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REINFORCED CONCRETE COLUMNS UNDER VARYING AXIAL LOAD AND BI-DIRECTIONAL LATERAL LOAD REVERSALS

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SUMMARY

A series of quarter-scale reinforced concrete columns were tested under varying axial load and bi-directional load reversals. The axial load was varied proportional to the lateral resistances of the column. An interaction among the triaxial resistances was clearly observed in the test. The columns were simulated by using Multi-Spring model (Ref.4). The results using the analysis model was shown to adequately simulate the behavior of the columns if a proper set of the parameters were selected for the component springs of the model.

INTRODUCTION

The behavior of reinforced concrete (RC) columns under earthquake loads has been studied by many investigators (for example, Refs. 1,2,3); in most cases, under a constant axial and uni-directional lateral loads. However, exterior and corner columns of a frame structure are subjected to varying axial load due to the earthquake overturning moment in addition to bi-directional lateral load reversals. The interaction between bi-directional lateral loads and varying axial load should be taken into account. A series of quarter-scale RC columns were tested under varying axial load and bi-directional lateral load reversals (Ref.5). A simple analytical model developed by Lai, Will and Otani (Ref.4) was employed to simulate the behavior of the columns.

SUMMARY OF TEST PROGRAM

Seven identical specimens (Fig.1) of quarter-scale (200x200mm section, 570 mm high) were tested (Ref.5), representing a part from the base to an arbitrarily assumed inflection point of a first-story column. Each column was reinforced by 8-D10 bars (D10: sectional area of 71.33 mm^2, yield strength of 418 MPa) and D6 hoops (D6: sectional area of 31.67 mm^2, yield strength of 386 MPa) at 50 mm. A vertical load and reversing bi-axial horizontal loads were applied on the top of a specimen by three servo-controlled actuators. The lateral displacement path for biaxial loading is shown in Fig.2 for the biaxial horizontal loading. Two cycles were repeated at each displacement amplitude of approximately 3/1000, 1/200, 3/200, 3/100 of the column height.

The properties of the specimens are listed in Table 1. The alphabet in a specimen name stands for the lateral loading direction; i.e., U for uni-directional loading and B for bi-directional loading. The first numeral indicates

Table 1 Test Specimens and Loading

Specimen Name	Lateral Load	Gravity Axial Stress Ratio	Axial Stress Range	Concrete Strength(MPa)
U8-0	Uniaxial	0.07	0.07	27.1
U8-1	Uniaxial	0.07	0.0 - 0.13	27.1
B8-0	Biaxial	0.07	0.07	27.1
B8-1	Biaxial	0.06	0.0 - 0.13	30.8
B8-2	Biaxial	0.06	-0.06 - 0.19	30.8
B40-1	Biaxial	0.32	0.19 - 0.45	30.8
B40-2	Biaxial	0.32	0.13 - 0.52	30.8

the level of gravity axial load in ton. The second numeral indicates the variation of vertical load; i.e., 0 (interior columns) for a constant axial load, and 1 (exterior columns) for variation of axial load only during the principal lateral loading, and 2 (corner columns) for variation of axial load during all lateral loading. An axial stress ratio is defined as axial stress level normalized by the concrete compressive strength. An axial stress range was defined as the range of the axial stress ratio varied during the test. The gravity axial stress ratio was selected for the axial load in a first-story column of an imaginary eight-story structure. The axial load was varied proportional to the column lateral resistance.

Lateral and axial displacements at top and base of the column specimen, footing rotation, and flexural rotation at the column base over a distance of two-thirds of effective depth of the column section were measured by strain gauge-type displacement transducers. Axial and lateral loads were measured by load cells in the actuators. The column lateral resistance was corrected for the secondary effect (P-delta effect).

A more significant degradation in stiffness and resistance was observed in specimens subjected to biaxial lateral loading than in the specimens subjected to uniaxial lateral loading for varying axial load of comparable amplitudes (Fig.3). The corner column specimens (B8-2, B40-2), subjected to larger variation of axial load during lateral loading, deteriorated earlier and more severely than the exterior column specimens (B8-1,B40-1). Under varying axial load, the resistance and stiffness was observed to increase with compression load, and decrease with decreasing axial load, the phenomenon which may be demonstrated by comparing the hysteresis relations of Specimens B8-0 and B8-2 (Fig.4). Numbers 1 to 7 indicate the displacement positions in Fig.2, and the numbers in brackets indicate the axial load in kN of the specimen B8-2. The difference in lateral resistances of the two

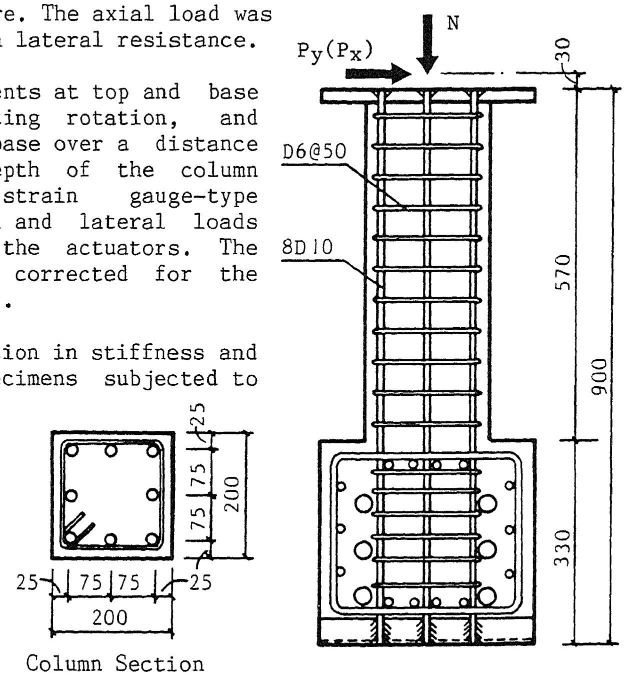


Fig.1 Test Specimen (Unit in mm)

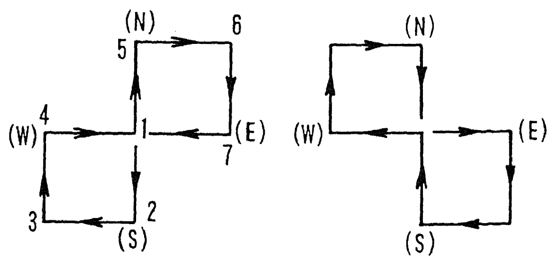


Fig.2 Displacement Path

specimens at points 3 and 6 is attributed to the difference in axial load levels. In Specimen B8-0, the lateral resistance in NS direction was reduced from point 5 to 6 during loading in EW direction, the phenomenon which was called a "biaxial bending interaction (Ref.1)." The interaction was further complicated by the change in axial load in Specimen B8-2; i.e., during reloading from points 6 to 7 in NS direction, accompanied by reduction in axial load, a larger reduction was observed in the lateral resistance in EW direction. A smaller reduction in resistance was observed from points 3 to 4 when the axial load increased during orthogonal loading. This phenomenon may be called a "triaxial interaction of varying axial load and biaxial bending."

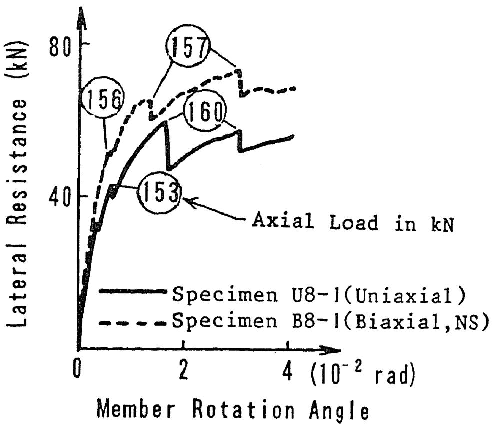


Fig.3 Effect of Biaxial Loading on Resistance

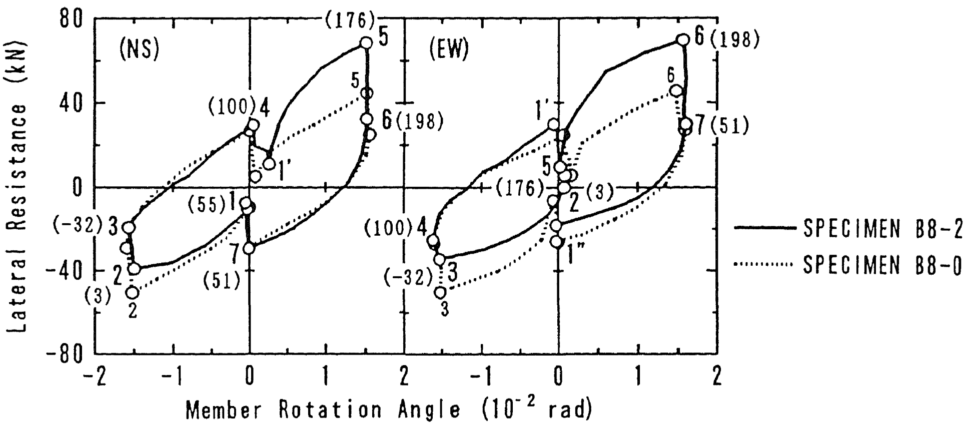


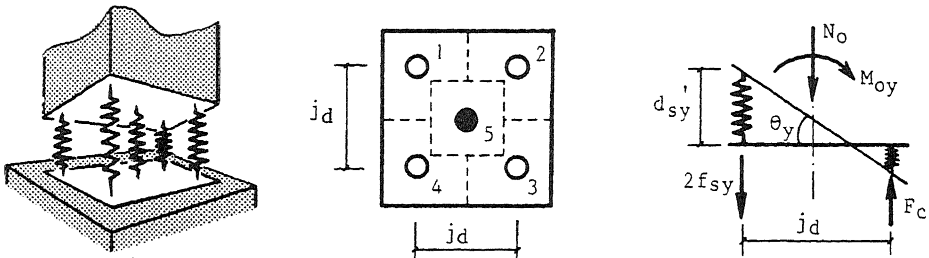
Fig.4 Effect of Varying Axial Load on Resistance

ANALYSIS MODEL AND RESULTS

The analysis model (Multi-Spring Model) developed by Lai, Will and Otani (Ref.4) was used to analyze the columns. The model assumes all inelastic flexural rotation to concentrate in an inelastic component at the column base. The inelastic component (Fig.5) consists of five uniaxial springs; i.e., four corner springs representing the stiffness of the reinforcing bars and concrete, and one center spring representing the stiffness of concrete (Ref.6). The plane section was assumed to remain plane after deformation.

The parameters of the Multi-Spring Model such as yield strength, yield deformation, and location of each spring must be defined by the column section and material properties. The yielding force of a steel spring, f_{sy}, was calculated as suggested by Ref.4. Other parameters were determined as follows. The yield compressive force of a concrete spring, f_{cy}, was evaluated by Eq.(1):

$$f_{cy} = f'_c A_c/5 \qquad (1)$$



(a) (b) (c)

○ Steel and Concrete Spring at Corner

● Center Concrete Spring

Fig.5 Multi-Spring Model

where, f'_c = concrete compressive strength; A_c = concrete section area. The distance between the corner springs, j_d, controls the resistance of a column, and must be determined to reflect the column properties. The resistance calculated by the model is roughly proportional to the axial force level below the balanced point B in Fig.6. Therefore, the distance j_d was determined from the flexural resistance M_{oy} at the gravity axial load level N_o by Eq.(2):

$$j_d = \frac{M_{oy}}{N_o/2 + 2f_{sy}} \qquad (2)$$

Note that there exist some discrepancy between the resistances calculated by an exact section analysis method and by the proposed method near the balanced point. Yield deformation of the steel spring, d'_{sy} was determined by assuming all the member inelastic flexural rotation to concentrate at the column base (Fig.5.c). The elastic bond slip of the longitudinal reinforcing bar was taken into consideration in the steel tensile yield deformation, d_{sy} (Eq.4):

$$d'_{sy} = \frac{\theta_y \cdot j_d}{1 + \dfrac{N_o + 2f_{sy}}{2f_{sy} + 2f_{cy}}} \qquad (3)$$

$$d_{sy} = 0.5\sigma_y \cdot L_d/E_s + d'_{sy} \qquad (4)$$

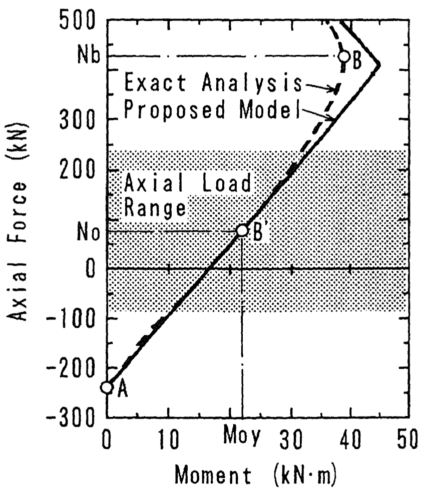


Fig.6 Comparison of the Model and Exact Analysis Interaction Diagram

where, σ_y= yield strength of steel; L_d= anchorage length (Ref.4); E_s= elastic modulus of steel; θ_y= inelastic rotation angle concentrated at the column base. θ_y was evaluated by assuming a triangular curvature distribution from the column base to the top with the yielding curvature developed at the column base. The yielding displacement of a concrete spring was assumed the same as that of a steel spring. The parameters evaluated are listed in Table 2 for Specimens B8-0, B8-1 and B8-2.

Table 2 Parameters of analysis model (unit in kN, mm)

Specimen	f_{sy}	f_{cy}	d	d_{sy}	d'_{sy}
B8-0	59.52	213.7	137.3	0.44	0.28
B8-1, B8-2	59.52	242.9	139.0	0.45	0.31

For the corner steel and concrete springs, a non-symmetrical skeleton curve

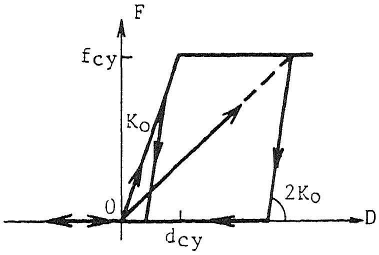
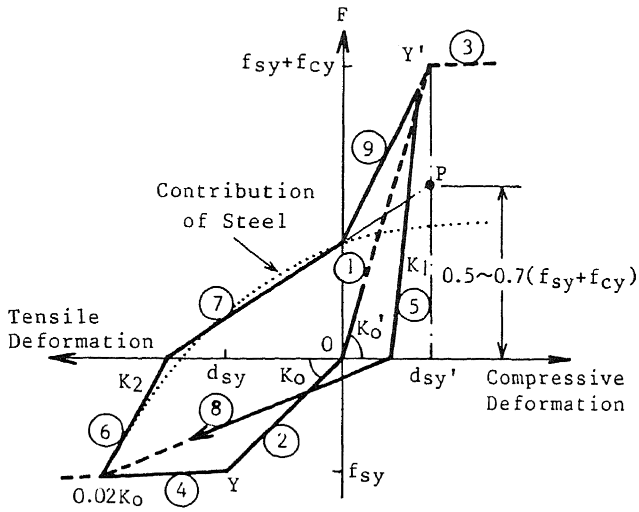


Fig.7 Hysteresis Model for Center Concrete Spring

is defined as shown in Fig.8. All hysteresis rules are similar to Takeda Model (Ref.7), but the pinching phenomenon is included because the concrete is not effective after a large tensile deformation. A simple force-deformation relation (Fig.7) was used for the center concrete spring. For concrete springs, no decay in resistance was assumed after the maximum resistance was attained.

Observed and computed lateral resistance-displacement relations are compared in Fig.9.



$$K_1 = \begin{cases} 2K'_o & (d_{max} \leqq d'_{sy}) \\ 2K'_o \, | d'_{sy}/d_{max} |^{0.4} & (d_{max} > d'_{sy}) \end{cases}$$

$$K_2 = \begin{cases} 2K_o & (d_{min} \leqq -d_{sy}) \\ 2K_o \, | d_{sy}/d_{min} |^{0.4} & (d_{min} > -d_{sy}) \end{cases}$$

Fig.8 Hysteresis Model for Corner Springs

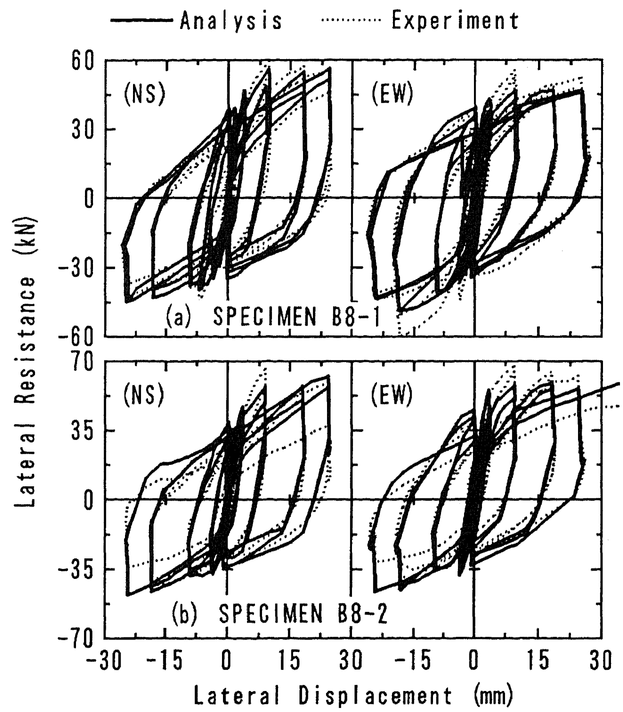


Fig.9 Analysis and Experiment Results

As a whole, the analysis results are consistent with the observed column behaviors(shown in dashed line). The non-symmetrical characteristics of the hysteresis due to varying axial load are well simulated in the analysis of Specimens B8-1 and B8-2. However, the degradation in resistance at large displacement was not simulated because the decay in concrete resistance at a large strain was not introduced in the hysteresis model.

CONCLUSIONS

A series of quarter-scale RC columns were tested under varying axial load and biaxial lateral load reversals. A non-symmetrical characteristic was observed in the columns subjected to varying axial load below the balanced load. The corner column, subjected to a large varying axial load due to biaxial earthquake overturning moment, shows less deformation capability. A complicated interaction was observed between varying axial load and bi-directional lateral loads. The interaction has a significant effect on the column behaviors.

The Multi-Spring Model was demonstrated to be simple and reliable to use in the analysis of a reinforced concrete column under varying axial load and bi-directional lateral load reversals.

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REFERENCES

1. S.Otani, V.W.-T.Cheung and S.S.Lai, "Reinforced Concrete Columns Subjected to Biaxial Lateral Load Reversals," Proceedings, Seventh WCEE, Istanbul, Turkey, 1980, Vol.6, pp.525-532.
2. S.Fujii, H.Aoyama, et al, "Experimental Study on Reinforced Concrete Columns Subjected to Biaxial Bending," (in Japanese), Proceedings, Kanto District Symposium, AIJ, No.44, 1973, pp.1423-43.
3. K.Maruyama, H.Ramirez, and J.O.Jirsa, "Behavior of Reinforced Concrete Columns under Biaxial Lateral Loading," Proceedings, Sixth European Conference on Earthquake Engineering, Dubrovnik, Yugoslavia, 1987, pp.135-141.
4. S.-S.Lai, G.T.Will, and S.Otani, "Model for Inelastic Biaxial Bending of Concrete Members," Journal, ASCE, Vol.110, 1984, pp.2563-84.
5. K.-N.Li, S.Otani and H.Aoyama, "Reinforced Concrete Column under Varying Axial Load and Bi-Direction Horizontal Load Reversals," Pacific Conference on Earthquake Engineering, Wellington, New Zealand. 1987.8.
6. G.E.Ghusn and M.Saiidi, "A Simple Hysteretic Element for Biaxial Bending of R/C Columns and Implemention in NEABS-86," Civil Engineering Department, Report No.CCEER-86-1, University of Nevada, Reno, July 1986.
7. T.Takeda, M.A.Sozen, and N.N.Nelsen, "Reinforced Concrete Response to Simulated Earthquake," Journal, ASCE, Vol.96, 1970.12, pp.2557-73.