SEISMIC PERFORMANCE OF REINFORCED CONCRETE C-BENT COLUMNS BASED ON A HYBRID LOADING TEST

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Abstract: C-bent columns have a unique seismic performance due to the eccentricity between the column center and the point where the dead load of the superstructure and the lateral inertia force apply. This results in an extensive deterioration of the flexural capacity and an increase of residual displacement. To study the effect of the eccentricity on the seismic performance of C-bent columns, a hybrid loading test was conducted.

1. INTRODUCTION

In urban areas, there exists a number of reinforced single columns with the lateral beams being longer in one side than the other. They are called C-bent columns or inversed L-shaped columns. C-bent columns are subjected to an eccentric dead load of the superstructure and the inertia force during an earthquake. As a consequence, a side of the eccentricity (side with longer lateral beam) and the other side of the eccentricity are subjected to compression and tension, respectively, due to the dead load of the superstructure. They are called hereinafter the eccentric compression side and the eccentric tension side, respectively.

To clarify the seismic performance of reinforced concrete C-bent columns, Kawashima and Unjoh conducted a shake table test (Kawashima and Unjoh 1994), and Tuchiya et al conduct a cyclic loading test (Tuchiya et al 1999). From the studies, it was found that an extensive failure occurred at the eccentric compression side of the columns and this resulted in a large residual displacement under a strong excitation. Based on a bilateral cyclic loading test on reinforced concrete C-bent columns, Kawashima et al pointed out that the restoring force deteriorates more significantly under the bilateral loading(Kawashima et al 2003).

To study the seismic response of reinforced concrete C-bent columns under a bilateral excitation, a hybrid loading test was conducted on six model columns with two eccentricities. This paper presents the experimental behavior of the models.

2. MODEL COLUMNS AND TEST PROCEDURE

Six model columns without an eccentricity and with the eccentricities of 0.5*D* and *D* (*D*: width of the columns) were constructed as shown in Table 1. They were designed in accordance with the current Japanese seismic design codes (JRA 1996) assuming that they are “small prototype” columns. They have a 400 mm×400mm square cross section with an effective height from the bottom to the

Table 1 Model Columns used in the Hybrid Loading Tests

Models	H-1	H-2	H-3	H-4	H-5	H-6
Eccentricities	0	0.5*D*	*D*	0	0.5*D*	*D*
Longitudinal Reinforcement Ratio (%)	1.27	1.35	1.9	1.27	1.35	1.9
Tie Reinforcement Ratio (%)	0.79	0.99	1.19	0.79	0.99	1.19
Concrete Strength (MPa)	28.7	32.1	31.3	31.2	29.1	28.6
Loading Type*	1			2		

*Loading Type=1: loading in the longitudinal direction using NS component of JMA Kobe record, and Type=2: loading in the bilateral direction using NS and EW components of JMA Kobe record

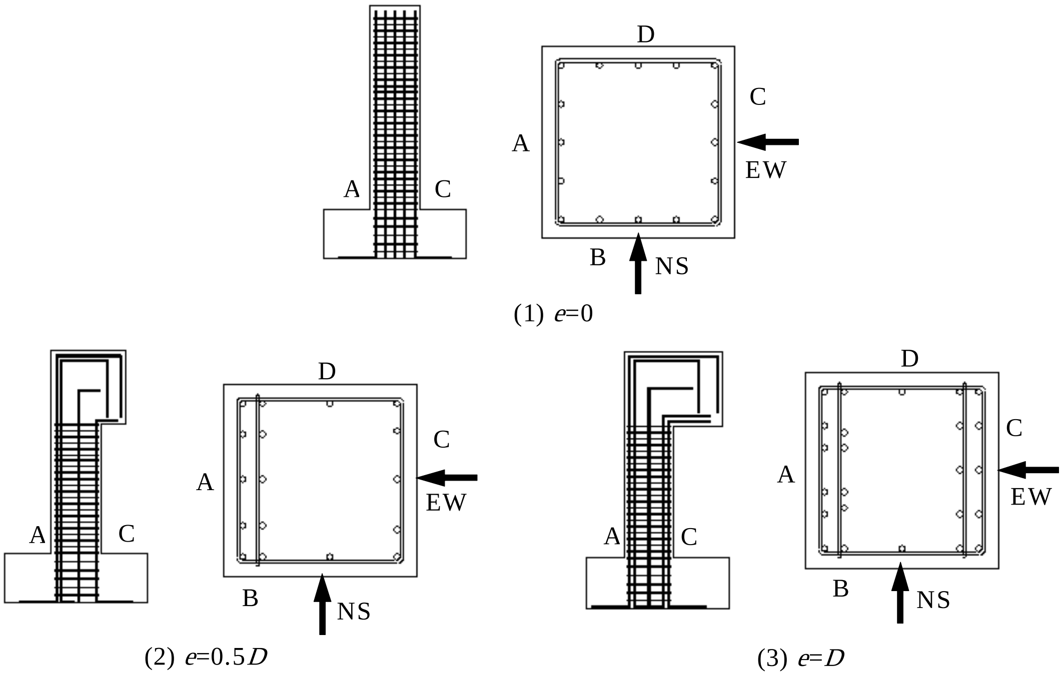
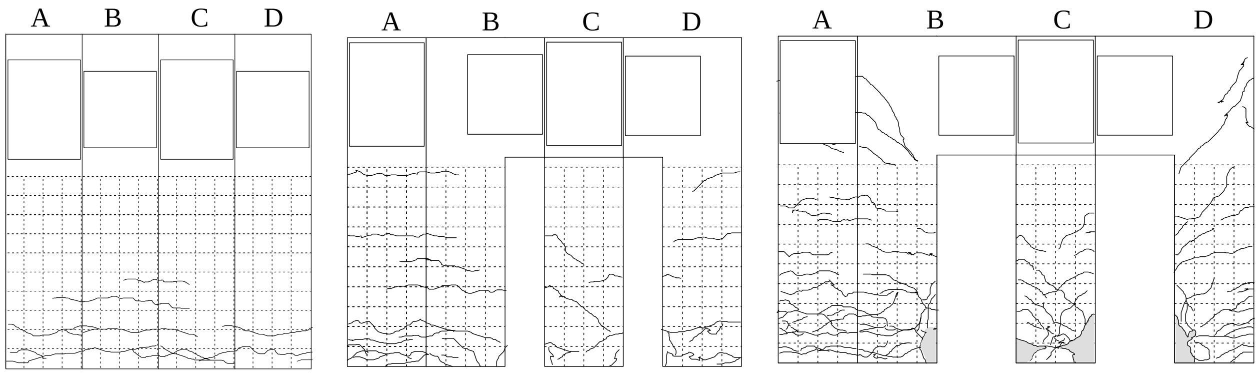


Fig. 1 Model Columns

loading point of 1350mm.

Fig. 1 shows the model columns. Deformed longitudinal bars with a 13 mm diameter (D13) are provided in double at the eccentric tension side in the column with an eccentric of 0.5*D*. On the other hand, the D13 longitudinal bars are provided in double at not only the eccentric tension side but also the eccentric compression side in the column with an eccentricity of *D*. The compression in the eccentric compression side is so large in the column with the eccentricity of *D* that the double reinforcements are required in the eccentric compression side. The longitudinal reinforcement ratio is 1.27%, 1.35% and 1.90% in the columns without an eccentricity and the columns with the eccentricities of 0.5*D* and *D*, respectively. D6 tie bars are provided at 50 mm interval for the entire column height. They are anchored by 135 degree bent hooks. Ties are provided in the inner longitudinal bars as well. The volumetric tie reinforcement ratio is 0.79%, 0.99% and 1.19% in the columns without an eccentricity and the columns with the eccentricities of 0.5*D* and *D*, respectively.

The loading test was conducted using the dynamic testing facility in the Tokyo Institute of Technology. The columns were subjected to unilateral excitation in the longitudinal direction (direction perpendicular to the eccentricity) and bilateral excitation under a constant vertical load of 160 kN, which induced a stress 1 MPa at the plastic hinge of the column. The ground acceleration recorded at JMA Kobe Observatory during the 1995 Kobe earthquake was used as an input motion by scaling down its intensity to 30% of the original. NS and EW components were used in the longitudinal and transverse directions, respectively. Since the lateral actuators in the longitudinal



(1) *e*=0 (H-1) (2) *e*=0.5*D* (H-2) (3) *e*=*D* (H-3)

Fig. 2 Damage of the Columns after the Tests under the Unilateral Excitation

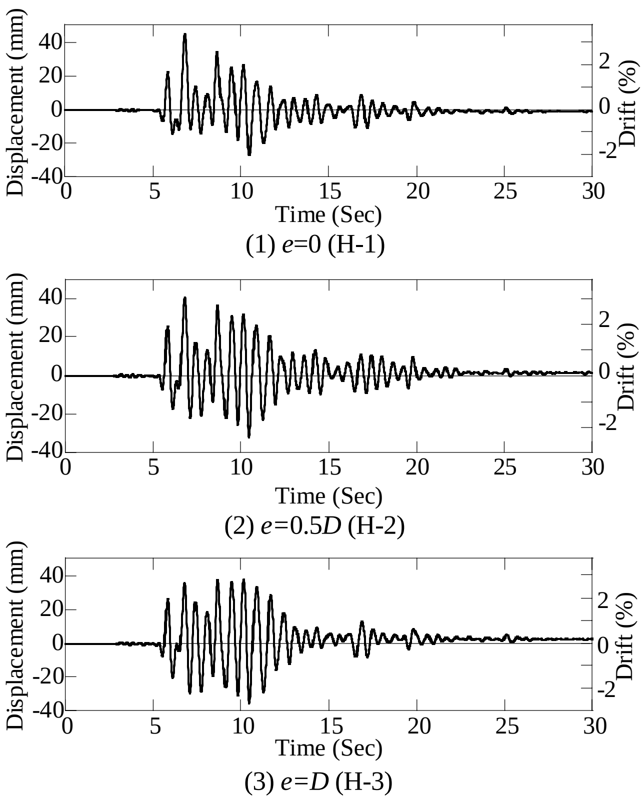


Fig. 3 Displacement Response under the Unilateral Excitation

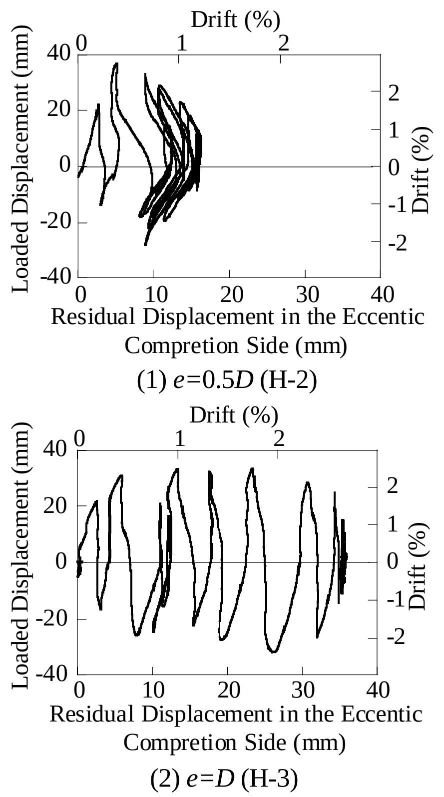


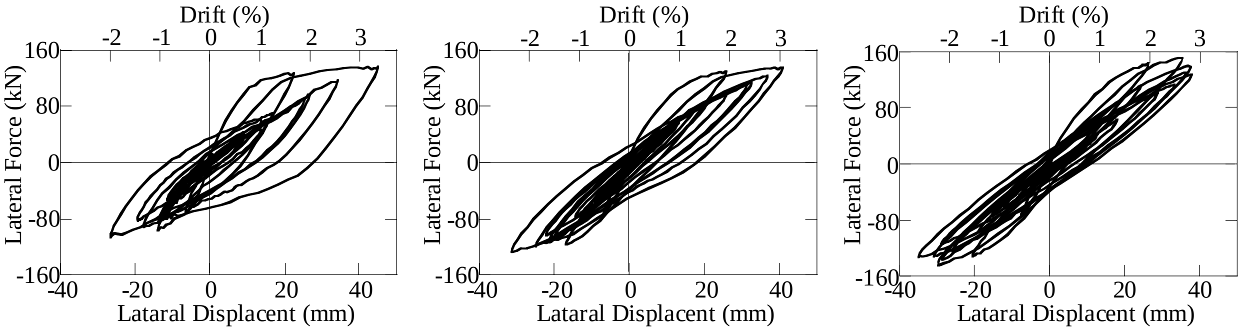
Fig. 4 Transverse Displacement of the Column under the Unilateral Excitation in the Longitudinal Direction

direction as well as the actuator in the vertical direction was set apart from the column center with an eccentricity, it is noted that a rotation occurred in the columns as a result of the eccentricity.

3. SEISMIC RESPONSE BASED ON A HYBRID LOADING TEST

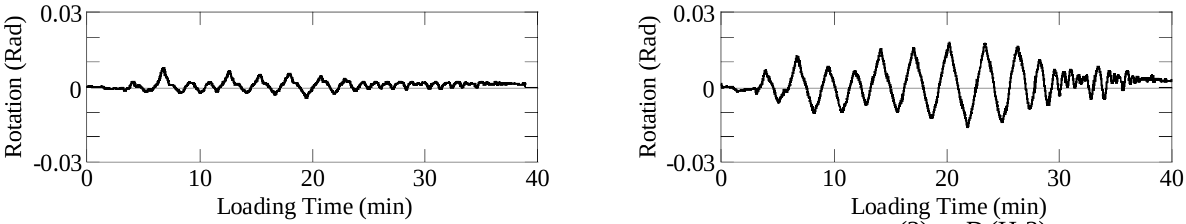
3.1 Seismic Response under Unilateral Excitation

Fig. 2 compares damage of the column without an eccentricity (H-1) and the columns with eccentricities of 0.5*D* (H-2) and *D* (H-3) after the tests. Only flexural cracks occurred at all surfaces in the columns without an eccentricity and an eccentricity of 0.5*D*, while spalling off of the covering concrete as well as flexural cracks occurred at the surface in compression side (B surface) in the



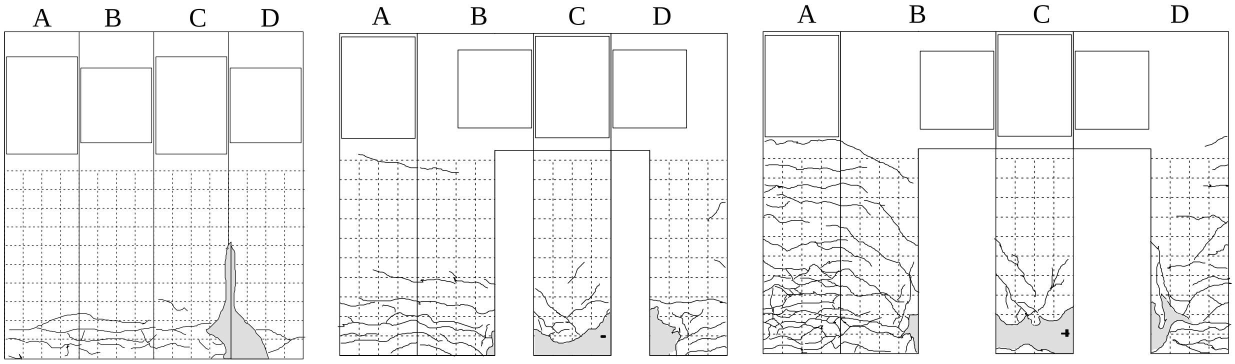
(1) e=0 (H-1) (2) e=0.5D (H-2) (3) e=D (H-3)

Fig. 5 Lateral Force vs. Lateral Displacement Hystereses under the Unilateral Excitation



(1) e=0.5D (H-2) (2) e=D (H-3)

Fig. 6 Rotations of the Columns Relative to the Footings under the Unilateral Excitation in the Longitudinal Direction



(1) e=0 (H-4) (2) e=0.5D (H-5) (3) e=D (H-6)

Fig. 7 Damage of the Columns after the Tests under the Bilateral Excitation

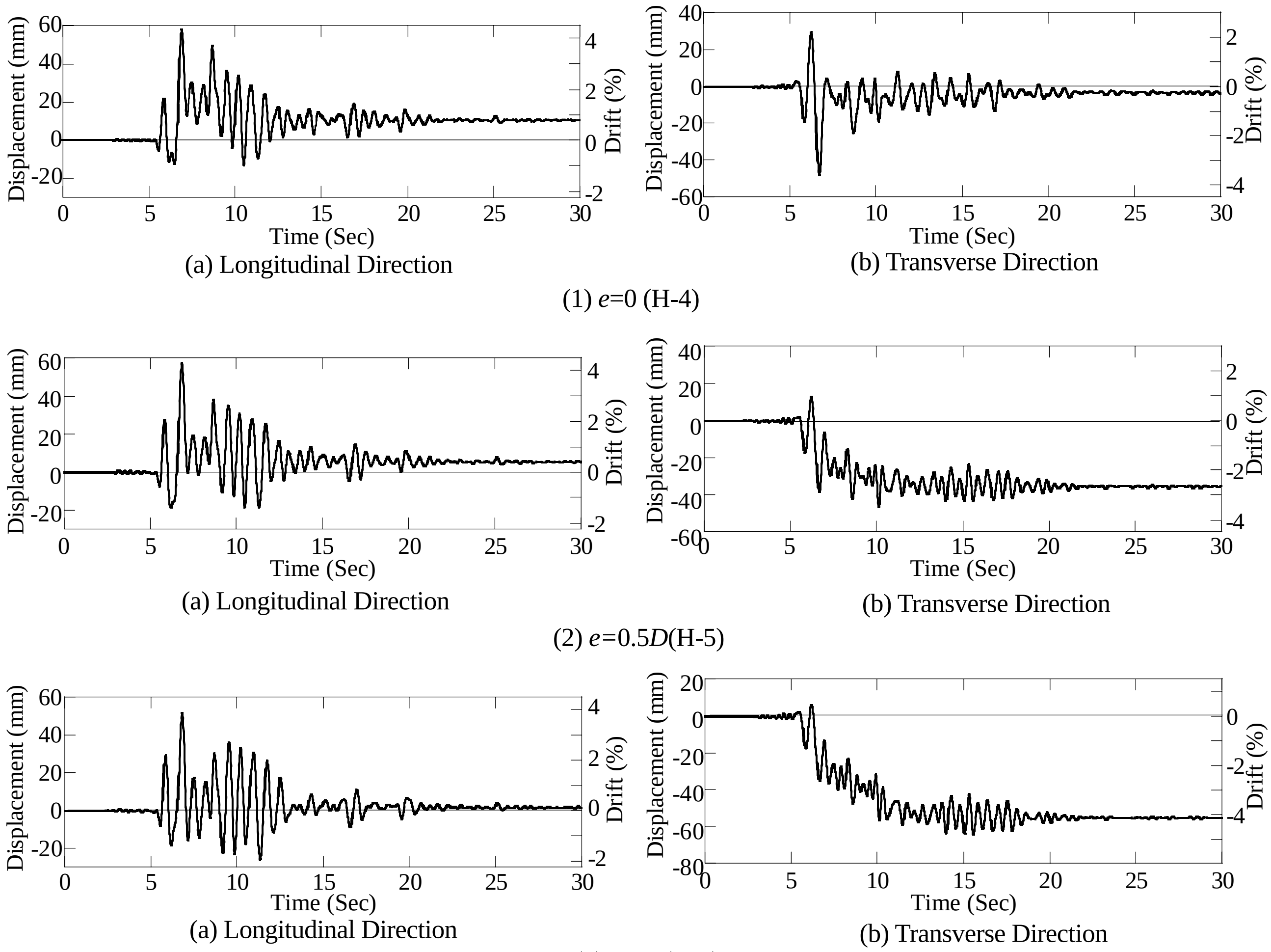
column with an eccentricity of D. Longitudinal and ties bars suffered no visible damage in the tests.

Fig. 3 shows the displacement response of the three columns. The maximum displacement was 3.4%, 3.0 % and 2.9% drift in the columns without an eccentricity and with the eccentricities of 0.5D and D, respectively. Residual drift in the longitudinal direction was not significant in the tests. A remarkable feature of the C-bent columns under the excitation in the longitudinal direction is the drifting of the columns in the eccentricity direction as shown Fig. 4. This resulted from the failure of concrete in the eccentric compression side. The residual drift reached 1.3% and 2.7% in the columns with the eccentricities of 0.5D and D, respectively.

Fig. 5 shows the lateral force vs. lateral displacement hysteresis of the columns. The maximum strength was 139.5kN, 139.6kN and 152.5kN in the columns without an eccentricity and with the eccentricities of 0.5D and D, respectively, and was stable during the entire excitations. The eccentricity resulted in rotations of the columns as shown Fig. 6. The maximum rotation was 0.008 and 0.019 radian in the columns with the eccentricities of 0.5D and D, respectively. It is obvious that the rotation increases as the eccentricity increases.

3.2 Seismic Response under Bilateral Excitation

Fig. 7 compares the damage of the column without an eccentricity (H-4) and the columns with eccentricities of 0.5D (H-5) and D (H-6) after the bilateral excitation. Spalling off of the covering



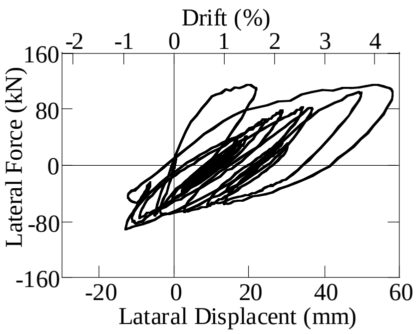
(3) *e*=*D* (H-6)

Fig. 8 Displacement Response under the Bilateral Excitation

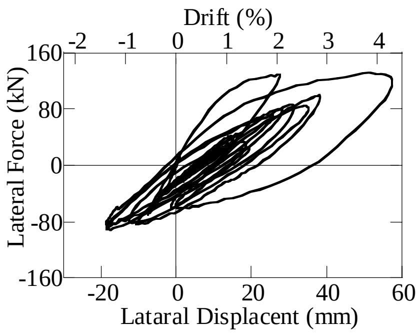
concrete as well as flexural cracks occurred at CD corner in the column without an eccentricity, while it occurred at the surface in the eccentric compression side in the column with the eccentricities of 0.5*D* and *D*. Longitudinal and ties bars did not suffer visible damage in the tests. It is apparent that more extensive failure occurred in the columns under the bilateral excitation than those under the unilateral excitation.

Fig. 8 shows the displacement response of the columns under the bilateral excitation. The maximum displacement in the longitudinal direction was 4.3%, 4.2% and 3.9% drift in the columns without an eccentricity and with the eccentricities of 0.5*D* and *D*, respectively. The maximum displacements under the bilateral excitation were 26-40% larger than those under the unilateral excitation. Residual drift was not significant in the longitudinal direction. On the other hand, the maximum displacement in the transverse direction was -3.6%, -3.5% and -4.6% drift in the columns without an eccentricity and with the eccentricities of 0.5*D* and *D*, respectively. Residual drift in this direction was -2.7% and -4.1% drift in the columns with the eccentricities of 0.5*D* and *D*, respectively, while it was -1.3% and -2.7% drift in the columns with the eccentricities of 0.5*D* and *D*, respectively, under the unilateral excitation. Residual drift under the bilateral excitation was much larger than that under the unilateral excitation.

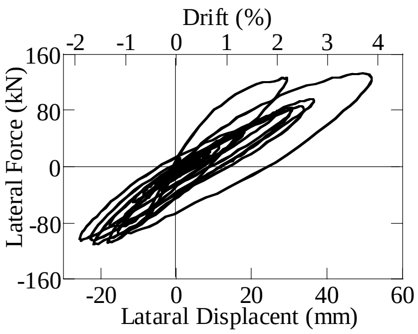
Fig. 9 shows the lateral force vs. lateral displacement hysteresis of the columns. The strength in the longitudinal direction was 116.7 kN, 129.8 kN and 133.6 kN in the columns without an eccentricity and with the eccentricities of 0.5*D* and *D*, respectively. The flexural strengths under the bilateral excitation were 7.0-16.4% smaller than those under the unilateral excitation. The restoring force was stable during the entire duration of the excitations. Significant deteriorations of the restoring



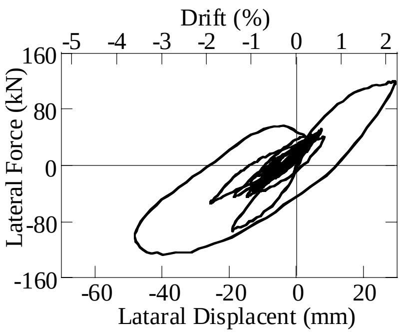
(a) Longitudinal Direction



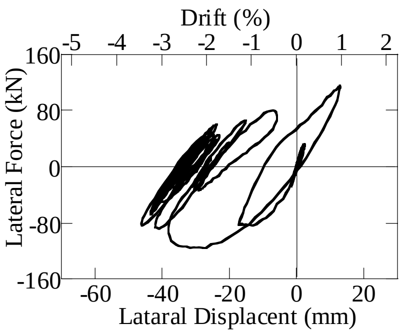
(a) Longitudinal Direction



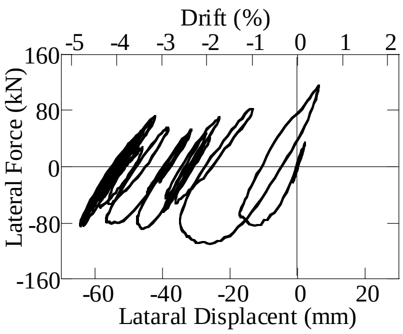
(a) Longitudinal Direction



(b) Transverse Direction
(1) *e*=0 (H-4)

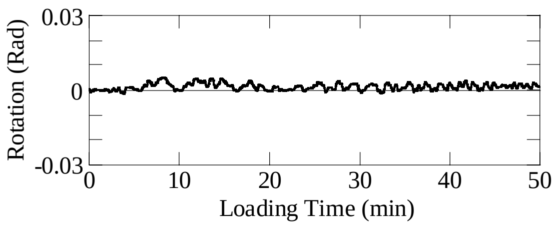


(b) Transverse Direction
(2) *e*=0.5*D*(H-5)

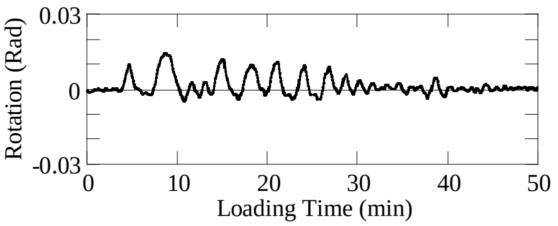


(b) Transverse Direction
(3) *e*=*D* (H-6)

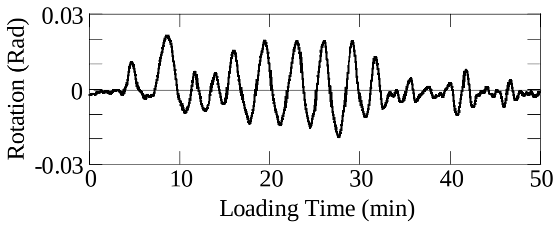
Fig. 9 Lateral Force vs. Lateral Displacement Hystereses under the Bilateral Excitation



(1) *e*=0 (H-4)



(2) *e*=0.5*D* (H-5)



(3) *e*=*D* (H-6)

Fig. 10 Rotations of Columns Relative to the Footings under the Bilateral Excitation

force did not occur in the longitudinal direction under the bilateral excitation. The strength in the transverse direction was 120.4 kN, 116.7 kN and 116.7 kN in the columns without an eccentricity and with the eccentricities of 0.5*D* and *D* respectively. The restoring force deteriorated to 71% and 75% of their strength in the columns with the eccentricities of 0.5*D* and *D*, respectively, at 3.5% drift.

Fig. 10 shows the rotations of columns relative to the footings in the columns. The rotation occurred in the columns without an eccentricity was limited (0.005 radian). On the other hand, the maximum rotation was 0.014 and 0.022 radian in the columns with the eccentricities of 0.5*D* and *D*, respectively. The rotation increases as the eccentricity increases.

Table 2 Model Columns used in the Cyclic Loading Tests

Models	C-1	C-2	C-3	C-4
Eccentricities	0.5*D*	*D*	0.5*D*	*D*
Longitudinal Reinforcement Ratio (%)	1.35	1.9	1.35	1.9
Tie Reinforcement Ratio (%)	0.99	1.19	0.99	1.19
Concrete Strength (MPa)	24.3	24.9	24.3	25.5
Loading Type*	1		2	

*Loading Type=1: loading in the longitudinal direction, and Type=2: loading in the bilateral direction

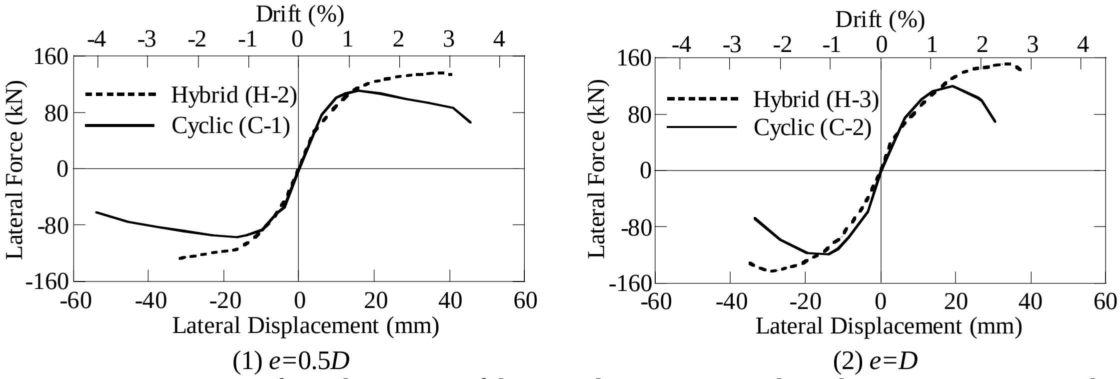


Fig. 11 Comparison of Envelope Curve of the Lateral Force vs. Lateral Displacement Hystereses under the Unilateral Loading

4. EFFECT OF LOADING HYSTERESIS

To clarify the effect of loading hysteresis, a result of cyclic loading tests of reinforced concrete C-bent columns conducted by Kawashima et al is presented here. Two columns with an eccentricity of 0.5*D* and two columns with an eccentricity of *D* were loaded unilaterally or bilaterally. In the bilateral loading, a rectangular orbit was used. Amplitude of the lateral displacement was stepwisely increased from 0.5% drift until failure with an increment of 0.5% drift. Three cyclic loading were conducted at each step. Due to the space limitation, only envelop curves of the lateral force vs. lateral displacement hysteresis are shown here.

Fig. 11 compares the envelops of the hysteresis between the hybrid loading test and the cyclic loading test under the unilateral excitation in the longitudinal direction. Deterioration of the flexural strength initiated at 3% and 2.5% drift in the columns with the eccentricities of 0.5*D* and *D*, respectively, under the cyclic loading test, while the restoring force was stable until 3% and 2.8% drift in the columns with the eccentricities of 0.5*D* and *D*, respectively, under the hybrid loading test. As a consequence, an extensive underestimation of the restoring force occurred at larger displacements under the cyclic loading test.

Fig. 12 compares the envelops of the lateral force vs. lateral displacement hysteresis between the hybrid loading test and the cyclic loading test under the bilateral excitation. Again, it is apparent that more extensive damage progressed in the columns subjected to the cyclic loading than those subjected to the ground motion excitation.

5. CONCLUSIONS

To clarify the seismic performance of reinforced concrete C-bent columns, a hybrid loading test was conducted. The following conclusions may be derived from the results presented herein.

1) Extensive failure occurs at the plastic hinge in the eccentric compression side under both the unilateral excitation and the bilateral excitation. This results in a large residual displacement in the

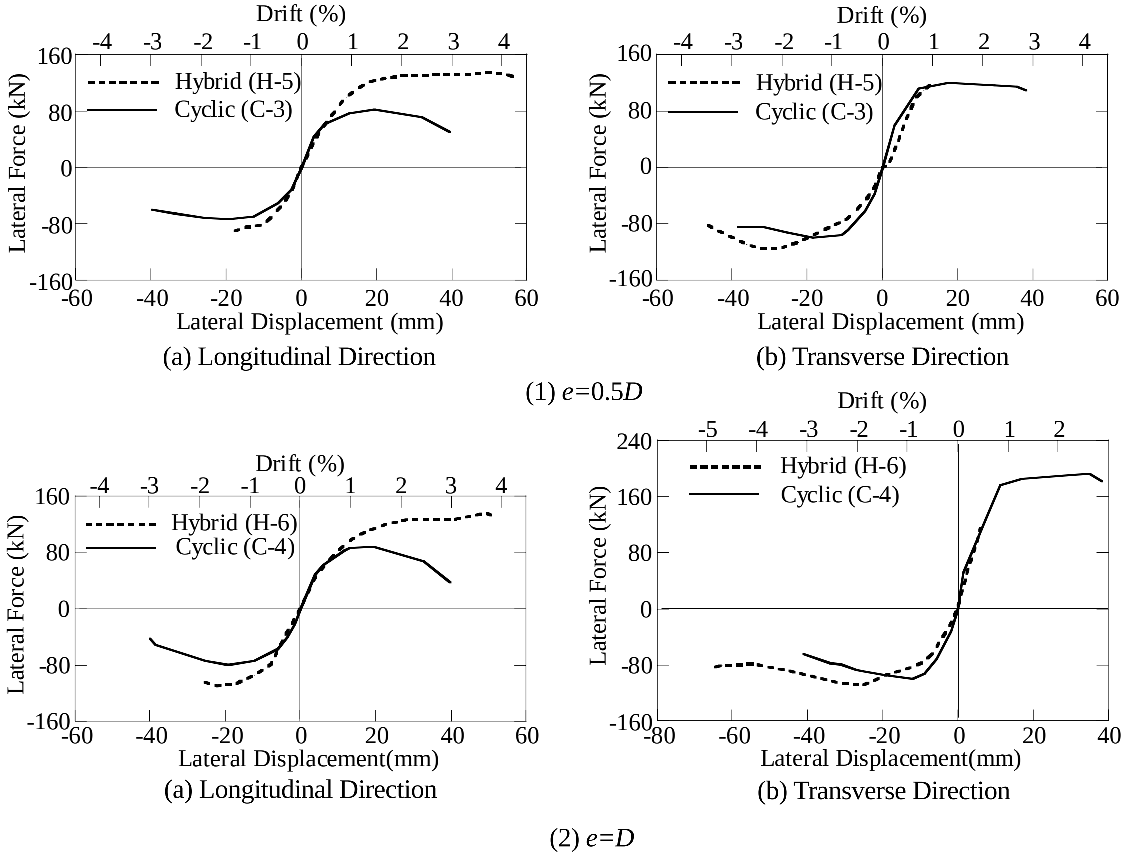


Fig. 12 Comparison of Envelope Curve of the Lateral Force vs. Lateral Displacement Hystereses under the Bilateral Loading

eccentric compression side. The failure and the residual displacement under the bilateral excitation are more extensive than those under the unilateral excitation.

2) The eccentricity results in rotations of the columns around their axis under both the unilateral excitation and the bilateral excitation. The rotation increases as the eccentricity is increases.
3) The cyclic loading test with the rectangular orbit results in more extensive deterioration of the flexural strength than that under the hybrid loading test.

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