD T (SEC)	MASS M (KG·SEC²/CM)	PEAK GROUND ACCELERATION $(\ddot{X}_O)_{MAX.}$ (GAL)		MAXIMUM RESPONSE DISPLACEMENT (CM)	
				NS	EW	ON-LINE TEST	ANALYSIS
1	UE-1	0.2	18.54	—	164.4	2.46	2.09
2	UE-2	0.4	74.16	—	41.11	1.99	1.21
3	UE-3	0.2	18.54	—	186.3	3.19	2.95
4	BI-1	0.2	18.54	202.2	164.4	2.66	2.20
5	BI-2	0.4	74.16	50.55	41.11	2.37	2.13
6	BI-3	0.2	18.54	229.1	186.3	4.21	3.71
7	FO-2	0.2	18.54	202.2	—	1.72	1.87
8	FO-4	0.4	74.16	50.55	—	1.09	1.24

FO-2 and FO-4 are referred from [11] and designated as UN-1 and UN-2 in this paper.

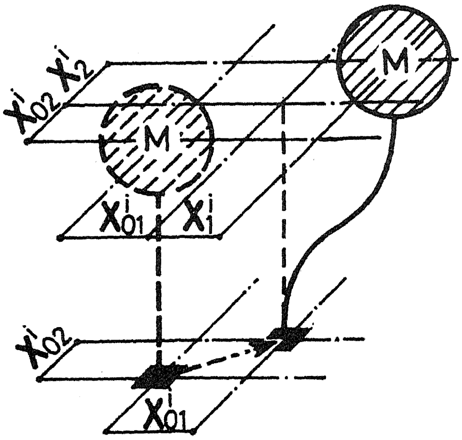


Fig. 1 System Coordinates

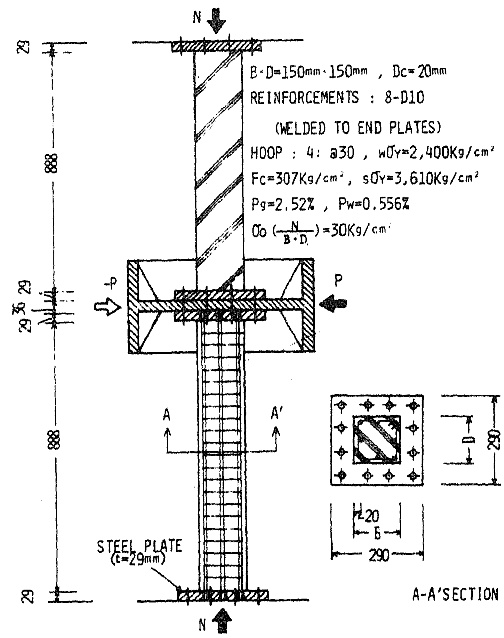


Fig. 2 Test Specimen

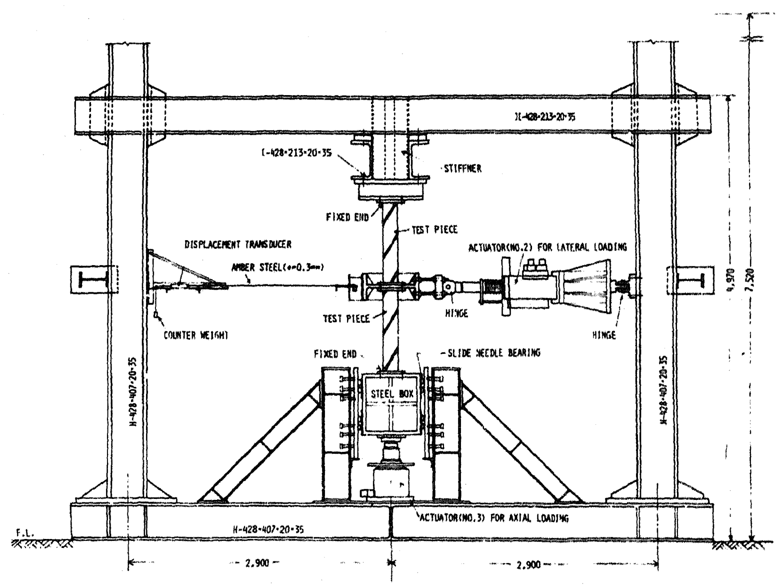
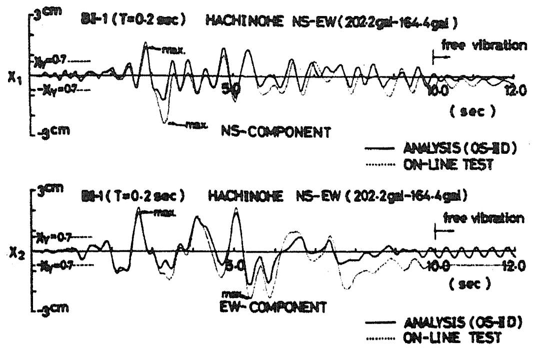
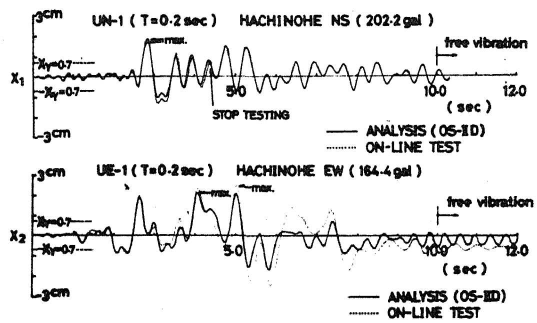


Fig. 3 Test Setup



a) Response to bi-directional ground motion



b) Response to uni-directional ground motion

Fig.4 Time History of Response Displacement

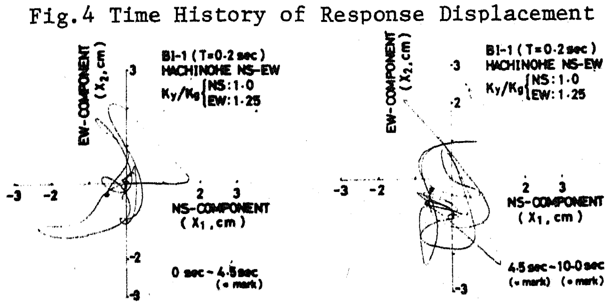


Fig.5(a) Response Displacement Trace (on-line test)

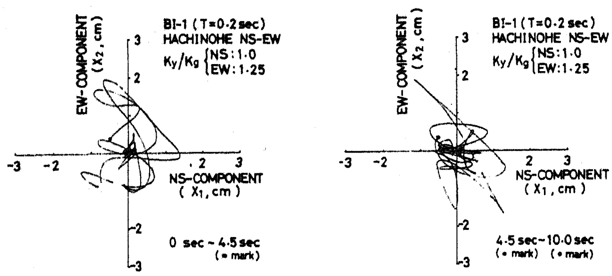


Fig.5(b) Response Displacement Trace (calculation)

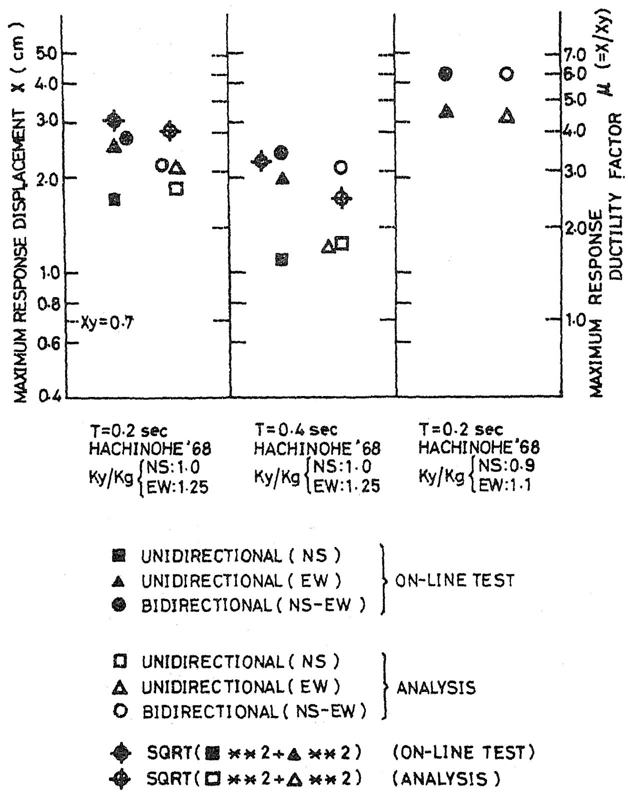
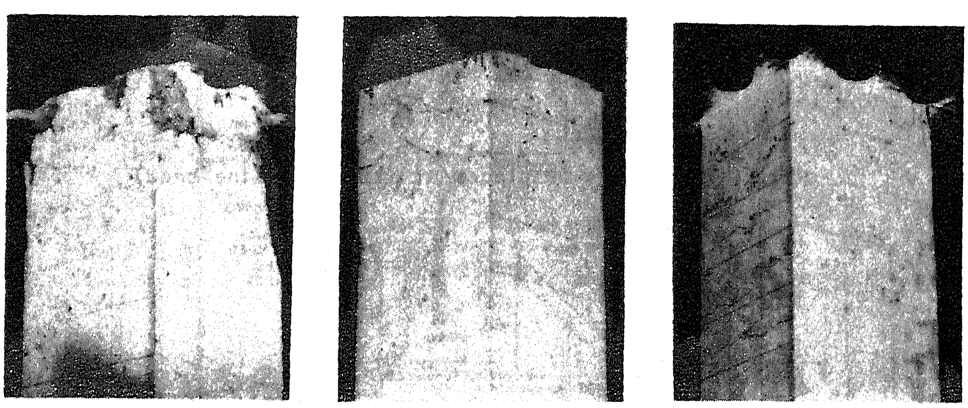


Fig.6 Maximum Response Displacement



a) Bi-directional BI-1

b) Uni-directional UE-1

c) Uni-directional UN-1

Fig.7 Crack Pattern