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# Response characteristics of reinforced concrete columns under bi-directional earthquake motions

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ABSTRACT: The purpose of this study is to investigate the response characteristics of reinforced concrete (hereafter refers to as "R/C") columns subjected to bi-directional earthquake motions using a two-way shaking table. The elasto-plastic behavior of R/C columns under bi-directional earthquake motions were evaluated by comparing the results of two-way shaking table test with those of one-way shaking table test. Furthermore, elasto-plastic bi-directional bending analysis was carried out in order to evaluate elasto-plastic behaviors of R/C columns subjected to bi-directional earthquake motions.

## 1 INTRODUCTION

In recent years, the experimental approaches (Tatsumi, Otani et al. 1989; Takiguchi et al. 1975; Okada et al. 1977) have often been applied to investigate strength and deformation properties of reinforced concrete columns under bi-directional loads. Most of these experimental studies were performed under the static loading condition. It is pointed out from these test results that the behavior of R/C columns under bi-directional loads is characterized by the brittle fracture and thus the reduction of strengths and stiffnesses is significant. However, these behavior of R/C columns under the bi-directional bending moments has been scarcely investigated under the dynamic load.

The purpose of this study is to investigate the response characteristics of R/C columns subjected to bi-directional earthquake motions using the two-way shaking table. The shaking table tests on R/C columns failing in flexure were performed under either uni-directional input excitation or bi-directional input excitations. The actual bi-directional acceleration waves observed during the earthquake were used as the bi-directional input excitations. Then the elasto-plastic behavior of R/C columns under bi-directional earthquake motions was evaluated by comparing the results of two-way shaking table test with those of one-way shaking table test. Furthermore, the elasto-plastic bi-directional bending analysis was carried out in order to evaluate elasto-plastic behaviors of R/C columns under bi-directional earthquake motions. The observed ultimate strength and load-displacement curves of the specimen were compared with the analytical ones obtained by the fiber method.

## 2 OUTLINE OF TEST

### 2.1 Specimens and material used

The configuration and bar arrangement of the specimen are shown in Figure 1. The structural variables are listed in Table 1. The specimens are the 1/9th scaled models of the prototype structures and are so designed as to fail in flexure. The size of column section is B x D = 80 x 80 mm, the steel ratio of longitudinal main bars $P_g$ = 2.0 % (4 - D6), the steel ratio of shear reinforcement $P_w$ = 0.44 % (2.6 $\phi$ - @30) and the shear-span ratio M/QD = 3.0. Normal Portland cement, river sand and river gravel (maximum size : 10 mm) are used for concrete mix. The mechanical properties of concrete and reinforcing bars are listed in Table 2.

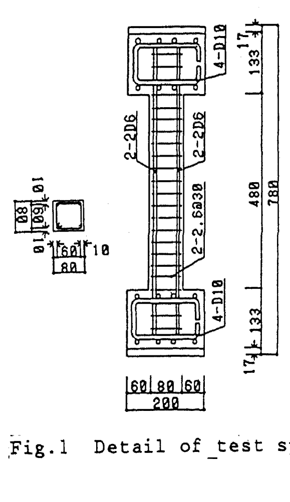



Fig.1 Detail of test specimen

## 2.2 Test equipment

The two-way shaking table, which can move hoirizontally in two directions simultaneously, is used in order to reproduce bi-directional earthquake motions. The test equipment is schematically shown in Figure 2. The plan and elevation of test equipment are shown in Figure 3. The specimen was modeled as the single-mass system, which is allowed to deflect only in the two horizontal directions. The steel weight of 22.8 kN was attached at the top of column specimen. In order to restrain the vertical and horizontal movements due to rotation of the weight, four pin-supported columns and horizontal pantograph were inserted in between the table and the weight and between the steel frame settled on the shaking table and the weight, respectively. As a result, the horizontal movement of the weight can be assured and the vertical displacement of the specimen can be restrained. The quantities and devices for measurement are as follows:

1. Relative displacement of specimen: Laser Sensor of untouched type (Figure 4)
2. Moment and Axial force at the top and bottom of column: Load Cell
3. Accelerations of mass weight and shaking table: Accelerometers
4. Strains of longitudinal bars at the top and bottom of column: Strain gauges

The sampling of measurements was made at an interval of 1/200 sec over the time duration of 20 sec. Note that the restoring force for the specimen shall be the shearing force calculated from the bending moments measured at the top and bottom of column.

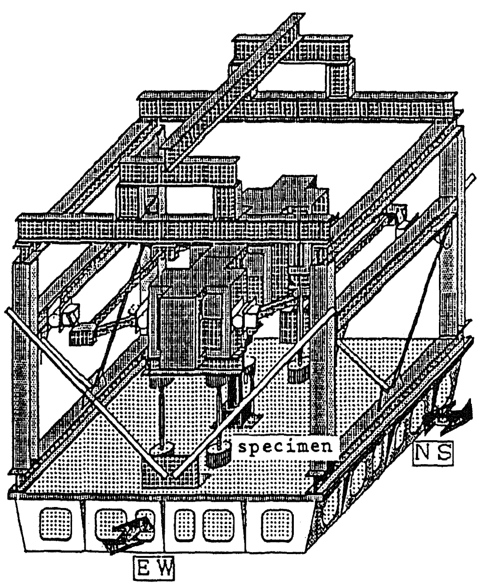



Fig.2 Test setup

Table 1 Structural variables

| Main Bar (Pg %) | Hoop (Pw %) | Shear-Span Ratio | Axial-Force Ratio |
|---|---|---|---|
| 4-D6 | 2.8φ-@30 | M/QD | N/BDFc |
| (2.0) | (0.44) | 3.0 | 0.14 |

Table 2 Mechanical properties

| Concrete | Steel Bar : D6 | |
|---|---|---|
| Copmpressive Strength | Yeild Strength | Yeild Strain |
| 25.9 MPa | 424.6 MPa | 2083 μ |

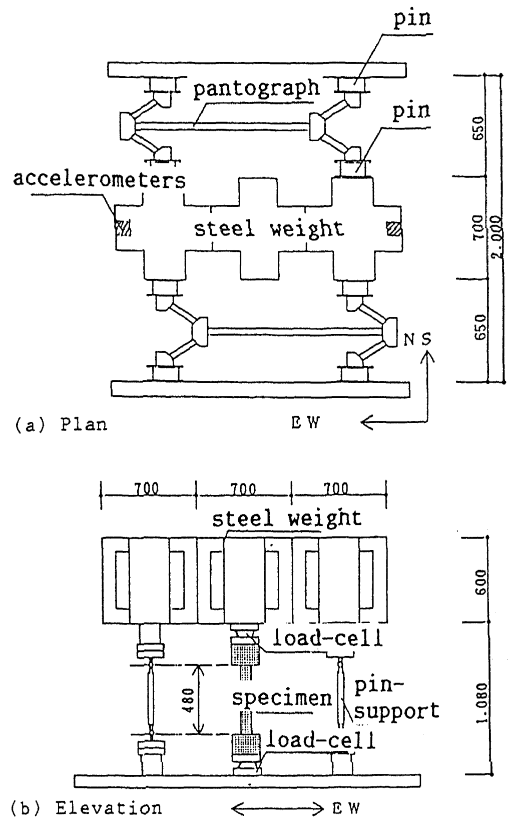



Fig.3 Plan and elevation of test setup

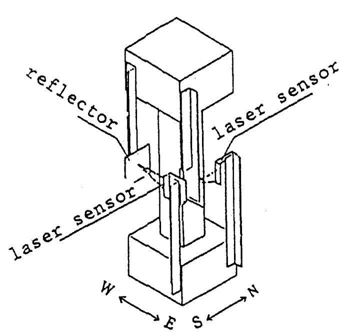



Fig.4 Measurement of relative displacement

## 2.3 Test program and input earthquake motions

The variable parameters of test and the input earthquake motions are listed in table 3. Six test specimens were prepared and they have the same dimensions and details. The ground motions used in the test were the Hachinohe NS and/or EW record(s) of 1968 Tokachi-Oki earthquake with the time duration of 30 sec. The test was carried out for two input excitation levels; that is, the elastic level in which the response of member remains within an elastic range and the elasto-plastic level in which the response of member reaches up to an elasto-plastic range. The input excitations for both cases were obtained by modifying the original excitations according to the similitude law.. The maximum accelerations for the elastic level test were 0.69 $m/sec^2$ for NS direction and 0.57 $m/sec^2$ for EW direction. On the other hand, the maximum accelerations for the elasto-plastic level test were 3.44 $m/sec^2$ for NS direction and 2.83 $m/sec^2$ for EW direction. The specimens of elastic level test are designated as EDX, EDY and EDXY and those of elasto-plastic level as DX, DY and DXY, where X corresponds to NS, Y to EW and XY to bi-direction.

Figure 5 shows the comparison between the time histories of acceleration waves of NS direction for the uni-directional and bi-directional motions measured on the shaking table. The agreement is fairly good and the good agreement was also observed for those of EW direction.

## 3 TEST RESULTS OF ELASTIC LEVEL

The maximum response values of uni-directional movements (NS direction: EDX, EW direction: EDY) and bi-directional motions (EDXY) are listed in Table 4. Figures 6 shows the comparison between the time histories of response displacements for the uni-directional and bi-directional movements. Although there are some differences between the maximum response values for EDX (or EDY) and EDXY, the correlations over all time history is relatively good. It was confirmed that the superimposed results of response values for EDX and EDY coincide with those of EDXY.

## 4 TEST RESULTS OF ELASTO-PLASTIC LEVEL

### 4.1 Final crack pattern

The final crack patterns of DY and DXY are shown in Figure 7. The flexural cracks were formed at the top and bottom of column in both specimens. The specimen DXY was severely damaged in the southeast (SE) and northwest (NW) corners of column in compari-

Table 3 Test program and input excitation

| Specimen | Input Level | Direction and Max.acc. |
|---|---|---|
| EDX | elastic | NS : 0.69 $m/sec^2$ |
| EDY | elastic | EW : 0.57 $m/sec^2$ |
| EDXY | elastic | NS : 0.69 $m/sec^2$<br>EW : 0.57 $m/sec^2$ |
| DX | elasto-plastic | NS : 3.44 $m/sec^2$ |
| DY | elasto-plastic | EW : 2.83 $m/sec^2$ |
| DXY | elasto-plastic | NS : 3.44 $m/sec^2$<br>EW : 2.83 $m/sec^2$ |

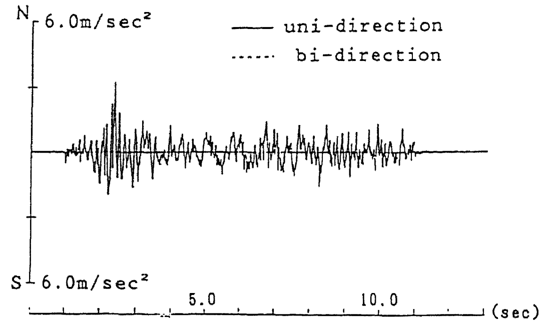


Fig.5 Measured acceleration of shaking table (NS direction)

Table 4 Maximum response values

| Specimen | EDX | EDY | EDXY | |
|---|---|---|---|---|
| Direction | NS | EW | NS | EW |
| Max.Input acc. ($m/sec^2$) | 0.67 | 0.50 | 0.73 | 0.52 |
| Max.Response acc. ($m/sec^2$) | 1.28 | 1.11 | 1.04 | 1.08 |
| Max.Displacement (mm) | 0.56 | 0.50 | 0.45 | 0.55 |
| Max.Shearing force (kN) | 2.54 | 2.62 | 2.30 | 2.59 |

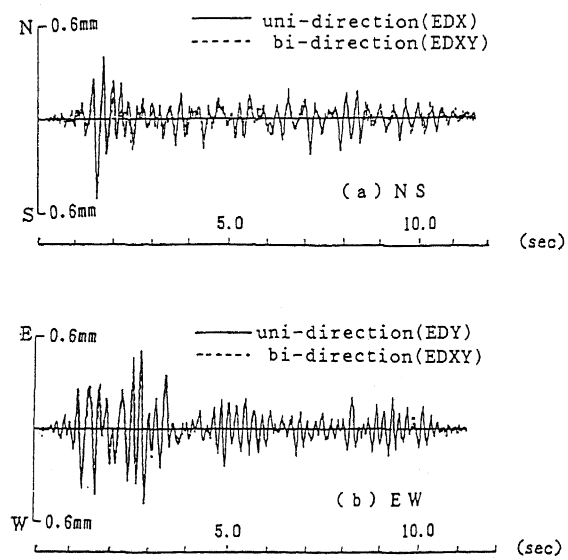


Fig.6 Time histories of response displacement

son with DX (or DY); that is, concrete crushing at the top and bottom of column, flexural-shear cracks at the north (N) and south (S) sides and splitting bond cracks of cover concrete along longitudinal bars at the S side were observed. Furthermore, it is interesting to note that no crack was observed in the case of DX, in spite of the fact that this specimen experienced the response level that the longitudinal bars were on the point of yielding.

## 4.2 Maximum response values

The maximum acceleration measured on the shaking table and the maximum response values are listed in Table 5. There are some differences between the maximum response displacements of DX (or DY) and DXY. On the other hand, the maximum response accelerations and maximum response shearing forces for DX (or DY) and DXY were almost similar to each other. These test results were different from those of elastic level tests in which the response-values for the bi-directional movements can be estimated by superimposing the response values for each uni-directional movement. Therefore, it is considered that the interaction of bi-directional movements has much influence on the strength and ductility of specimen.

## 4.3 Time histories of response displacements and response hysteresis curves

The time histories of response displacements and the response hysteresis curves of DX and DY are compared with those of DXY in Figures 8 and 9, respectively. The response characteristics of DX and DY are very different from those of the corresponding directions for DXY. As is seen from the comparison between the response displacements of DX and DXY as shown in Figure 8(b), they are similar to each other from the beginning through 2.0 sec. After that, the response values of DXY increased in comparison with those of DY and significant residual displacement was observed. On the other hand, the response of DXY in the NS direction is different from that of DX as shown in Figure 8(a); that is, the response displacements of DXY increased in the S direction at the initial stage and the subsequent response displacements were also large. Furthermore, it is seen from the comparison between the time histories for each direction that the natural periods of the specimens are extending after the maximum response displacement. This indicates that the stiffness reduction of specimen is severe in comparison with that of the uni-directional test. Similar tendency was also observed on the response hysteresis curves; that is, the stiffness reduction in the NS direction occurred due to the plasti-

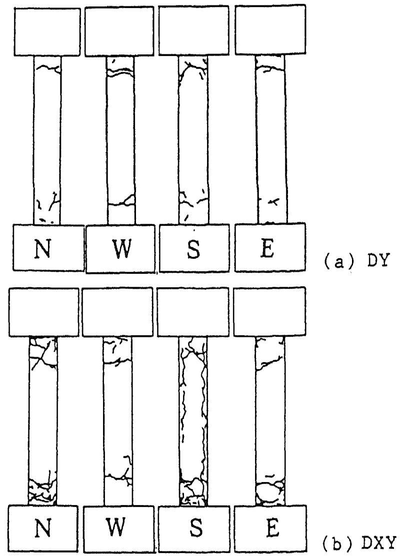



Fig.7 Final failure pattern

Table 5 Maximum response values

| Specimen | DX | DY | DXY | |
|---|---|---|---|---|
| Direction | NS | EW | NS | EW |
| Max.Input acc. (m/sec²) | 3.23 | 2.39 | 3.25 | 2.39 |
| Max.Response acc. (m/sec²) | 5.02 | 5.45 | 5.30 | 5.04 |
| Max.Displacement (mm) | 4.8 | 6.6 | 10.1 | 9.4 |
| Max.Shearing force (kN) | 11.17 | 12.35 | 11.18 | 11.80 |

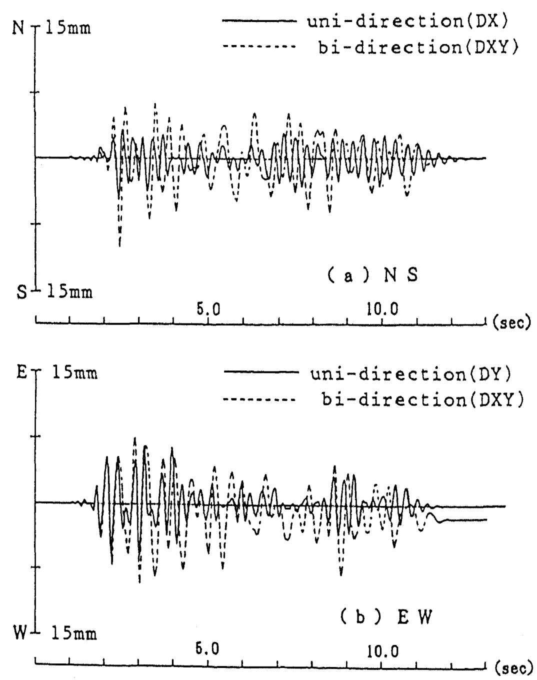



Fig.8 Time histories of response displacement

fication in the EW direction and the maximum response shearing force was observed with the sudden increase of response displacement. *The* strength reduction in the EW direction occurred after the maximum response shearing force.

## 5 ELASTO-PLASTIC BI-DIRECTIONAL BENDING ANALYSIS

### 5.1 Analytical procedure

The adopted analytical procedure is the fiber method which was extended to the bi-directional bending problem(Kanda, Shirai & Adachi et al. 1988; Kitajima, Adachi, Kanda & Koizumi 1991). The R/C member is discretized into l segments along the member axis and m along Y direction and n along Z direction as shown in Figures 10 and 11. The axis of coordinate, the member end forces and deformations and the deformations of the section are assumed as shown Figure 10. In each slice, it is assumed that the plane section remains plane after deformation. The stress~strain relationship of each fiber element is assumed to be uni-axial and non-linear. The stress-strain relationships for concrete and reinforcing bars are evaluated by applying the Endochronic theory (Bazant et al. 1976) and the model proposed by Ciampi et al. 1982, respectively.

### 5.2 Comparison between test and analytical results

The proposed analytical procedure is applied to evaluate flexural strength envelope of the column test specimens under bi-directional loading. The analysis was performed for 6 combinations of bi-directional loads; that is, the adopted ratios of applied incremental horizontal displacements in the east-west direction to those in the north-south direction were 1:0, 1:0.2, 1:0.4, 1:0.6, 1:0.8 and 1:1. Figure 12 shows the comparison between the trace of observed shearing forces for the test specimen and the calculated flexural strength envelope. The axial force fluctuated during the testing process because the vertical displacement of the specimen was restrained by the pin-supported rods inserted to restrain the rotation about the horizontal plane of the weight. The analysis was carried out for the axial force that was set equal to the maximum value (N = 45.77 kN) of fluctuating axial forces. It seems that the trace of shearing forces near the maximum response in the test agree well with the analytical results.

Furthermore, the observed load-displacement curves of the specimen was compared with the analytical ones obtained by the fiber method. The load-displacement curves

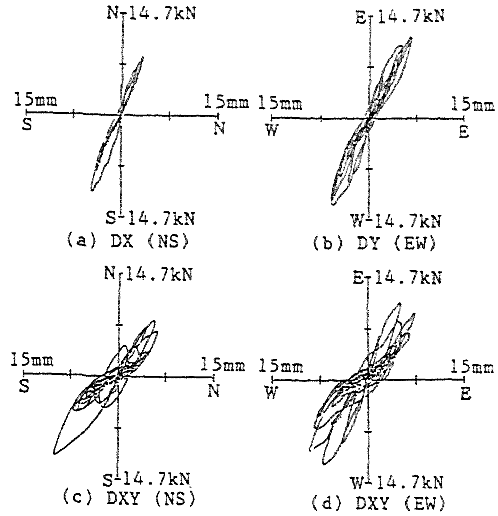



Fig.9 Response hysteresis curves

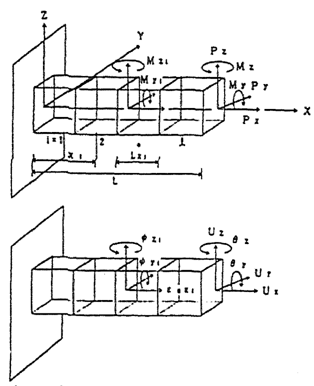



Fig.10 Discretization of member

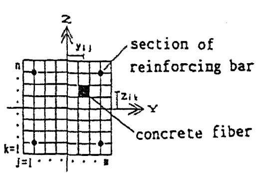
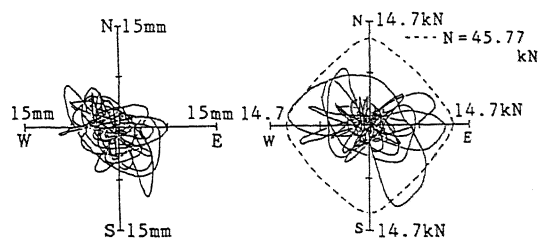



Fig.11 Discretization of section




(a) Trace of displacement (b) Trace of shearing force

Fig.12 Trace of shearing force and displacement were obtain from the static loading test which were controlled by imposing the response displacement histories observed from the shaking table test for DXY(Adachi, Nakanishi et al. 1990). The specimen was modeled as a cantilever column which was loaded in such a way that the inflection point is at the center of span. The element discretization was decided in light of the results of the previous investigation (Kanda, Shirai & Adachi et al. 1988). The analysis was carried out by applying the incremental axial force first, and then applying the incremental horizontal displacement observed by the tests. The axial force fluctuated during the testing were considered in the analysis. Figure 13 shows the comparisons between the predicted and observed load-displacement curves. It seems that the predicted hysteretic behaviors agree well with the test results. But, the predicted swelling of loops differed from the observed one. This may be due to the difference between the resistance mechanism predicted by the analysis and that observed by the test. In the test, the bond splitting cracks were observed in an early stage of loading. On the other hand, the bond splitting cracks were not considered in the analysis.

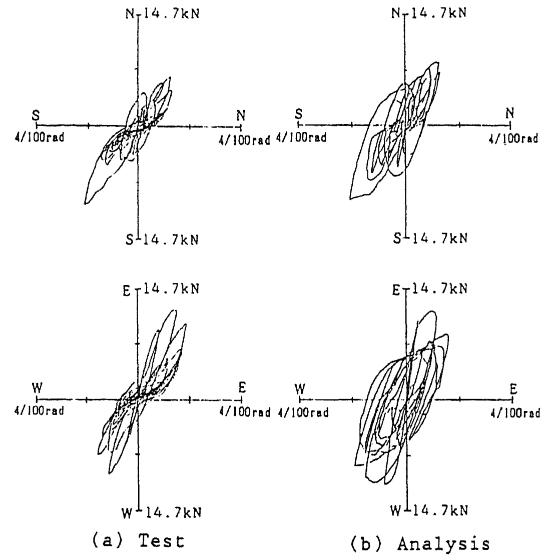



Fig.13 Load - displacement curves

## 6 CONCLUSIONS

The two-way shaking table tests were performed to investigate the behavior of R/C columns subjected to the bi-directional excitations, and the conclusions obtained through this study can be summarized as follows.

1. The Strengths and stiffnesses of R/C columns subjected to bi-directional excitations decrease in comparison with those under uni-directional excitations.
2. From the trace of shearing forces and displacements observed in the tests, it was recognized that the plastic flow occurred at the critical section of R/C columns.
3. The natural period of the R/C columns was extended under the bi-directional excitations. And these response characteristics differed from those under the uni-directional excitations.
4. The strengths of R/C columns under the bi-directional bending moments calculated by the fiber method agreed well with the test results.
5. From the behaviors obtained by the bi-directional bending analysis, it was recognized that the bond slip and shearing displacement can not be ignored.

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