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BRIEF NOTE

RESPONSE OF REINFORCED CONCRETE COLUMNS TO BI-DIRECTIONAL HORIZONTAL FORCE AND CONSTANT AXIAL FORCE

by

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SYNOPSIS

As the first phase of the project on "Earthquake Response of Reinforced Concrete Buildings to Bi-directional Ground Motion" granted by the Ministry of Education, the Japanese Government, six reinforced concrete columns were tested under bi-directional horizontal cyclic loading and the computer simulation based on the nonlinear stress-strain relationships of concrete and reinforcing bar was performed. The variable was the pattern of the horizontal displacement trace in the plane of the column section; linear reciprocal, elliptical and circular traces. An influence of the traces to the ultimate strength and ductility is mainly discussed in this paper.

INTRODUCTION

The importance of bi-directional response of building frames during earthquake has been recently recognized and several researches were carried out on the earthquake response to bi-directional ground motion and on the static response to bi-directional bending or combined bending and shear (1-7). Enough information has not been obtained, however, it is suggested that a coupling of bi-directional components of the ground motion or the horizontal response displacement, which is usually not considered in the conventional seismic design, would significantly affect to the response of the building frames. This paper is concerned with the test results to examine the effect of various bi-directional horizontal displacement traces, which represent the typical response displacement traces, to the restoring force characteristics of reinforced concrete columns.

TEST SETUP AND TEST COLUMNS

Fig. 1 shows the test setup. The top of the test column was fixed to the heavy steel frame by the high tensile friction bolts

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and the bottom was also fixed to the steel box which was movable only to the vertical direction. Two components of the horizontal displacement were enforced to the center of the column by the electro-hydraulic actuators (#1 and #2), one of which was located perpendicular to another. Displacement transducer were installed at the other side of each actuator and connected to the column center by the flexible amber steel wires to control the movement of the actuators. A constant axial stress of 10% of the concrete compressive strength was applied by the other actuator (#3) and kept constant during the test.

Fig. 2 shows the detail of the column. The upper and lower parts were made seperately and bolted together to the middle steel deivce. The column was designed according to the AIJ Building Code Requirements for R/C Structures so that the flexural yielding took place before shear failure under uni-axial bending and shear.

TEST PROGRAM

The sinusoidal signals of 0.01 Hz were given to the actuators (#1 and #2) and the amplitudes of the displacements and the phase difference were controlled to give the column the various horizontal displacement traces. The feed-back circuit was composed between the signals and the measured displacements. Six traces used for the test are shown in Table 1. The displacement amplitudes, the phase differences and the number of the cycle are also shown there.

TEST RESULTS

Fig. 3 shows the force-displacement characteristics under unidirectional cyclic loadings. The column BC-1 was subjected to linear reciprocal cyclic loading to the principal axis and the direction of loading for the column BC-3 was diagonal to the principal axis. The column BC-1 showed the strength deterioration due to the cyclic loading, but, did not collapse until the 30-th cycle in the RUN-IV. The column BC-3 showed the similar behavior to BC-1, but, collapsed at the 25-th cycle of RUN-IV, which was the 63-rd cycle from the beginning. Fig. 4 shows the measured restoring force traces of the columns BC-4, 5 and 6 (RUN-III and IV). The patterns were clothoid curves which curvatures increased gradually due to the strength deterioration, while the displacement traces were well controlled. A change of the principal axis was also observed. The columns BC-4 and 5, subjected to the elliptical displacement traces, collapsed at the earlier stage of RUN-IV. The column BC-6, subjected to the circular displacement trace, had the smallest ductility and collapsed at the 14-th cycle of RUN-III, of which displacement amplitude was about twice of the yield displacement (μ=2).

The crack patterns at the 14-th cycle of RUN-III are shown in Photo 1. The spalling of concrete is seen in the column BC-6, subjected to the circular displacement trace, while it is not seen in the column BC-1 subjected to the uni-directional cyclic loading.

COMPUTER SIMULATION

The computer program OS-2S has been developed to simulate the test results. The basic concept is similar to the program OS-1D developed for the earthquake response simulation to uni-directional ground motion based on the nonlinear stress-strain relationships of concrete and steel reinforcement (8). Stress-strain relationship in Fig. 6 was used for concrete elements and Ramberg-Osgood function was used for steel elements. The column cross section was devided into 225 concrete finite elements and 8 steel elements (Fig. 5) and the bi-directional bending moment-curvature relationships was calculated so that the strain of each element satisfied the assumed compatibility and the stress satisfied the assumed nonlinear stress-strain relationships (Fig. 6) and the equilibrium condition of axial force. The bi-directional horizontal force-displacement relationship was calculated from the moment-curvature relationship assuming the distributions of the moment and curvature along the column length as shown in Fig. 7.

The examples of the calculation are shown in Fig. 8. A good correlation between the test and the calculation was obtained on the ultimate strength and the pattern of the restoring force traces including the strength deterioration and the inclination of the principal axis due to the bi-directional cyclic loading.

CONCLUDING REMARKS

Concluding remarks on the effects of the various horizontal displacement traces to the strength and ductility of reinforced concrete columns are;

1) The developed testing system was suitable for the bi-directional cyclic loading,

2) Significant strength deterioration and loss of ductility due to bi-directional cyclic liading were observed. This behavior should be considered in developing a rational seismic design method, and

3) The developed computer program OS-2S could simulate well the test results.

ACKNOWLEDGEMENTS

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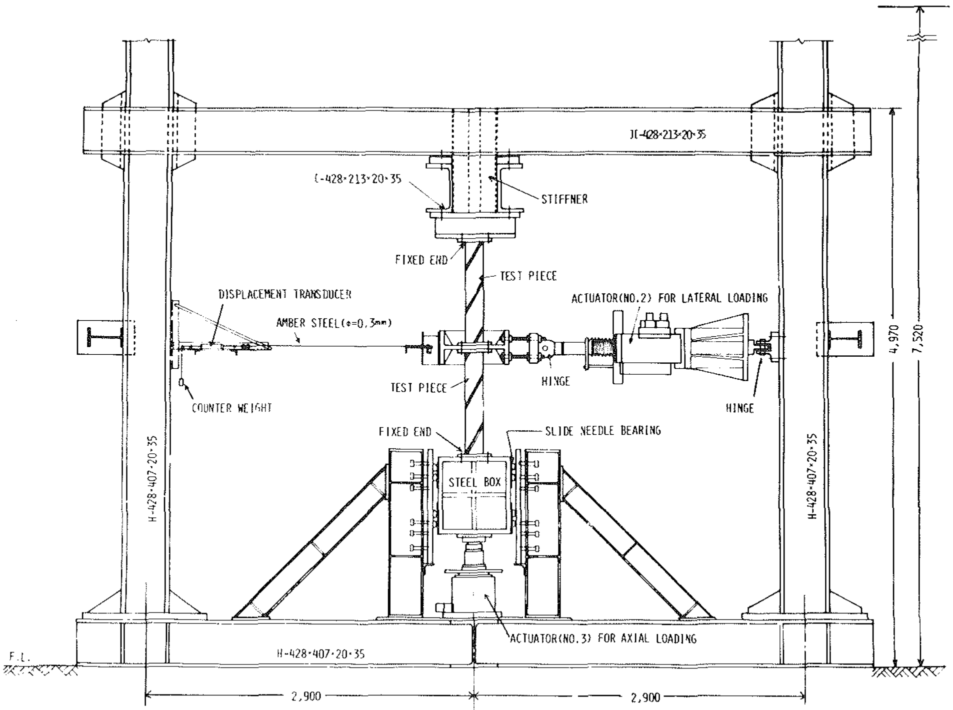


Fig. 1 Test Setup

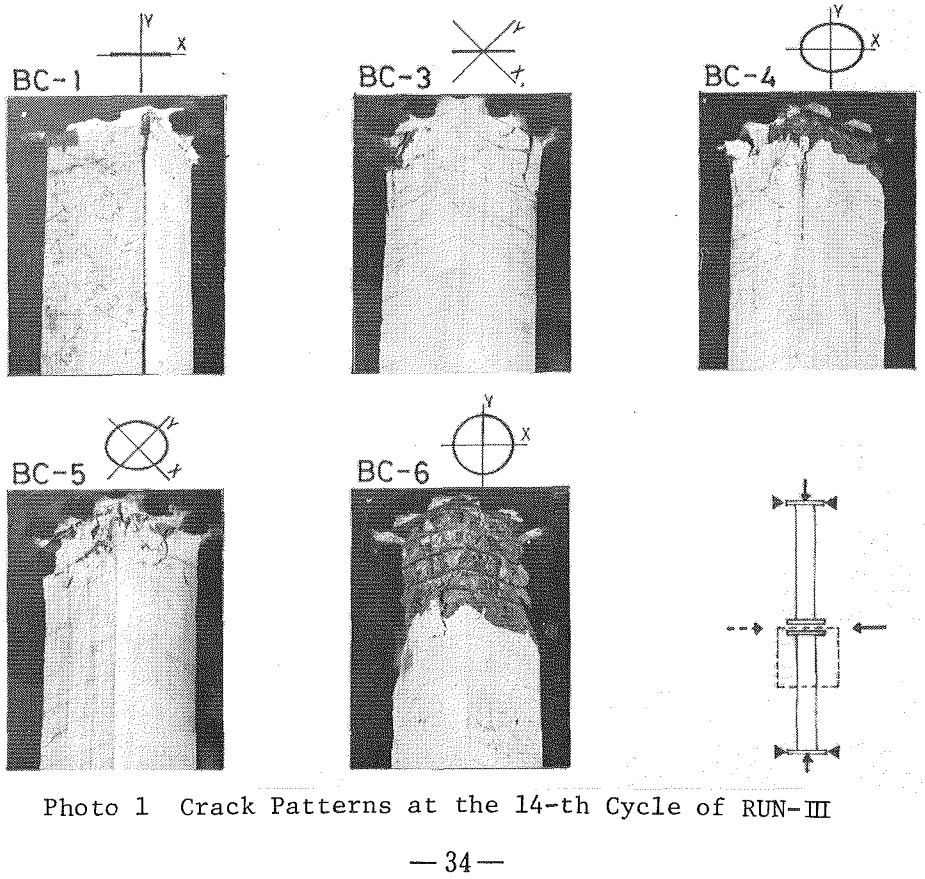
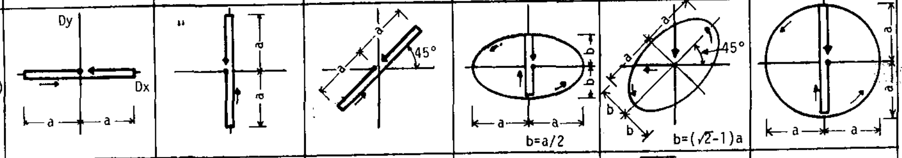


Photo 1 Crack Patterns at the 14-th Cycle of RUN-III

Table 1 Displacement Traces and Number of Cyclic Loading

TEST PIECE		BC - 1	BC - 2	BC - 3	BC - 4	BC - 5	BC - 6
DISPLACEMENT HISTORY $D_x=A\cdot\sin(\omega t+\phi)$ $D_y=B\cdot\sin(\omega t)$							
A		a	0	$a/\sqrt{2}$	a	$\sqrt{2-\sqrt{2}}\,a$	a
B		0	a	$a/\sqrt{2}$	a/2	$\sqrt{2-\sqrt{2}}\,a$	a
ϕ		-	-	0°	90°	45°	90°
RUN	a (RADIAN)	CYCLES NUMBER (SUM)	CYCLES NUMBER (SUM)	CYCLES NUMBER (SUM)	CYCLES NUMBER (SUM)	CYCLES NUMBER (SUM)	CYCLES NUMBER (SUM)
I	3 mm. (1/300)	1	1	1	1	1	1
II	7 mm. (1/125)	6 (7)	7 (8)	6 (7)	6 (7)	6 (7)	6 (7)
III	14 mm. (1/60)	31 (38)	11 (19)	31 (38)	31 (38)	31 (38)	14 (21) COLLAPSE
IV	20 mm. (1/45)	30 (68)	STOP TESTING FOR UNSTABLE CONDITION OF CONTROL SYSTEM	25 (63) COLLAPSE	7 (45) COLLAPSE	4 (42) COLLAPSE	

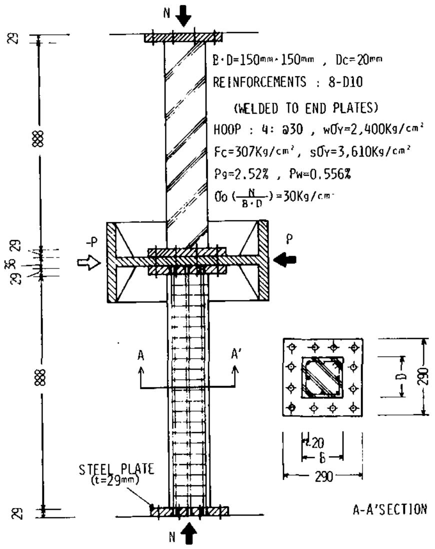
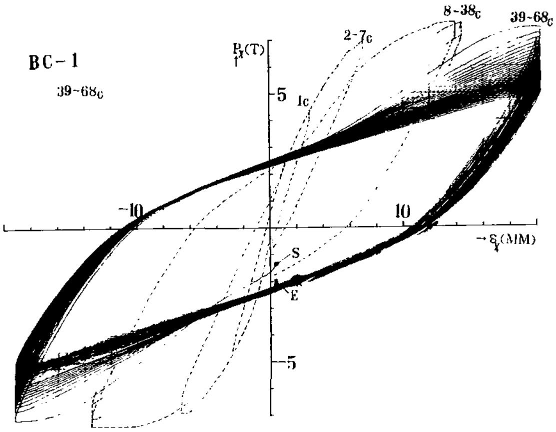
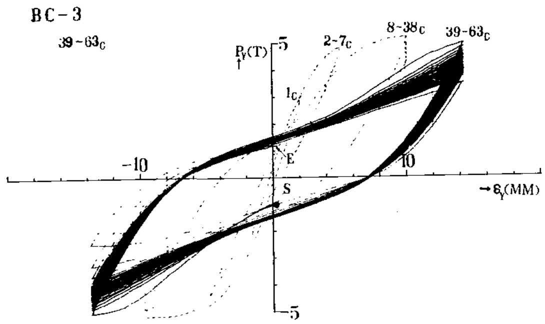


Fig.2 Detail of Test Column



a) Column BC-1



b) Column BC-3

Fig.3 Measured Force-Displacement Under Uni-Directional Loading

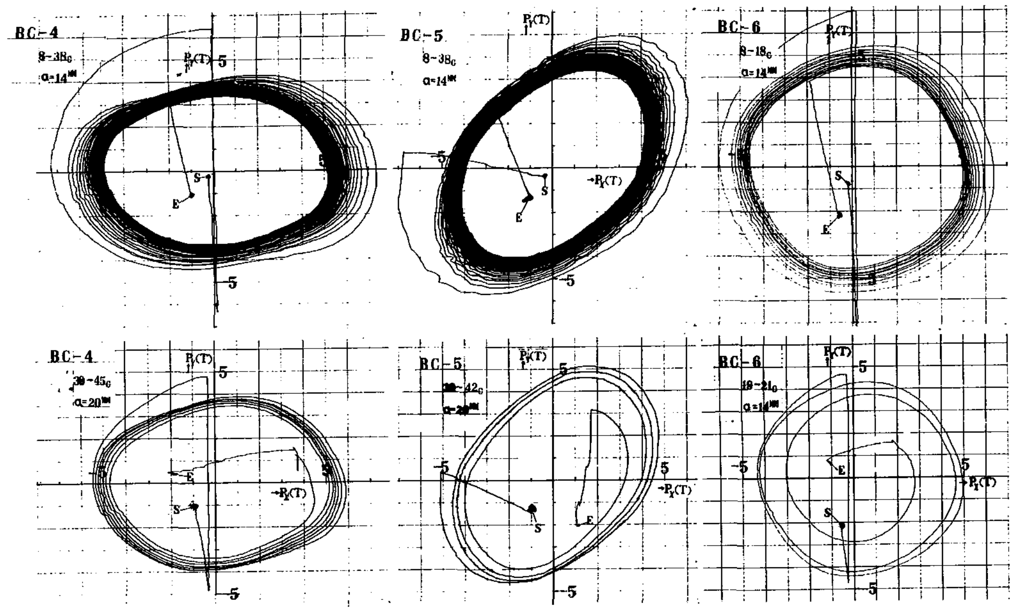


Fig.4 Measured Restoring Force Traces at RUN-Ⅲ and RUN-Ⅳ

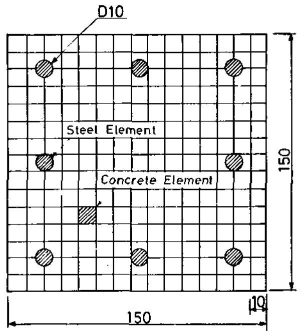


Fig.5 Finite Elements of Cross Section

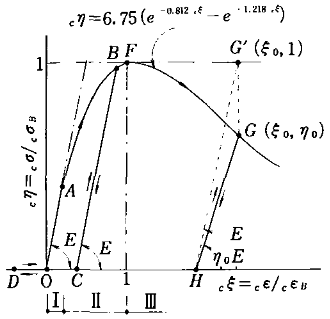


Fig.6 Stress-Strain of Concrete

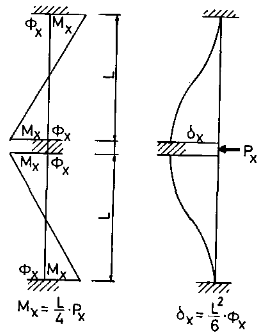


Fig.7 Assumed Moment and Curvature Distribution

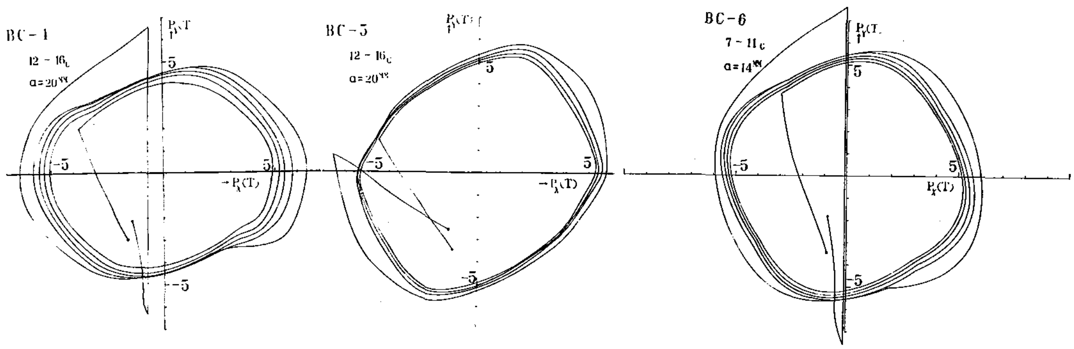


Fig.8 Examples of Computed Restoring Force Traces