第 9 回地震時保有耐力法に基づく橋梁等構造の
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Seismic Performance of Bridge supported by C-bent Columns

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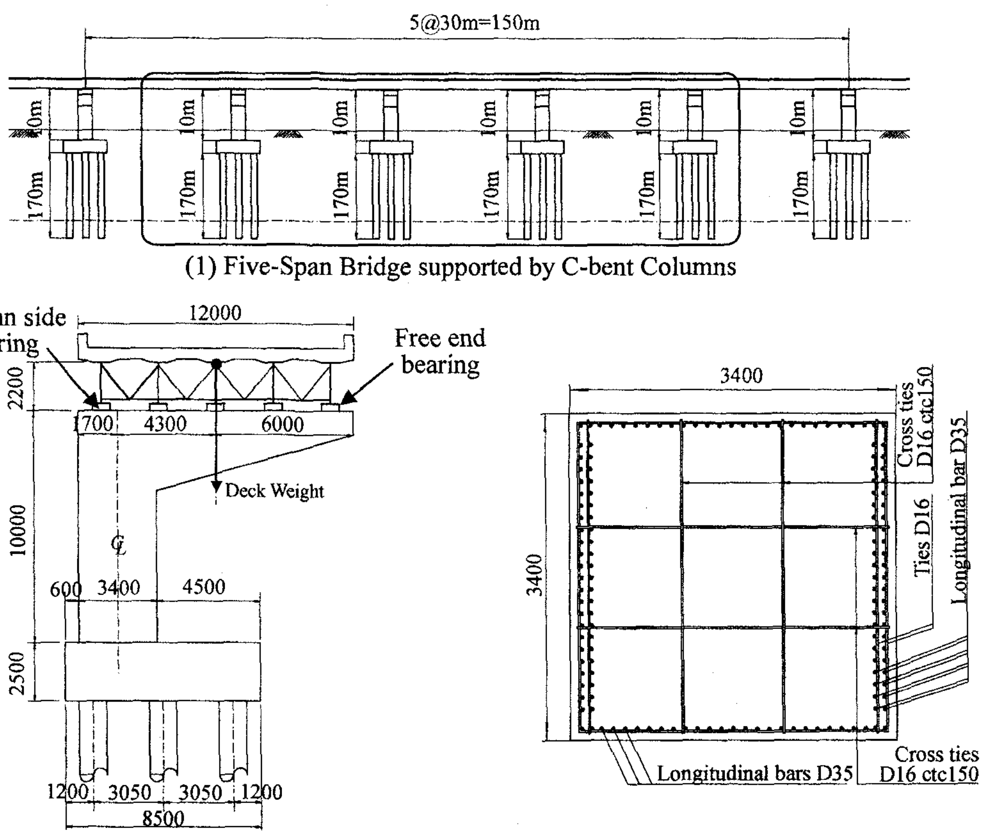
1. INTRODUCTION

Since C-bent columns exhibit complicated behavior combining biaxial bending, torsion as well as axial force during an earthquake, 3-D analytical idealization is essential to evaluate their seismic performance[1), 2)]. Furthermore, effect of bearing conditions is important, because occurrence of the seismic torsion of the columns likely depends on the bearing conditions[3)]. Therefore the seismic performance of a bridge supported by C-bent columns including a residual displacement, column rotations and force/displacement demand of the bearings should be carefully evaluated.

To clarify the seismic performance of a bridge supported by C-bent columns, 3-D dynamic response analysis under multi-directional excitation is conducted on a total bridge system including a superstructure, bearings, columns, and foundations.



(1) Five-Span Bridge supported by C-bent Columns

(2) Column Configuration (3) Column Section

Fig. 1 Target Bridge

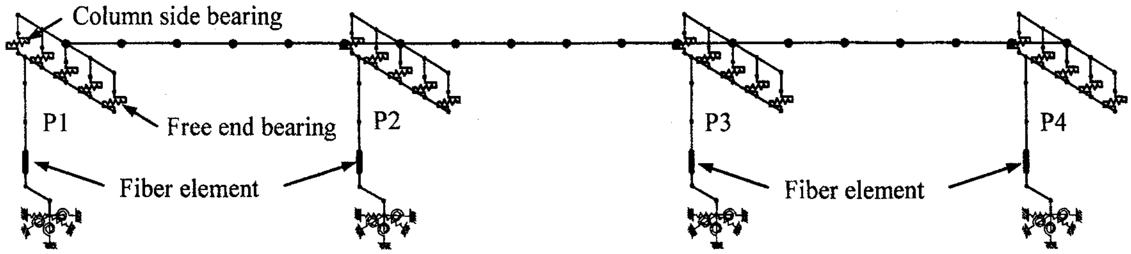
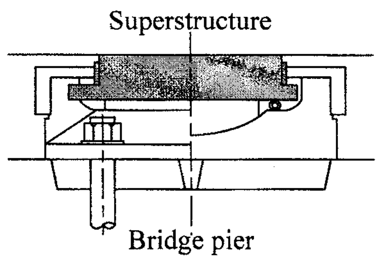
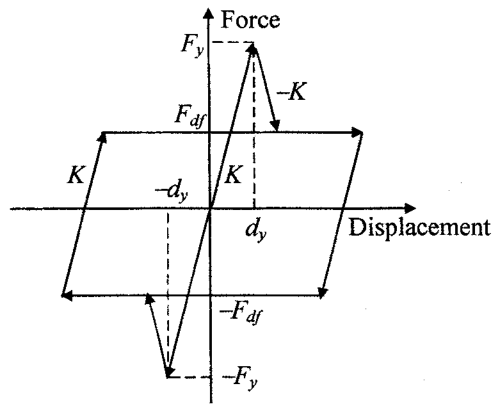


Fig. 2 Analytical Idealization



(1) Fixed Steel Bearing



(2) Model of Nonlinear Behavior of Fixed Bearing

Fig. 3 Fixed Steel Bearing and Its Nonlinear Model[9)]

2. TARGET BRIDGE

Fig. 1 shows a target bridge consisting of a five-span continuous deck supported by reinforced concrete C-bent columns and pile foundations. This bridge is 150-meter long and composed five equal spans. Each span is 30 m long and 12 m wide. The superstructure is composite type and supported by six piers with 10-meter height. The columns have a 3.4 m x 3.4 mm square cross section. The shear-span ratio is 3.7. Axial stress at the plastic hinge region of the columns resulted from the dead weight of the superstructure is 0.86 MPa. The eccentricity between the column center and the deck center, D, is 4.3 m.

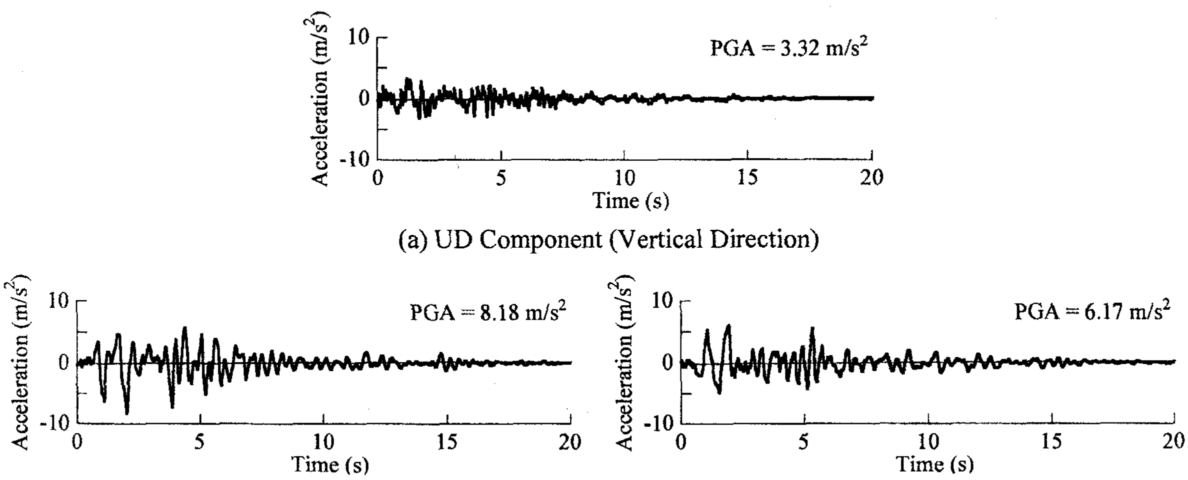
The bottom of the piles reaches a gravel layer at 17 m below the ground surface. The footing is 2.5 m thick, 8.5 m long and 8.5 m wide. Nine 17 m long cast-in-place reinforced concrete piles with a diameter of 1.2 m support a footing. The columns and the foundations are designed based on the current seismic design codes[3)] under Type-I (middle -field) and Type-II (near-field) ground motions at a site corresponding to the moderate ground condition (Type-II Ground Condition).

Based on **Fig. 1**(3), 35 mm diameter deformed longitudinal bars with a nominal strength of 295 MPa (SD295A) are provided in double at not only the eccentric tension side but also the eccentric compression side in the column. The longitudinal reinforcement ratio is 1.21 %. 16 mm diameter deformed tie bars (D16SD295A) are provided at 150 mm interval for the entire column height. Tie bars are provided in the inner longitudinal bars as well. The volumetric tie reinforcement ratio is 0.76 %. Concrete strength of the columns is 21 MPa.

First, five fixed steel bearings assumed to be employed at the top of each pier to support the deck. Then the steel bearings are assumed to be replaced with 129 mm thick, 850 mm long and 850 mm wide rubber bearings. The lateral stiffness of the rubber bearing is 5.63 MN/m. The leftmost bearing and the right most bearing shown in **Fig. 1**(2) are defined hereinafter as the column side and the free end bearings, respectively.

3. ANALYTICAL IDEALIZATION

To simulate the seismic response of the bridge, both superstructure and substructure are idealized by finite elements as shown in **Fig. 2**. The deck and the column body other than the plastic hinge are idealized by linear beam elements. The plastic flexural deformation of the columns at the plastic



(b) NS Component (Longitudinal Direction) (c) EW Component (Transverse Direction)

Fig. 6 Input Ground Acceleration (JMA Kobe Ground Motion Record)

hinge region is idealized by a fiber element. The plastic hinge length L_p is assumed a half of the column width[3]. In this analysis, the hysteretic behavior of torsion vs. column rotation is disregard. Pier cracking torsional stiffness is assumed to be 50 % of that full section which is determined based on the experimental results[1),2)].

In the fiber element, the stress vs. strain relation of confined concrete is idealized by a model by Hoshikuma and Kawashima et al.[5] and unloading and reloading hystereses are idealized based on a model by Sakai and Kawashima[6]. Furthermore, the modified Menegotto-Pinto model [7), 8)] is used to idealize the stress vs. strain relation of the reinforcements.

The fixed steel or rubber bearings are modeled by a set of spring elements in the longitudinal and transverse directions. The fixed steel bearings are first assumed to be used. Although the deck and the fixed bearings restrained the seismic torsion of the C-bent columns, the columns may slightly rotate during an earthquake. This slight rotation of the columns may result in larger lateral displacement in the column side bearing than the free end bearing, which results in a larger reaction force in the bearing at the column side than the other side. Thus an analysis which includes the effect of bearing failure is conducted. To include the nonlinear behavior of the steel bearings, a model proposed by Tirasit and Kawashima[9] is used. **Fig. 3** shows the configuration of the fixed steel bearing and the nonlinear hysteretic model. The fixed steel bearing is assumed to behave elastically before failure. The strength F_y of a fixed steel bearing is evaluated as

$$Fy = 1.7 k_h R_{DL} \quad (1)$$

in which k_h: the seismic coefficient and R_{DL}: the reaction in bearing due to dead weight of superstructure. k_h and R_{DL} are assumed to be 0.78 and 108 t, respectively. Therefore, the strength F_y of a fixed steel bearing by Eq. (1) is 1.43 MN. After failure displacement d_y , the fixed bearing is assumed to suffer damage and its lateral force capacity decreases and becomes dependent on the friction force F_{df} between the upper and the lower parts of bearing. The friction force is assumed as

$$F_{df} = \mu R_{DL} \quad (2)$$

where μ: the friction coefficient which is assumed to be 0.15 in both transverse and longitudinal directions, and R_{DL}: the reaction in bearing due to dead weight of the superstructure.

To study the application of rubber bearing for the bridge supported by C-bent columns, the five steel bearing are replaced with five rubber bearings. The rubber bearings are modeled by a linear spring with a lateral stiffness of 5.63 MN/m in the longitudinal and transverse directions.

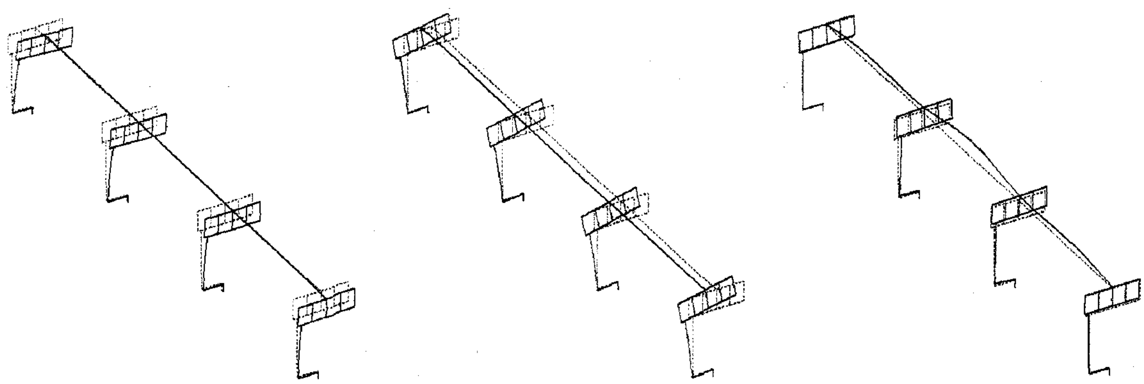
To analyze the seismic response of the bridge under multi-directional excitation, NS, EW and UD components of JMA Kobe ground accelerations shown in **Fig. 4** are imposed to the analytical models in the longitudinal, transverse and vertical directions simultaneously. The constant acceleration

Table 1 Natural Periods of Bridge with Fixed Bearings

Mode no.	Direction	Natural Periods (s)	Effective mass ratio (%)
1	Longitudinal	0.578	71
2	Transverse	0.508	56
7	Vertical	0.22	44

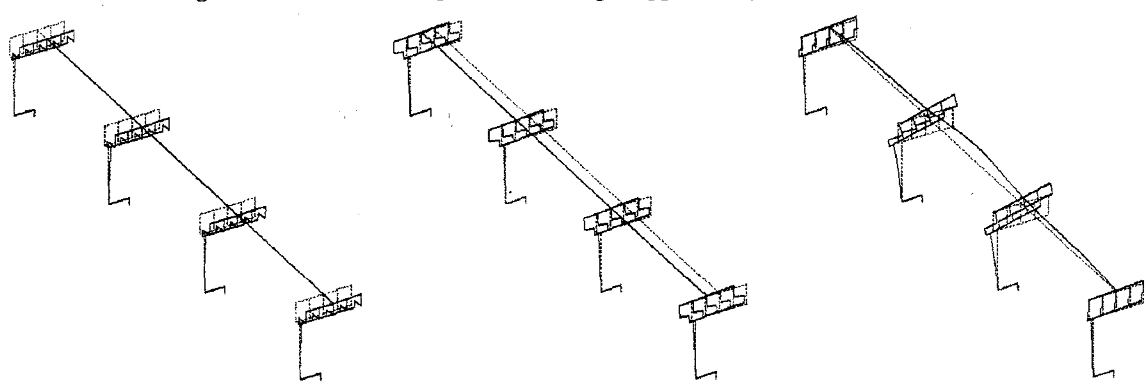
Table 2 Natural Periods of Bridge with Rubber Bearings

Mode no.	Direction	Natural Periods (s)	Effective mass ratio (%)
1	Longitudinal	0.948	49
2	Transverse	0.911	42
11	Vertical	0.262	30



(1) 1st Mode: Longitudinal Direction (2) 2nd Mode: Transverse Direction (3) 7th Mode: Vertical Direction

Fig. 5 Natural Mode Shapes of the Bridge supported by the Fixed Steel Bearings



(1) 1st Mode: Longitudinal Direction (2) 2nd Mode: Transverse Direction (3) 11th Mode: Vertical Direction

Fig. 6 Natural Mode Shapes of the Bridge supported by the Rubber Bearings

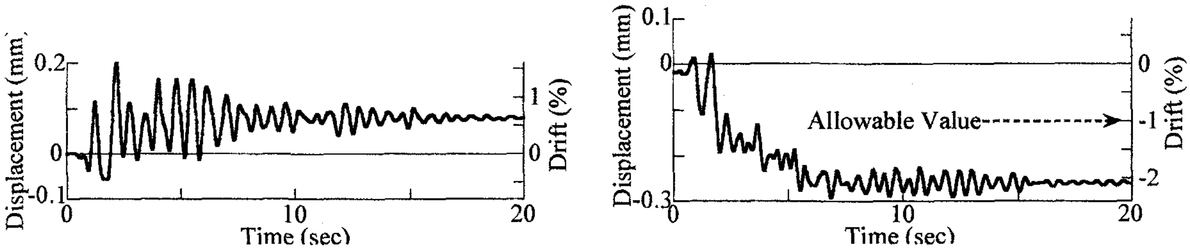
is assumed in each step of numerical integration and time step interval of integration is 0.001 sec.

4 NATURAL PERIODS AND MODE SHAPES

The natural periods and the effective mass ratios of the bridges supported by the fixed steel and rubber bearings are shown in **Tables 1**. The natural mode shapes of the bridges are presented in **Fig. 5** and **6**. The fundamental modes of both bridges are in the longitudinal direction. The fundamental periods are 0.578 seconds and 0.948 seconds in the bridges supported by the fixed steel and rubber bearings, respectively.

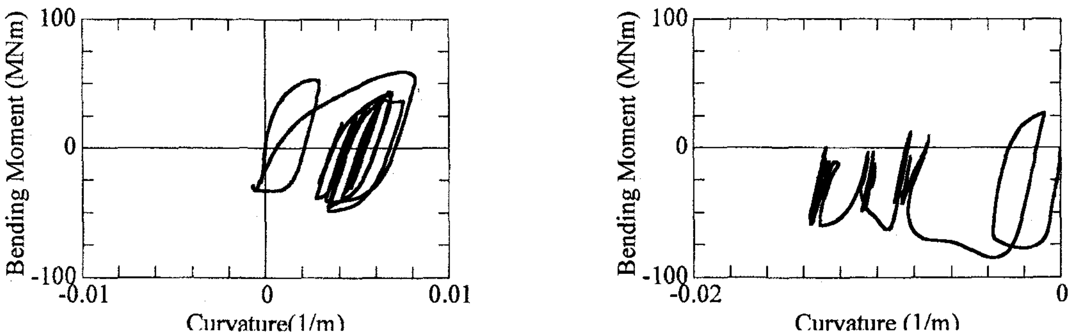
5 SEISMIC PERFORMANCE OF BRIDGE SUPPORTED BY STEEL BEARINGS

Because stiffness of the superstructure is so large that the seismic response of all the columns is quite similar. Thus the analytical results of one column (P1) are presented here. **Fig. 7** shows the displacement response of the deck center of the column in the longitudinal and transverse directions. The maximum displacement in the longitudinal direction is +4.3 % drift at 2.3 sec, and the residual displacement after the excitation reaches 0.6 % drift. The most important feather of the C-bent columns is the accumulation of residual displacement in the transverse direction due to the column eccentricity.



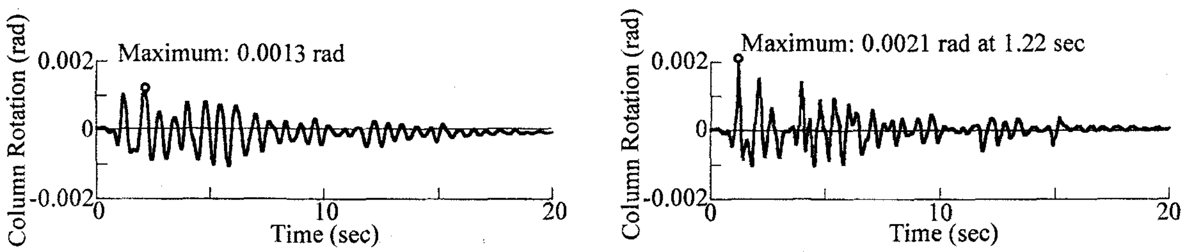
(1) Longitudinal Direction (2) Transverse Direction

Fig. 7 Displacement Response of the Bridge supported by the Steel Bearings



(1) Longitudinal Direction (2) Transverse Direction

Fig. 8 Moment vs. Curvature Hystereses of the Column with the Steel Bearings



(1) Without Damage of the Fixed Steel Bearings (2) With Damage of the Fixed Steel Bearings

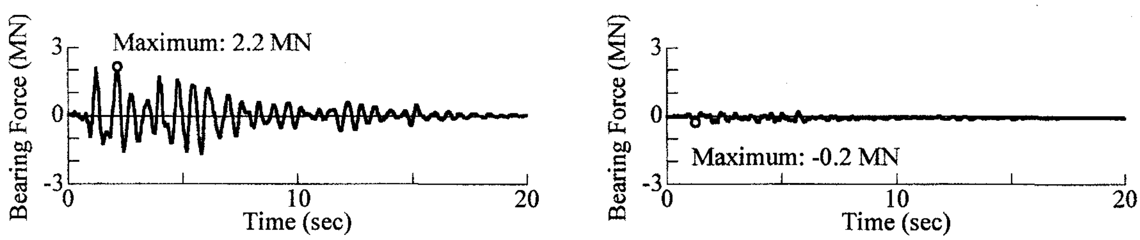
Fig. 9 Rotation of the Bridge Column supported by the Steel Bearings

The maximum displacement in the transverse direction is -2.3 % drift at 7.1 sec, and the residual displacement after the excitation is -2.1 % drift, which exceeds the acceptable value (1% drift).

The bending moments vs. curvature hystereses at the plastic hinge region in the column in the longitudinal and transverse directions are shown in **Fig. 8**. Based on the hystereses in the transverse direction, post-yield stiffness at negative side (eccentric compression side) is quite small, and plastic deformation accumulates in this direction. The maximum curvature is -0.014 /m in the transverse direction, while it is 0.008 /m in the longitudinal direction.

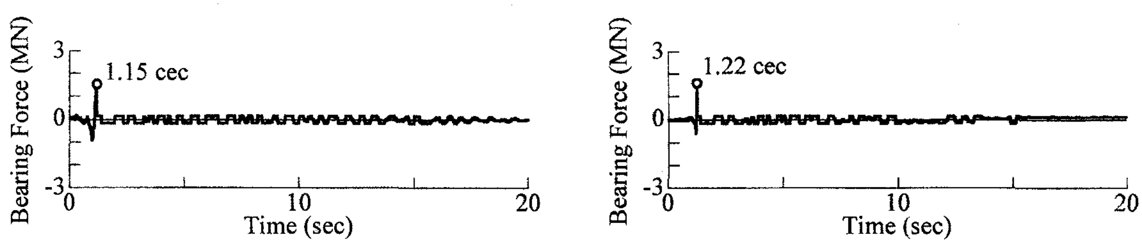
Although the deck is fixed by the steel bearings to the C-bent columns, the columns slightly rotates under strong excitation. **Fig. 9** shows the rotation of the bridge column P1 around its axis. The result which takes into account damage of the fixed steel bearings as will be described later is also presented in this figure for comparison. The maximum rotation of the column is 0.0013 radian at 2.3 sec.

As described above, this slight rotation of the columns results in a larger bearing displacement in the column side bearing than the free end bearing, which likely causes undesirable damage in the column side bearing. Comparison of the bearing lateral reaction forces between the column side bearing and the free end bearing is shown in **Fig. 10**. It is obvious that the bearing force is much larger at the column side than that at the free end. The maximum forces are 2.21 MN and -0.21 MN in the bearings at column side and the free end, respectively. Therfore the bearing lateral strength



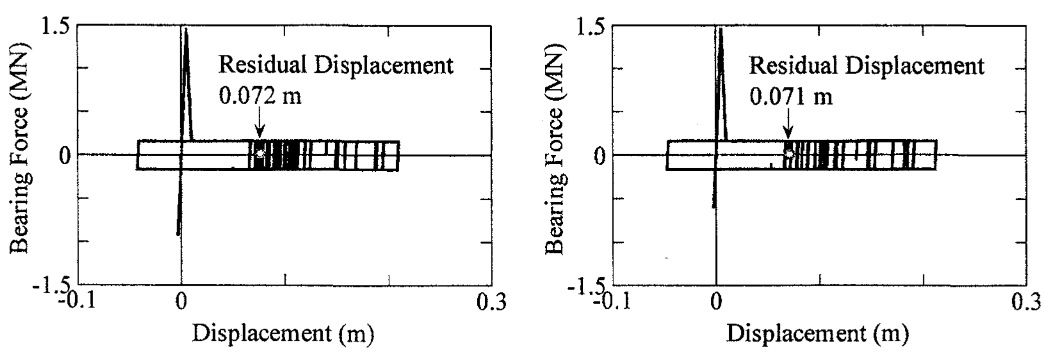
(1) Column Side Bearing (2) Free End Bearing

Fig. 10 Bearing Force of the Fixed Bearings at the Column side and the Free End



(1) Column Side Bearing (2) Free End Bearing

Fig. 11 Bearing Force of the Damaged Fixed Bearings at the Column Side and the Free End



(1) Column Side Bearing (2) Free End Bearing

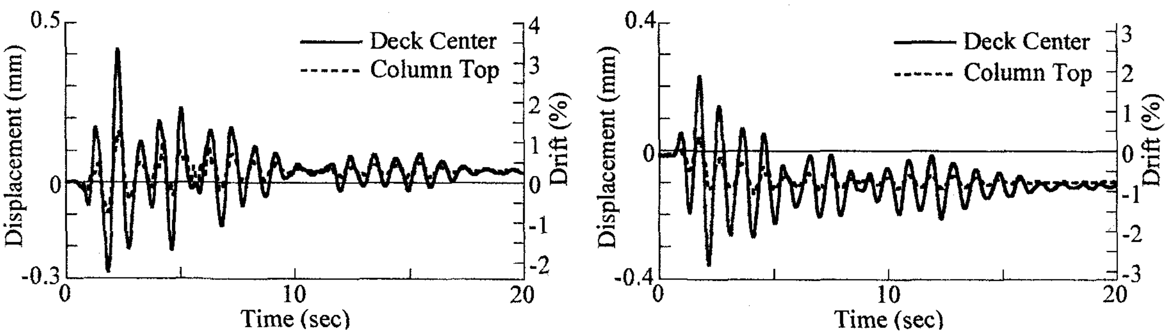
Fig. 12 Hystereses of Damaged Steel Bearing in the Longitudinal Direction

demand should be carefully evaluated by a dynamic response analysis on the total bridge system including a superstructure, bearings, C-bent columns and foundations.

6 EFFECT OF DAMAGE OF FIXED STEEL BEARINGS

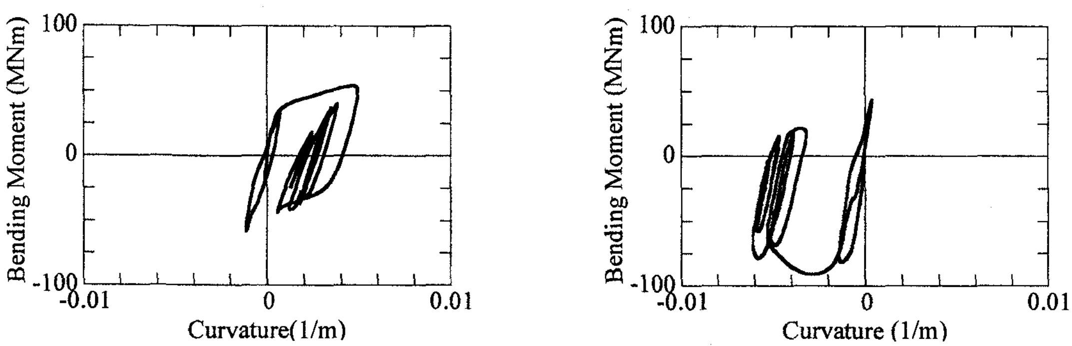
An analysis which takes into account damage of the fixed steel bearings is conducted. The analytical results of column P1 are presented here. The bearing lateral reaction forces in the column side bearing and the free end bearing are compared in **Fig. 11**. Based on **Fig. 11**, the lateral reaction force of the column side bearing first reaches the maximum strength (1.43 MN) at 1.15 sec, and then it deteriorates significantly due to failure of the bearing. At 1.22 sec, the reaction force of the free end bearing reaches the maximum strength, and it deteriorates significantly. From 1.15 sec and 1.22 sec, the column side bearing and the free end bearing exhibit hysteretic behavior, respectively, as sown in **Fig 12**.

This failure of the fixed steel bearings allows increase of the column rotation around its axis as shown in **Fig. 9.** The maximum rotation is 0.0021 radian at 1.22 sec, which is 62 % larger than the rotation obtained by the analysis without damage of the fixed steel bearings. The rotation of the column increases significantly from 1.15 sec corresponding to the failure of the column side bearing, and the rotation reaches the maximum value (0.0021 radian) at 1.22 sec corresponding to the failure of the free end bearing.



(1) Longitudinal Direction (2) Transverse Direction

Fig. 13 Displacement Response of the Bridge supported by the Rubber Bearings



(1) Longitudinal Direction (2) Transverse Direction

Fig. 14 Moment vs. Curvature Hystereses of the Bridge Column with the Rubber Bearings

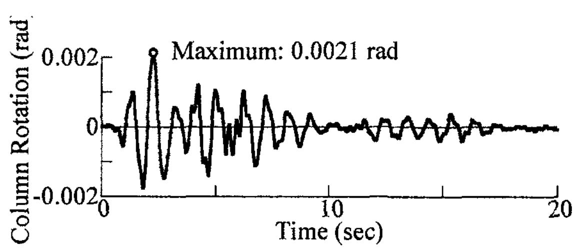


Fig. 15 Rotation of the Bridge Column with the Rubber Bearings

7 USE OF RUBBER BEARINGS

The five steel bearing are replaced with rubber bearings with a lateral stiffness of 5.63 MN/m as presented above. **Fig.13** shows displacement response of the deck center and the column top of the column P1. The bending moment vs. curvature hystereses of the plastic hinge region of the column are shown in **Fig. 14**. The maximum displacement of the deck is 3.2 % and -2.9 % drifts in the longitudinal and transverse directions, respectively, while the maximum displacement of the column top is 1.2 % and -1.1 % drifts in the longitudinal and transverse directions, respectively. The residual displacement of the deck center after the excitation reaches 0.3 % and -0.9 % drift in the longitudinal and transverse directions, respectively, which are smaller than the acceptable value (1 % drift). The accumulation of the residual displacement in the transverse direction is less significant, because use of the rubber bearing decreases the plastic deformation of the columns as shown in **Fig. 14**. It is likely that rubber bearings are effective to mitigate plastic deformation of C-bent columns as well as the residual displacements due to the eccentricity.

Although a rubber bearing is effective to mitigate the residual displacement, use of the rubber bearing increases the rotation of C-bent columns around the their axis compared to use of fixed bearings as shown in **Fig. 15**. The maximum rotation is 0.0021 radian at 2.3 sec, which is 62 % larger than the rotation obtained by the analysis with steel bearings (see **Fig. 9**(1)).Thus the rotation of the C-bent columns should be carefully evaluated in the seismic design when a deck is supported by rubber bearings.

8 CONCLUSIONS

To clarify the seismic performance of a bridge supported by C-bent columns, 3-D dynamic response analysis was conducted on a total bridge system. Fixed steel bearings first assumed to be used to support the deck. Then the steel bearings are assumed to be replaced rubber bearings. Based on the analytical results presented herein, the following conclusions may be deduced.

(1) If we consider the response of a total bridge system including a deck, bearings, columns, and foundations, seismic torsion of the C-bent columns depends on the supporting conditions of the deck by bearings.

(2) For a bride supported by steel bearings, special consideration should be given in the design of steel bearings because the lateral reaction force induced in the bearing is larger in the column side than the other side. If the reaction force of the bearings exceeds their strength capacity and the bearings exhibit nonlinear behavior, which increases the rotation of C-bent columns around their axis.

(3) When the deck is fixed by steel bearings, a large residual displacement, which exceeds the acceptable value, likely to be develop in the eccentric compression direction due the eccentricity of the columns.

(4) A rubber bearing is effective to mitigate plastic deformation of columns as well as the residual displacemen. However, use of the rubber bearing increases the rotation of the columns around their axes compared to use of fixed bearings. Thus the rotation of the C-bent columns should be carefully evaluated in the seismic design.

REFERENCES

1) Kawashima, K., Watanabe, G., Hatada, S. and Hayakawa, R.: Seismic Performance of C-bent Columns based on a Cyclic Loading Test, *J. Structural Mechanics and Earthquake Engineering*, JSCE, No. 745/I-65, pp. 171-189, 2003.
2) Nagata, S., Kawashima, K. and Watanabe, G.: Seismic Response of RC C-bent Columns based on a Hybrid Loading Test, *Proc. 1st International Symposium on Advances in Experimental Structural Engineering*, pp. 227-234, Nagoya, Japan, 2005.
3) Kondo, Y., Unjoh, S. and Terayama, T.: Investigation on Torsional Behavior of Reinforced Concrete Columns subjected to Eccentric Moment, *Proc. 1st Symposium on Ductility Design Method for Bridges*, pp. 163-166, Tokyo, Japan. 1998.
4) Japan Road Association: *Part V seismic design, design specifications of highway bridges*, Maruzen, Tokyo, Japan, 2002.
5) Hoshikuma, J., Kawashima, K., Nagaya, K. and Taylor, A. W.: Stress-Strain Model for Confined Reinforced Concrete in Bridge Piers, *J. Structural Engineering*, ASCE, 123(5), pp. 624-633.1997.
6) Sakai, J. and Kawashima, K.: An Unloading and Reloading Stress-Strain Model for Concrete confined by Tie Reinforcements, *Proc.12th World Conference of Earthquake Engineering*, No. 1432 (CD-ROM), Auckland, New Zealand, 2000.
7) Menegotto, M. and Pinto, P.E.: Method of Analysis for Cyclically Loaded R.C. Plane Frames including Changes in Geometry and Non-Elastic Behavior of Elements under Combined Normal Force and Bending, *Proc. IABSE Symposium on Resistance and Ultimate Deformability of Structures Acted on by Well Defined Repeated Loads*, pp. 15-22, 1973.
8) Sakai, J. and Kawashima, K.: Modification of the Giuffre, Menegotto and Pint Model for Unloading and Reloading Paths with Small Strain Variations, *J. Structural Mechanics and Earthquake Engineering*, JSCE, No. 738/I-64, 159-169, 2003.
9) Tirasit, P. and Kawashima, K.: Seismic Torsion Response of Skewed Bridge Piers, *J. Earthquake Engineering*, No. 28, Perper No.116 (CD-ROM), 2005.