VERIFICATION TEST AND EARTHQUAKE RESPONSE OBSERVATION OF A BASE ISOLATED BUILDING WITH ECCENTRIC ROLLER BEARINGS

Akihiko NAKAE[1], Susumu OTSUKA[2], Nobuyasu KAWAI[3], Isao AOKI[4], Toru NAGAOKA[5], Ikuo SHIMODA[6] And Sumio KAWAGUCHI[7]

SUMMARY

Eccentric roller bearing is a base isolation device made of stainless steel and its restoring force is produced by the gravity like a pendulum. This bearing consists of two size of eccentric roller of large and small radii with eccentric distance. Because the natural period is independent of mass of superstructure, this bearing makes it possible to achieve the long effective natural periods for a wide range of structures. Two story RC building supported by these bearings with viscous dampers is completed. Through the verification tests and the earthquake response observations, the validity of the developed base isolation device and the response reduction effect against earthquakes are confirmed.

INTRODUCTION

A seismic isolation device for buildings using stainless steel eccentric rollers utilizing the gravity to produce a restoring force was developed ten-odd years ago. After the Great Hanshin-Awaji Earthquake in 1995, this type of isolation systems started to be applied to exhibition cases, floors and then buildings. This paper reports the results of performance verification tests and the earthquake response observation of the eccentric roller bearing isolation system carried out on a building.

OUTLINE OF BASE ISOLATED BUILDING

The base-isolated building is the two-story RC-structured laboratory belonging to Housing and Urban Development Corporation. Designed total floor area is 203 m^2 and the weight is 536.9 tf. In June of 1997, the eccentric roller bearing was installed on the foundation of the building. Figure 1 shows the isolated building and the plan of isolated layer. Figure 2 shows the eccentric roller bearing and the viscous damper employed in this building. The eccentric roller base isolation device supporting the superstructure consists of two stages of the isolated layers, each comprising four eccentric roller bearings forming a XY-motion mechanism, and separated by an intermediate plate. The specifications of the eccentric roller bearings used in this system are shown in Table 1. Since the eccentric roller bearing has no damping capacity, four shearing type viscous dampers are used. Table 2 shows the specifications of the viscous damper.

[1] *Building Design & Planning Dept. Okumura Corp. Tokyo, Japan Email:oku07675@gm.okumuragumi.co.jp*
[2] *Building Design & Planning Dept. Okumura Corp. Tokyo, Japan Email:oku07675@gm.okumuragumi.co.jp*
[3] *Building Design & Planning Dept. Okumura Corp. Tokyo, Japan Email:oku07675@gm.okumuragumi.co.jp*
[4] *Head Office of Engineering , TENOX Corp. , Tokyo , Japan*
[5] *Saitama Regional Branch , Housing & Urban Development Corp. , Saitama , Japan*
[6] *Technical Dept. , OILES Corp. , Tokyo , Japan*
[7] *Technical Dept. , OILES Corp. , Tokyo , Japan*

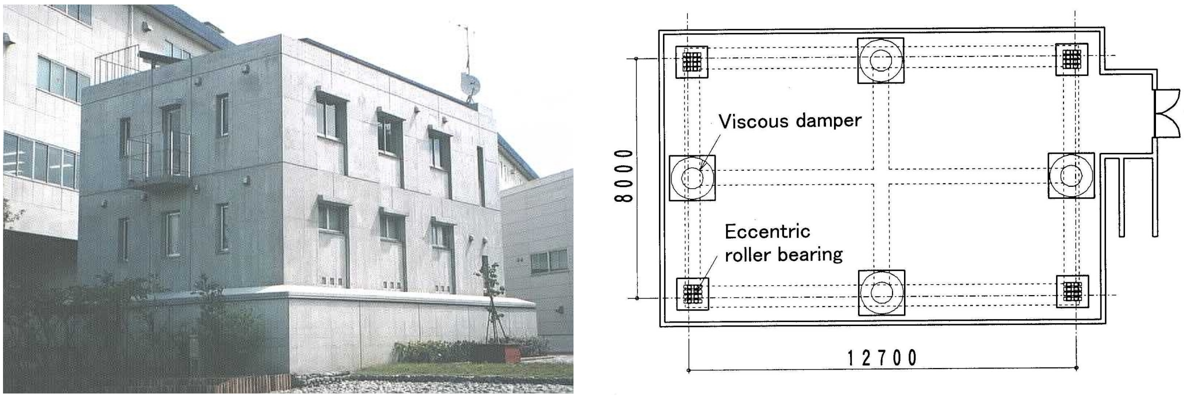


Figure 1: View of base-isolated building and plan of isolated layer

View of eccentric roller bearing

View of viscous damper

Figure 2: View of base isolation device

Table 1: Specifications of eccentric roller bearing (per unit)

Item	Specification
External dimensions	$100^{W} \times 100^{D} \times 50^{H}$ cm
Maximum applicable load	250tf
Radii of large & small rollers	6.0 cm , 5.0 cm
Eccentric distance	0.25 cm
Maximum relative displacement	±34.56 cm

Table 2: Specifications of viscous damper (per unit)

Item	Specification
External dimensions	$150^{W} \times 150^{D} \times 30^{H}$ cm
Viscous material	Butanoic polymer
Area of the resistance plate	3848.45 cm^2
Shear clearance	1.0 cm

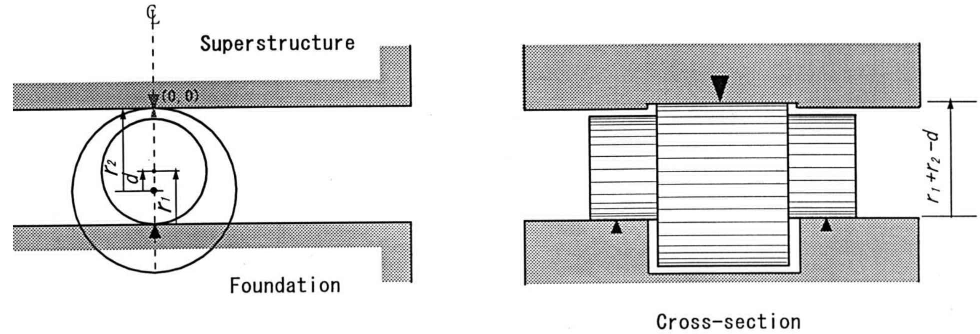
MECHANISM OF BASE ISOLATION DEVICE

The eccentric roller bearings have 6 cm radius in the thick portions, 5 cm radius in the thin portions and 0.25 cm eccentric distance. There are rails arranged in parallel above and under the eccentric roller bearings. The thick portions of the rollers touch the upper rails and the thin portions sit on the lower rails. When the superstructure moves in earthquake, the eccentric roller rolls, the superstructure is slightly lifted up in accordance with its horizontal displacement. The relations between the rotational angle of the rollers and the horizontal and vertical displacements are shown in Equations (1) and (2).

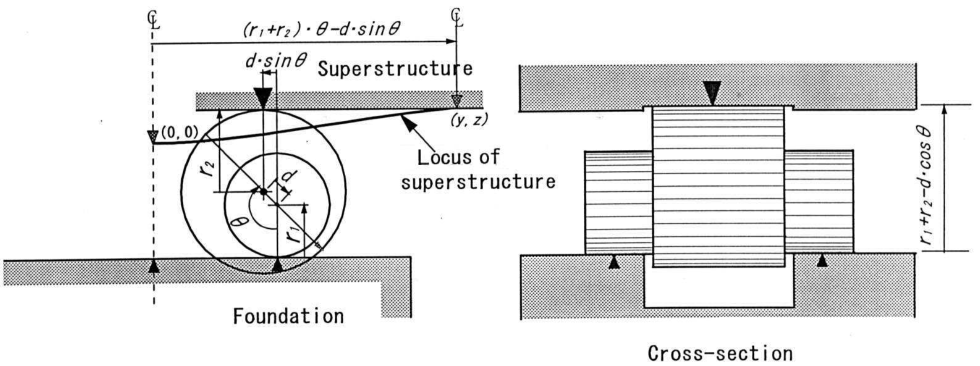
$$y_\theta = (r_1 + r_2)\cdot\theta - d\sin\theta \tag{1}$$

$$z_\theta = d(1-\cos\theta) \tag{2}$$

where r_1 and r_2 are the radii of thin and thick portions of the roller respectively (cm), d is the eccentric distance (cm), θ is the rotational angle of the roller (radian), and y_θ and z_θ are the horizontal and vertical displacements respectively (cm).



State with no rolling of a eccentric roller



State with rolling of a eccentric roller

Figure 3: Operation of the isolation device

The variation in the displacement y_θ and z_θ in relation to the rotational angle (θ) indicates the locus of the superstructure. When the rotational angle (θ) changes from 0 degree to ±180 degree, the superstructure moves from the origin (0,0) to the point [$\pm 2(r_1+r_2)\pi$, $2d$]. Since the tangential gradient leans toward the origin when the rotational angles are between ±180 degree, a restoring force is applied to the superstructure. The restoring force, Q (tf), produced in the horizontal direction can be expressed by following equation.

$$Q = m_\theta (g + \ddot{z}_0)\frac{d\sin\theta}{r_1 + r_2 - d\cos\theta} \tag{3}$$

where m_θ is the mass of the superstructure supported by the eccentric rollers (t) , $\ddot{z}_0$ is the vertical input acceleration (cm/s^2) and g is the gravity acceleration (cm/s^2).

Equation (3) shows how the eccentric roller converts the vertical inertia force including the gravity to the horizontal restoring force as shown in Figure 4. The restoring force has the non linearity and it starts to decrease as the rotational angle of the roller exceeds ±90 degree (±17.3 cm). The potential energy of the superstructure will continue to increase with the rotational angles between ±180 degree (±34.6 cm) maintaining the superstructure stable. The relationship between the rotational angle and the potential energy of the roller are analogous to the locus of the superstructure. Although the maximum rotational angle of the eccentric roller is 180 degree, in view of the horizontal installation accuracy and the motion of the foundation during earthquake, the allowable horizontal displacement for the design was set to 32 cm, which corresponds to a rotational angle of 165 degree of the eccentric roller.

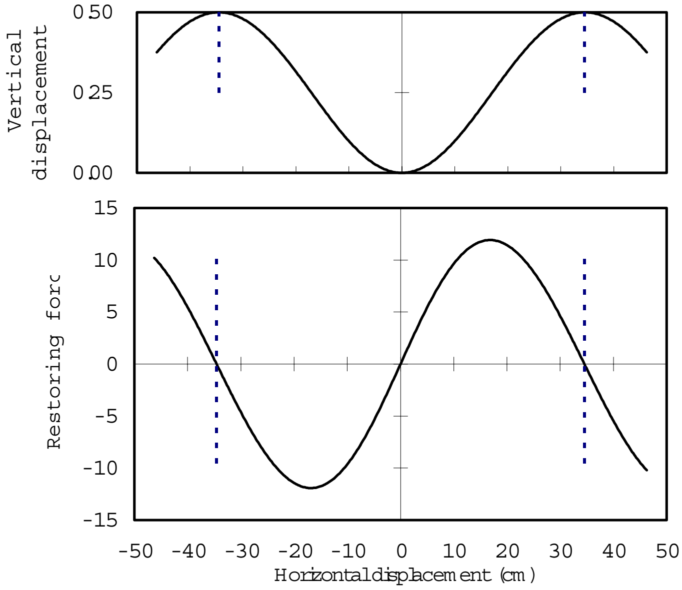


Figure 4: Locus of superstructure and displacement – restoring force curve

The natural period of the eccentric roller is irrespective of weight it supports and determined only by the shape of the roller. The smaller the horizontal displacement (the rotational angle of the roller) , the shorter the natural period. And when the horizontal displacement becomes greater, the natural period becomes longer. When the amplitude of the rotational angle is the smallest, the natural period T_0 is expressed by Equation (4).

$$T_0 = \frac{2\pi(r_1 + r_2 - d)}{\sqrt{gd}} \tag{4}$$

This eccentric roller bearing isolation system exhibits a natural period of 4.31 seconds when the amplitude is minimal. When the horizontal displacement exceeds 17 cm (maximum amplitude angle 90 degree), the natural period starts to lengthened sharply and becomes infinite when the horizontal displacement reaches 34 cm (maximum amplitude angle 180 degree). (Refer to Figure 5)

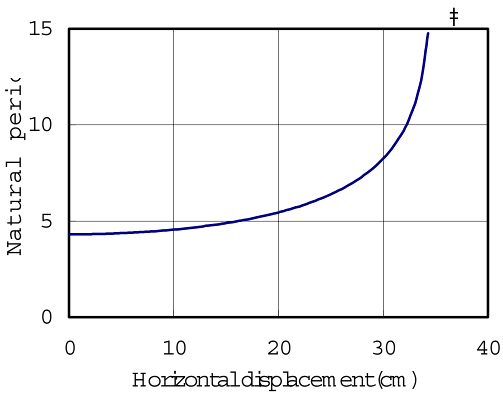


Figure 5: Relationship between natural period and maximum displacement

The roller bearing is made of special stainless steel of high weather resistance and its surface is hardened. The element test results certify that frictional coefficient is below 1/1000. The eccentric roller bearing isolation system are equipped with a rack and pinion mechanism for prevention of roller slippage and a sliding type lifting prevention mechanism.

The eccentric roller bearing has no damping capacity, then the shearing type viscous dampers are applied to this seismic isolation system. When an earthquake occurs, the disk type resistance plate fixed to the superstructure moves in the viscous material contained in the compartment fixed on the base structure. Thus, a resisting force is generated in response to the relative velocity between the foundation and the superstructure. The shearing resisting force, Q_V (kgf), of the damper is expressed by Equation (5).

$$Q_V = 0.42e^{-0.043T} S\left(\frac{|\dot{y}_\theta|}{d}\right)^{0.59} \tag{5}$$

where T is the temperature of the viscous material (℃), S is the area of the resistance plate (cm^2), d is the clearance between the resisting plate and the base plate, and $\dot{y}_\theta$ is the relative velocity (cm/s).

SEISMIC RESPONSE ANALYSIS

Preliminary evaluation of the base-isolated performance of the building was conducted using geometric non-linear models of the eccentric roller bearings. Weight of the superstructure for analytical models were 536.9 tf. The results of the analyses for the long side of the building are reported below. In the analyses, equation (1) and (2) expressing the horizontal and vertical displacements with the rotational angle were used. Whether the eccentric rollers roll or not due to the friction were determined step by step.

As an input earthquake ground motion for the response analyses, the NS and UD components of El Centro (1940) were used. The maximum acceleration were set to 766.2 cm/s^2 for NS, maximum velocity of 75 cm/s, and 462 cm/s^2 for UD as an input motion level for confirmation of the safety margin. Figure 6 shows the response acceleration time histories at the first floor and the relative displacement for the base-isolated layer.

The results of the analyses clearly indicates that the analyzed eccentric roller bearing isolation system has exhibited smaller response acceleration compared with that of the conventional systems and the response displacement are also smaller. It has also become clear that the framework of the isolated building has a sufficient margin against the cracking displacement.

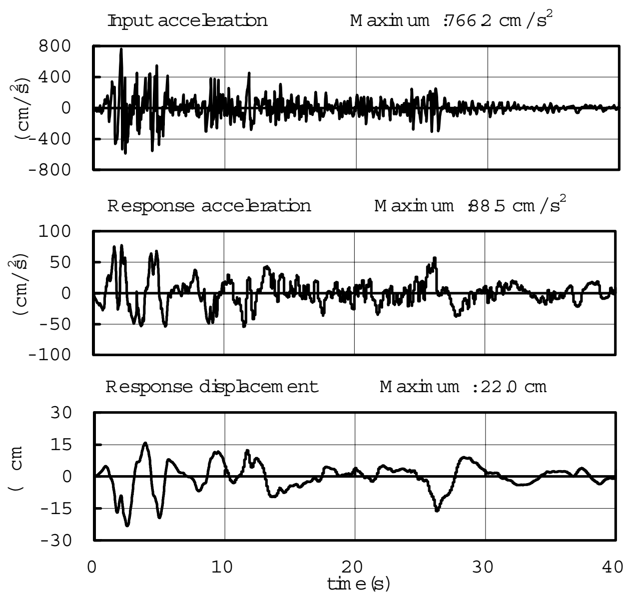


Figure 6: Response time histories (Simulated)

VERIFICATION TEST

After the completion of the building, the static force application and free vibration tests were conducted for confirmation of the fundamental characteristics of the eccentric roller bearings. In the static force application test, center hole jack was set on the pedestal located on the foundation and steel wire were fixed to the pedestal on the first floor. A relative displacement of 32 cm (critical design displacement) was applied to the isolated layer by pulling the wire with the jack. In the free vibration test, hydraulic releasing devices were installed between the jack and wire. After application of the design displacement of 32 cm, the wire were released to apply free vibration to the building. The verification test were performed both on the longer and shorter sides of the building. This paper reports the results on the longer side of the building.

Figure 7 shows the relations between the restoring force and the horizontal displacement. The non-linearity inherent to the eccentric rollers as shown in Figure 4 was confirmed by the test. The restoring forces of the eccentric rollers are determined only by the supporting weight and the shapes of the rollers as indicated by Equation (3). Because of the dimensional accuracy of the rollers, the weight of the building can be estimated using the restoring force obtained in the experiment. The weight of the building was estimated to be 465 tf. The restoring forces for this weight are plotted in the figure with dashed lines and are very similar to the experiment results.

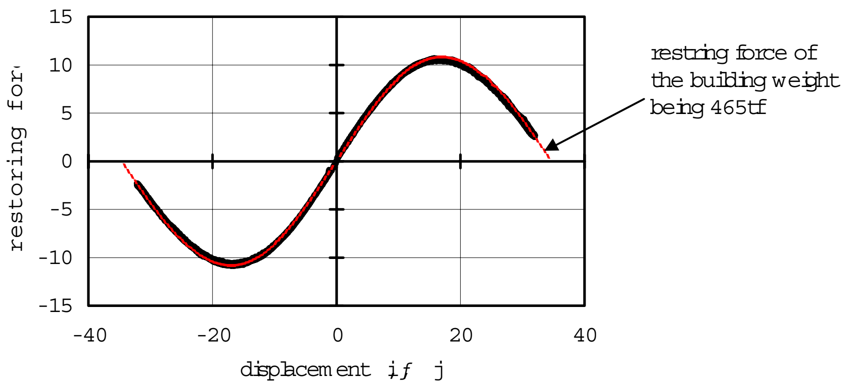


Figure 7: Restoring force - displacement curve (Experiment)

Using the results of the free vibration tests as explained earlier, this paper now examines the dynamic characteristics of the eccentric roller base isolation device. The tests were conducted for the eccentric roller bearings without damper operation. Figure 8 shows the response acceleration of the first floor of the building and the relative displacement response time histories. Free vibrations continued for more than 200 seconds. This indicates the superior movability of the rollers with very small friction. As the acceleration time histories in Figure 8 represent, each peak of about 23 cm/s^2 splits into two parts in about 40 seconds after the release of the force. During this period, the maximum horizontal displacements exceed 17 cm. In the free vibrations without damper operation, the inertia force is considered to balance with the restoring force when the small friction is neglected. As seen in Figure 7, peak acceleration of 23 cm/s^2 is corresponds to maximum restoring force and the split occurs due to the decrease of the restoring force.

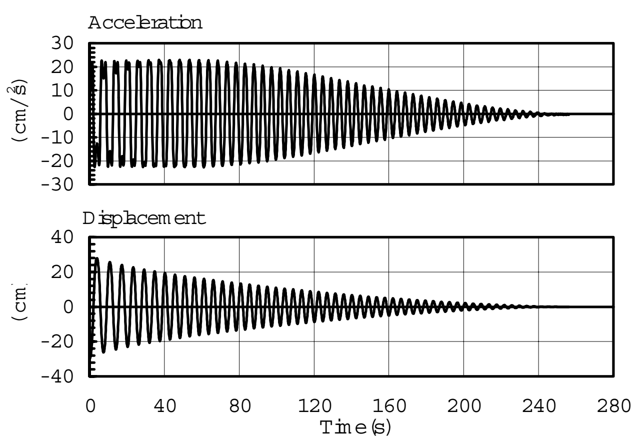


Figure 8: Time histories in free vibration test

Using the displacement time histories in this figure, the relations between the maximum displacement amplitude and the vibration period in each cycle were evaluated. Figure 9 shows the relationship between the natural period and amplitude. The vibration period exceeded 8 seconds when the horizontal displacement was 30 cm, while it was 4 second on the small amplitude level. The theoretical relationship between the natural period and maximum displacement as shown in Figure 5 is also shown in Figure 9. As seen in Figure 9, the natural period and the maximum amplitude of the experiments are very similar to the theoretical relationship. This superior aseismatic performance has been proved in the experiments for the comparatively light weight structure.

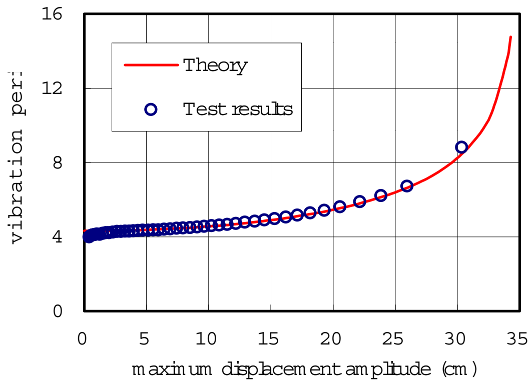


Figure 9: Relationship between natural period and maximum displacement (Experiment)

EARTHQUAKE OBSERVATIONS

After the completion of the building, the earthquake response observation is continuously carried out. Several earthquake responses have been observed, and they are shown in Table 3. The observed earthquakes were medium or small classes.

Table 3: Observed earthquakes

Name Specifications	Direction	Maximum acceleration (cm/s^2)			Displacement (mm)
		Basement	1st floor	Roof floor	Base-isolated layer
East Off Izu Peninsula	NS	6.00	0.94	1.38	0.26
1998.5.3, Mj5.4	EW	6.50	1.25	1.31	0.40
South Chiba	NS	19.75	2.00	2.81	0.65
1998.5.16, Mj4.9	EW	11.56	1.06	1.75	0.32
East Off Chiba	NS	3.56	1.44	1.50	0.59
1998.6.14, Mj5.6	EW	3.63	1.50	1.56	0.46
Tokyo Bay	NS	25.30	3.50	7.75	1.28
1998.8.29, Mj5.1	EW	23.94	4.63	6.56	1.96
Tokyo Bay	NS	25.34	2.32	3.67	0.41
1998.11.8, Mj4.9	EW	18.12	2.17	2.60	0.74

Tokyo Bay Earthquake (August 29, 1998) is the largest one and maximum ground acceleration is about 25 cm/s^2 in EW-direction. Thought the maximum displacement of the bearings is very small from 0.2 mm to 2.0 mm, the maximum response acceleration of the superstructure is reduced into from 1/3 to 1/8 of that of ground motion.

In order to verify the adequacy of the analytical model regarding the non-linearity of eccentric roller bearings and viscous dampers, simulation analyses of the earthquake response observations were carried out. The models were the same as those used in the preliminary evaluation, however, the building weight was revised to 465 tf, a re-estimated weight based on the test results. In the simulation analysis, friction coefficient of 1/10000 in the smaller displacement levels and viscous material temperature of 25.6 ^{o}C were used. The resisting force of dampers are reduce to 1/2 of the evaluated value by Equation (5) , because the response was quite smaller than the design revel. The simulated results are shown in Figure 10 in comparison with observed time histories. It is confirmed that the numerical results well describes the observed response data of the building during actual earthquake.

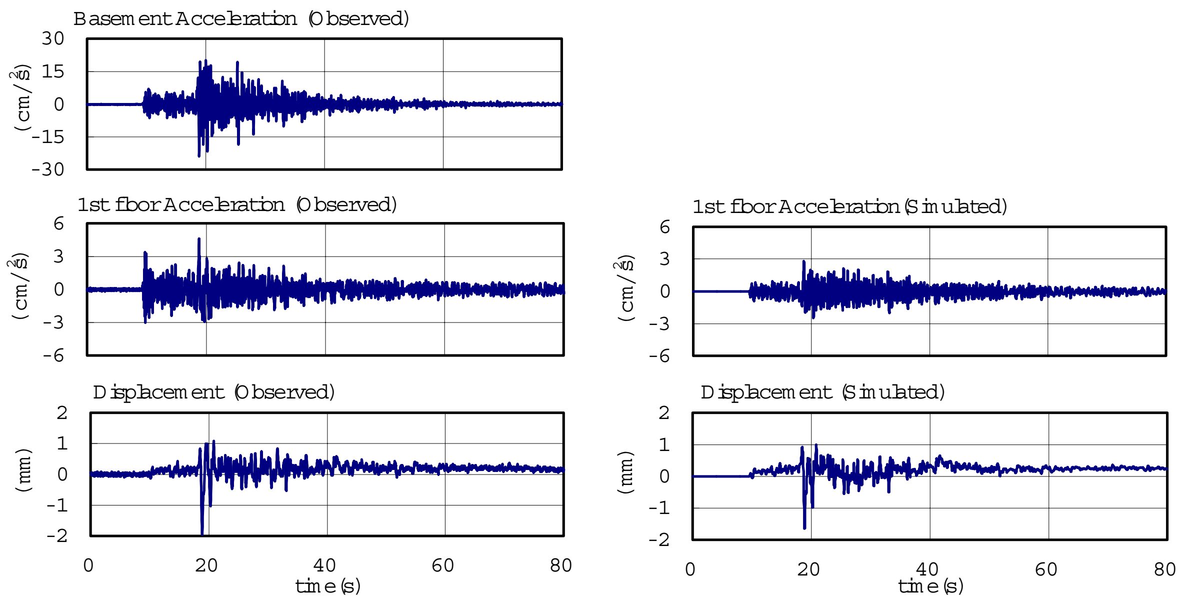


Figure 10: Time histories of observed and simulated results

CONCLUSIONS

The eccentric roller bearing isolation system can effectively prolongs the natural periods by changing the shape of the eccentric rollers. It is a superior isolation system because the natural period will be longer according to the increment of the displacement. By conducting the performance verification tests including free vibration tests, the fundamental properties and performance have been confirmed. Through the earthquake response observations, it is also verified that this system is sufficiently applicable to the actual buildings. In addition, the numerical simulation of the earthquake response is performed with a geometric non-linear model of this bearing. It is also confirmed that the non-linear model well describes the response of the building during actual earthquake.

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