CONTROL EFFECT OF SEMI-ACTIVE SWITCHING OIL DAMPER INSTALLED IN ACTUAL HIGH-RISE BUILDING DURING LARGE EARTHQUAKES

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ABSTRACT :

This paper estimates the dynamic characteristic, especially damping, of an actual high-rise building with two kinds of oil dampers from records of the building's responses during large earthquakes. The building is located in Niigata prefecture, Japan, which has recently been subjected to four large earthquakes: the Mid Niigata prefecture Earthquake in 2004, the Noto Hanto Earthquake in 2007, the Niigataken Chuetu-oki Earthquake in 2007 and the Iwate-Miyagi Nairiku Earthquake in 2008. During these earthquakes, valuable records were obtained of the response of the building and behavior of the semi-active oil damper. From the observed responses, equivalent damping ratios are estimated larger than 6% in the transverse direction in which the semi-active oil dampers are applied and larger than 4% in the longitudinal direction in which the passive oil dampers are applied. Thus, high damping property of the building equipped with oil dampers is verified during earthquakes. The effect of the dampers was also discussed with reference to a seismic design model. By comparing the damping ratio added by the dampers estimated from the earthquake records with that estimated from the seismic design model with passive oil dampers, it was verified that the passive oil dampers showed almost the same results as expected, and the semi-active oil dampers showed high performance in adding damping, which was about 1.7 times as large as that expected by a passive oil damper.

KEYWORDS: structural control, semi-active oil damper, damping, observed record

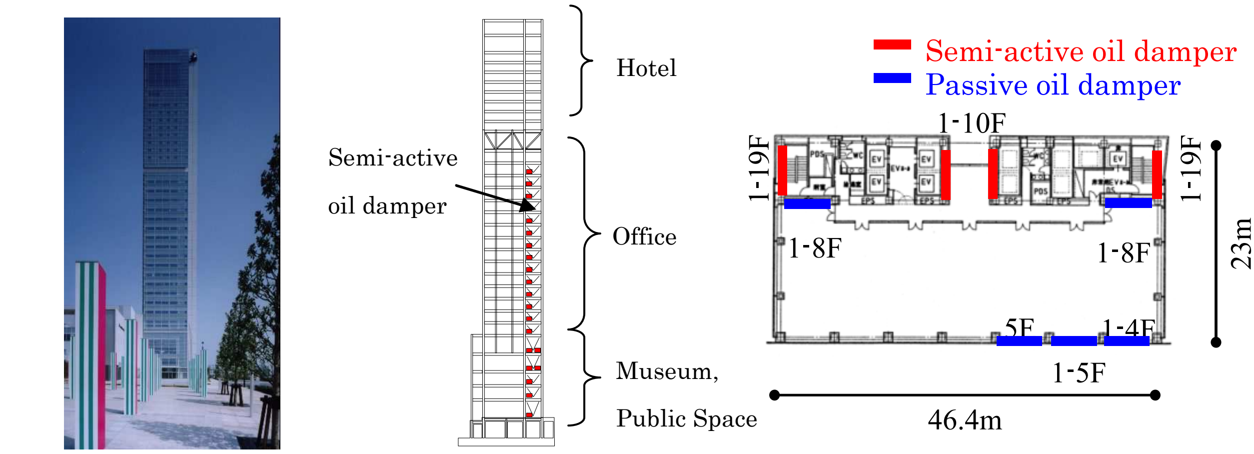
1. INTRODUCTION

In the last two decades a lot of research and application are carried out on structural control devices (Spencer, 2003, etc.). Recently many high-rise buildings in Japan are being equipped with some kind of structural control device. However, there are few seismic response records from buildings equipped with these device. Therefore, their effects in actual buildings in actual earthquakes have been insufficiently verified. A high-rise building with two kinds of oil dampers, semi-active and passive, recently experienced four large earthquakes and valuable records of its response and the behavior of the semi-active oil dampers were obtained. This paper reports the high damping characteristics of this building and the effects of the semi-active oil dampers.

2. OUTLINE OF BUILDING AND SEMI-ACTIVE OIL DAMPER

2.1. Outline of high-rise building

The building was constructed in 2003, in Niigata prefecture. Figure 1(1) shows its exterior. It is 140m high and has 31 floors above ground and one underground. The lower floors are used as museum and public space, middle floors are used as offices and the upper floors are used as hotel, as shown in Figure 1(2). Columns are concrete-filled steel tubes and the beams are steel. Oil dampers are mainly designed to reduce building responses under severe earthquakes. However, strong wind blow at winter season in these areas and uncomfortable transverse directional vibrations were expected during winds because of its slender shape. Therefore, the dampers in the transverse direction were upgraded to semi-active oil dampers, which also work for very small vibrations and absorb twice as much energy as conventional oil dampers. Figure 1(3) shows the distribution of the dampers. 72 semi-active oil dampers are set in the transverse direction and 40 passive oil dampers are set in the longitudinal direction.



(1) Exterior of the building (2) Section of Building (3) Plan

Figure 1 Photo and drawings of building

2.2. Outline of semi-active oil damper

Figure 2 shows the semi-active oil damper installed in the building. One of the features of this damper is that the whole system which consists of a controller and an oil damper equipped with sensors is closed as shown in Figure 2. This makes it as easy to use this semi-active oil damper as it is use to a conventional oil damper. Table 1 shows its specifications.

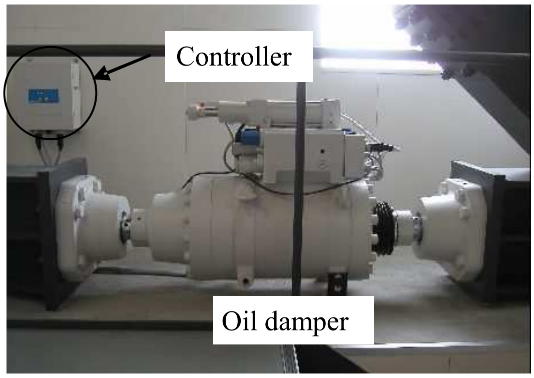


Figure 2 Installed semi-active oil damper

Table 1 Specifications of semi-active oil damper

Item	Specification
Maximum design force F_{max}	1,500kN
Relief force F_R	1,300kN
Maximum piston stroke	120mm
Stiffness k_d	500MN/m
Size	ϕ370mm, 1435mm
Power consumption	Approximately 50W

Oil dampers are usually installed in the inter-story spaces of buildings with braces as shown in Figure 3. Their mechanical model is described as a Maxwell model. Under the constraint of the Maxwell model, a conventional passive oil damper with a linear damping coefficient behaves like a spring when the damping coefficient is too large and doesn't generate any force when it is too small. Therefore, there is an optimum damping coefficient that produces the maximum energy absorption capacity for the passive oil damper. On the other hand, the semi-active oil damper's control law maximizes the energy absorption capacity under the constraint of the Maxwell model by switching the damping coefficient, as described in Kurino et al. (2003). Figure 4 show the behavior of the Maxwell model and its elements under this control law. The damping coefficient (C(t)) is usually kept large (Cmax). When vibration starts C(t) is kept to Cmax from point A to B, so the dashpot doesn't move and the spring accumulates energy. At point B, at which the velocity changes direction, C(t) is changed to a very small value (Cmin) and the dashpot absorbs the energy accumulated in the spring. When the force decreases to point C, C(t) is changed to Cmax again and the damper continues this cycle. The force-displacement relation of a semi-active oil damper under this control law is shown in Figure 5. The force-displacement relation of a passive oil damper with an optimum damping coefficient is also shown in Figure 5. These areas show the energy absorption capacity of the damper. The semi-active oil damper can absorb twice as much energy as the passive oil damper.

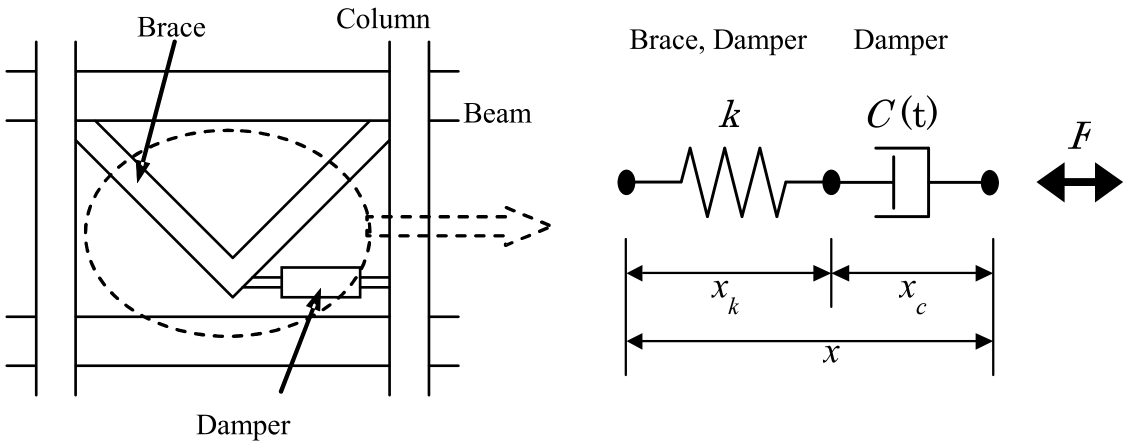
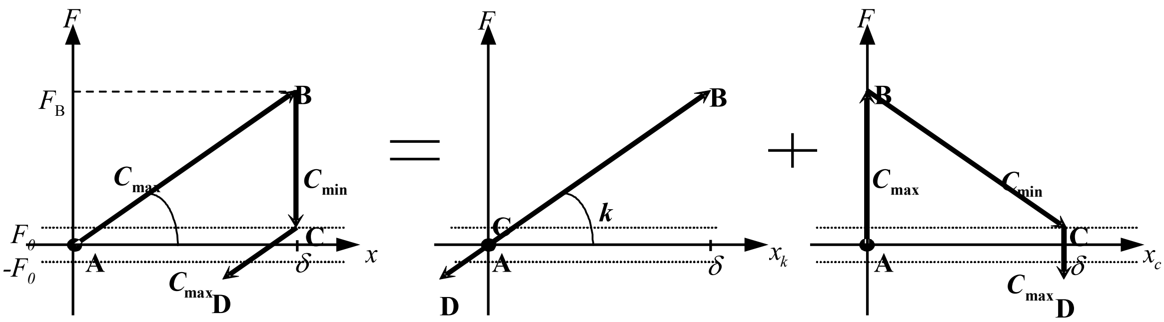


Figure 3 Mechanical model of oil damper installed in a building



(a) Maxwell model (b) Spring element (c) Dashpot element

Figure 4 Behavior of semi-active oil damper

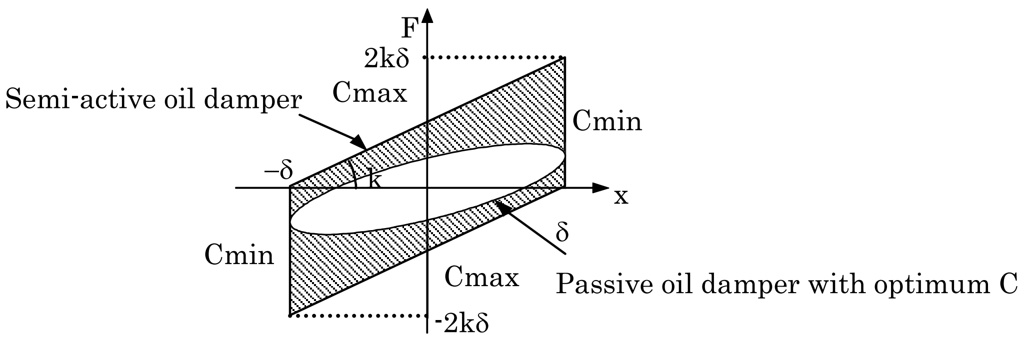


Figure 5 Force-displacement relation of dampers under harmonic excitation

Damper characteristics and performance have been verified through full-scale device tests (Kurino et al., 2003), and forced vibration tests (Tagami et al., 2002, Shimizu et al., 2004). It is now being applied or planned for more than 20 buildings and this number will increase.

3. OBSERVED RESPONSE DURING EARTHQUAKE

Acceleration sensors were set on the roof floor mainly to observe the building's response under strong winds such as typhoons. The 5th floor semi-active oil damper's force and stroke were also observed to check its behavior. On October 23 2004, the building was subjected to the Mid-Niigata Prefecture Earthquake in 2004 whose JMA (Japan Meteorological Agency) magnitude was 6.8 and epicentral distance was about 73km. In order to estimate the dynamic characteristics of the building from records of after shocks, an acceleration sensor was quickly added to the first basement floor. Large after shocks occurred in November 8 and records were obtained during earthquake. And there were three more large earthquakes in 2007 and 2008. The first was the Noto Hanto Earthquake in 2007, whose JMA magnitude was 6.9 and epicentral distance was about 220 km. The second was the Niigataken Chuetu-oki Earthquake in 2007, whose JMA magnitude was 6.8 and epicentral distance was about 57 km. The third was the Iwate-Miyagi Nairiku Earthquake in 2008, whose JMA magnitude was 7.2 and epicentral distance was about 200km.

During these earthquakes, the maximum damper force reached 640kN, which was the maximum force of this damper in an actual building. These records are very valuable because such large responses of a structural controlled building and a structural control device in an actual building are rare. Figure 6 shows the location of the building and the epicenters. Table 2 shows the maximum acceleration of the roof floor and the first basement floor and the maximum force of the semi-active oil damper in each earthquake.

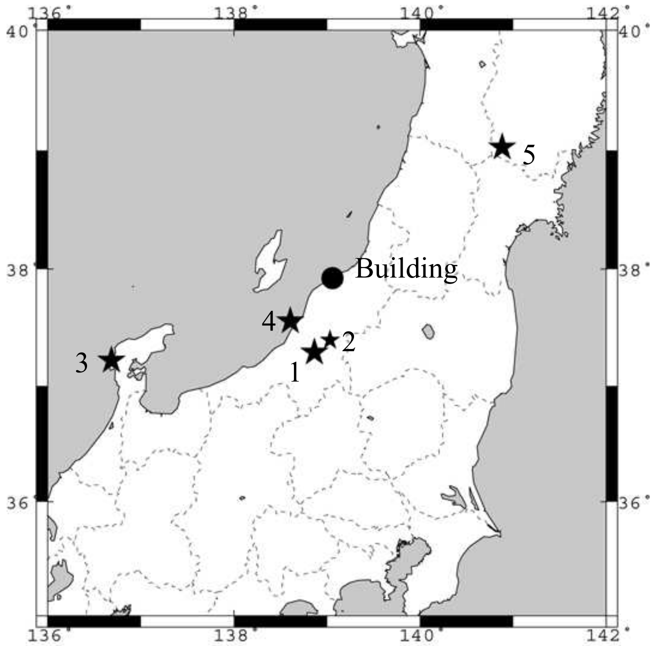


Figure 6 Location of building and epicenters

Table 2 Maximum values of observation records

	Earthquake	B1F Acceleration (cm/s^2)		RF Acceleration (cm/s^2)		Force (kN)
		Longitude	Transverse	Longitude	Transverse	
1	Mid Niigata (main)	-	-	50.8	74.4	262
2	Mid Niigata (after)	7.6	4.0	18.1	14.7	111
3	Noto Hanto	11.1	8.8	28.9	38.6	127
4	Chuetu-oki	24.0	20.0	46.8	99.6	640
5	Iwate-Miyagi Nairiku	-	-	28.8	31.1	195

Figure 7 shows the observed acceleration at RF and the force-stroke relation of semi-active oil damper during each earthquake. The force-stroke relation shown in Figure 7(c) shows the typical parallelogram shape produced by this control law (see Figure 5).

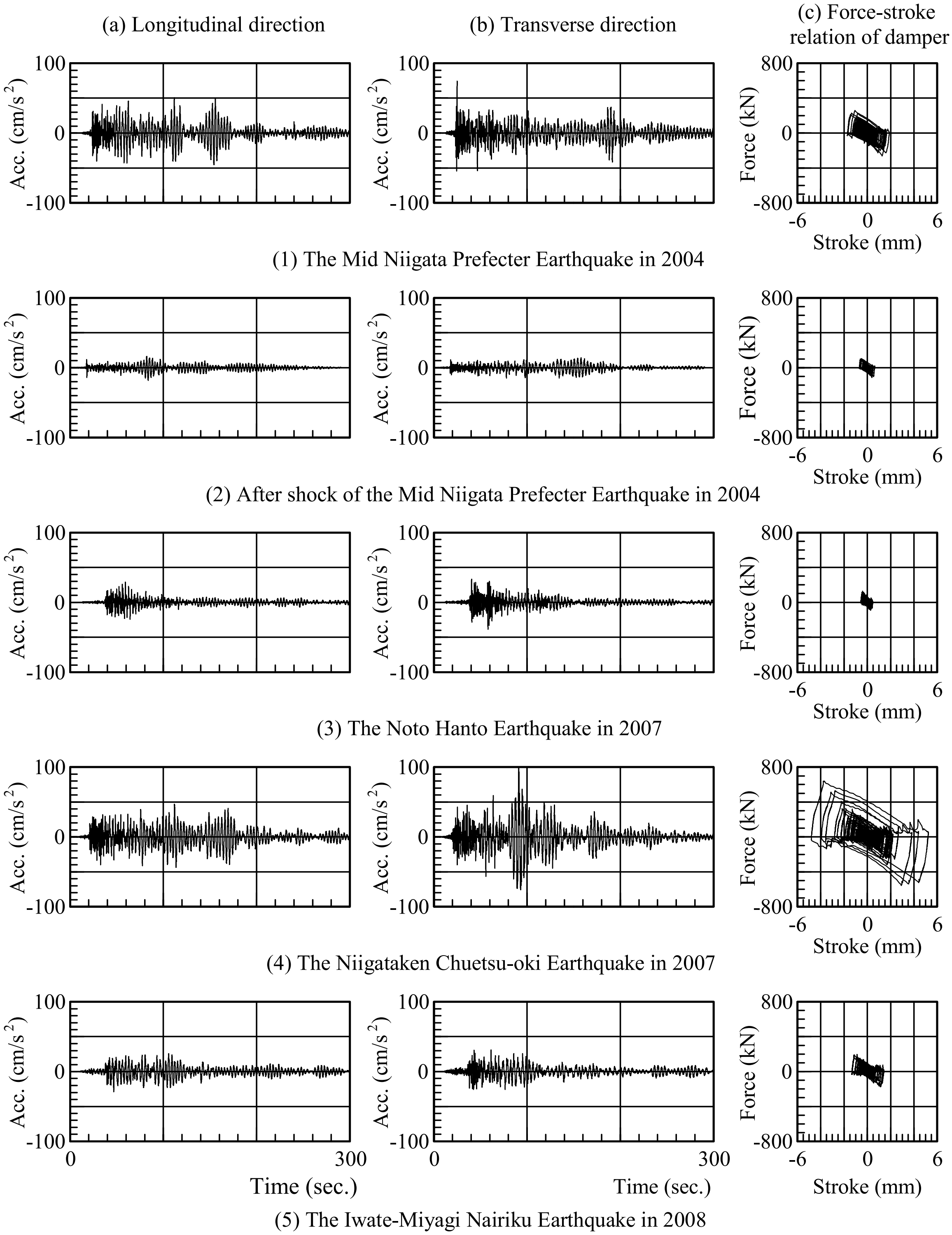
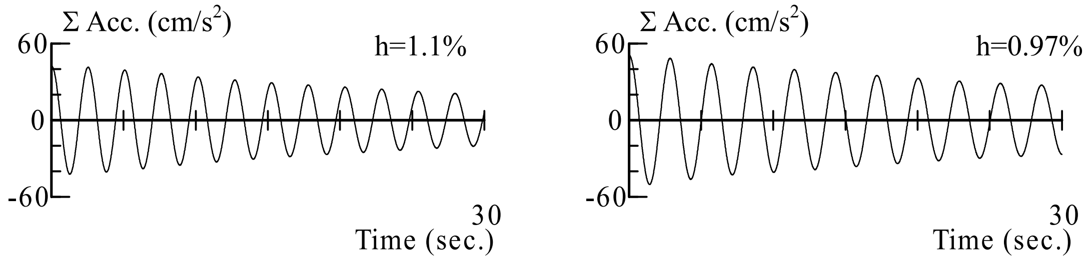


Figure 7 Observation records during earthquake

4. ESTIMATION OF DYNAMIC CHARACTERISTICS OF BUILDING

In this section, dynamic characteristics such as natural frequency and equivalent damping ratio are estimated. In particular, damping is discussed and the effect of dampers is verified. Only the first mode, which is the dominant vibration mode of the building, is considered.

Before discussing damping during earthquakes, damping during microtremors is demonstrated, because the vibration level of microtremors is small enough to neglect the effect of dampers. Equivalent damping ratios of the building during microtremors were estimated by the Random Decrement (RD) technique (Tamura et al., 1993). Time histories of free vibrations obtained by the RD technique are shown in Figure 8. Estimated damping ratios were 0.97% in the transverse direction and 1.1% in the longitudinal direction. On the basis of damping of conventional steel structures shown in Satake, 2003, these results were inferred as damping without dampers.



(a) Longitudinal direction (b) Transverse direction

Figure 8 Random decrement and free vibration decay response of microtremor

Next, the dynamic characteristics under earthquake vibrations are estimated. First, the time history of the roof floor acceleration is filtered to extract the first vibration mode. Then a Single Degree of Freedom (SDOF) system that makes the mean-square error ε the smallest is identified as shown in the following Eqn. 1.

$$\ddot{x}(t) + 4\pi h f \dot{x}(t) + \varpi^2 x(t) = -{}_1\ddot{X}_{B1F}(t)$$
$$\varepsilon = \int_0^T ({}_1\ddot{X}_{RF}(t) - {}_1\beta_{RF}\ddot{x}(t))^2 dt \rightarrow \min \qquad (1)$$

where x(t) is the response of a SDOF system, h is the damping ratio of a SDOF system, *f* is the natural frequency of a SDOF system, ${}_1\ddot{X}_{B1F}$ is the filtered acceleration record at the first basement floor, *T* is the duration of the earthquake, ${}_1\ddot{X}_{RF}$ is the filtered acceleration record at the roof floor, and ${}_1\beta_{RF}$ is a first mode participation function at the roof floor. As a result, the natural period and the damping ratio of the SDOF system are identified as those of the building.

In Figure 9, the dotted line shows the filtered acceleration record at the roof floor, and the full line shows the identified time history of the record of the Niigataken Chuetu-oki Earthquake in 2007. These lines show a significant match. Figure 10 shows the identified 1st mode natural frequencies and damping ratios of each record. The amplitudes are the maximum displacement of the roof floor. Identified damping ratios are from 6.4% to 6.7% in the transverse direction and from 4.3% to 4.8% in the longitudinal direction. Compared with the microtremor case shown by the dot and dashed line in Figure 10(2) the high damping characteristic of the building with oil dampers are verified.

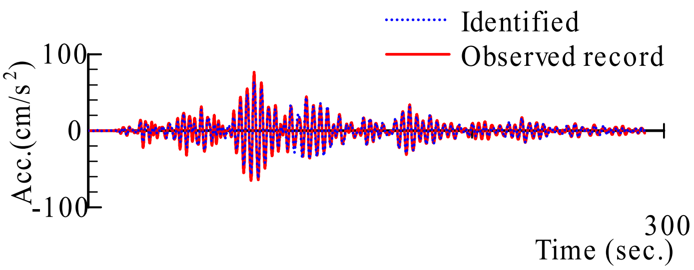
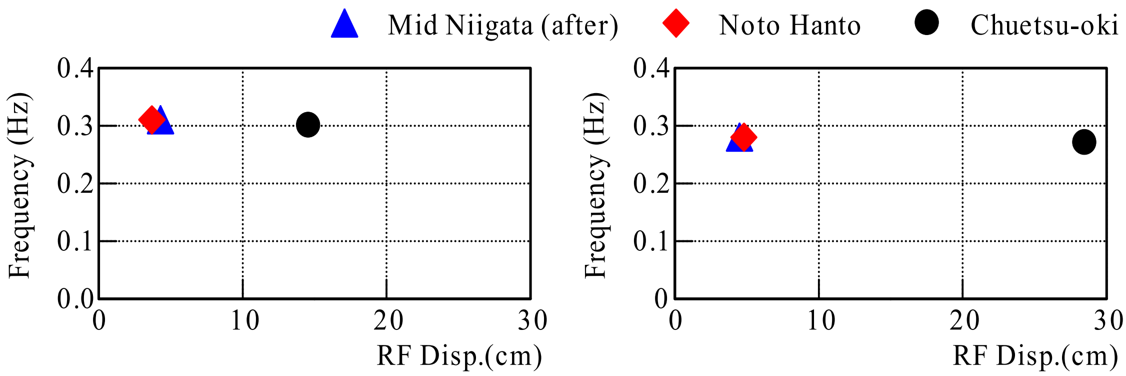
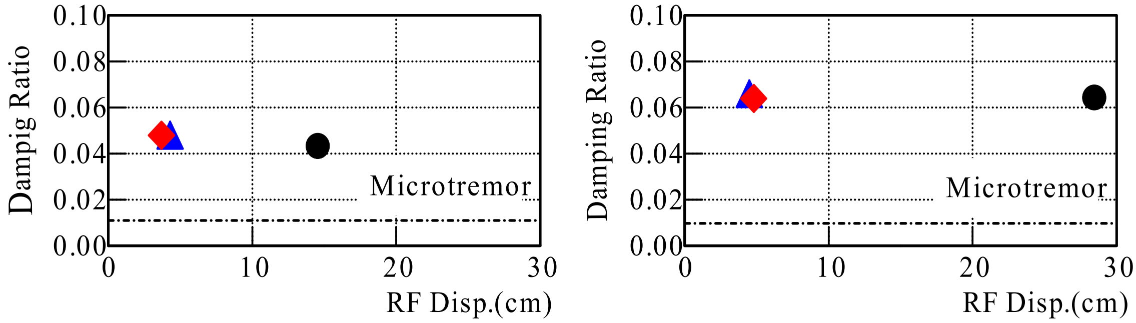


Figure 9 Transverse directional acceleration at roof floor
(The Niigataken Chuetsu-oki Earthquake in 2007)



(a) Longitudinal direction (b) Transverse direction

(1) 1st mode natural frequency

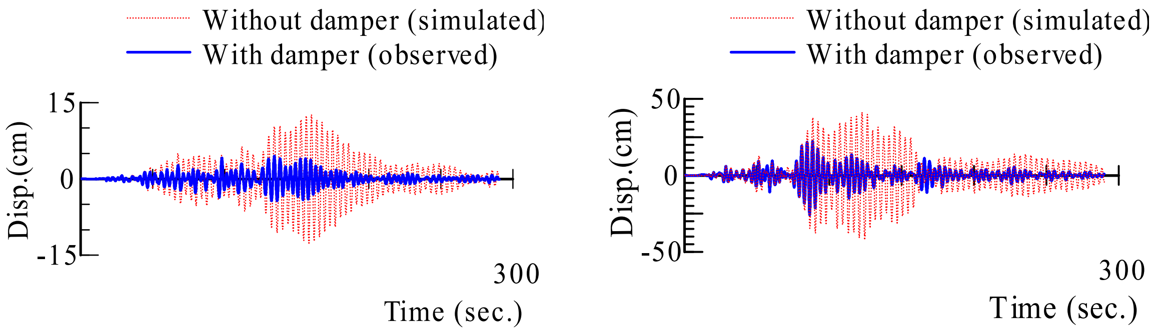


(a) Longitudinal direction (b) Transverse direction

(2) 1st mode damping ratio

Figure 10 Estimated dynamic characteristics

In Figure 11, the dotted line shows displacement estimated with analytical study compared with the full line shows observated displacement at the roof floor at after shock of the Mid Niigata Prefecture Earthquake in 2004 and the Niigataken Chuetu-oki Earthquake in 2007. Displacement was greatly reduced with the effect of semi-active oil damper.



(1) After shock of the Mid Niigata (2) The Niigataken Chuetsu-oki

Figure 11 Control effect of semi-active oil damper
(Transverse directional displacement at the roof floor)

5. CONTROL EFFECT UNDER STRONG WIND

This section demonstrates the effect of the semi-active oil dampers during strong winds. In 2004, 10 typhoons struck Japan. One of them, Typhoon 16, had a maximum daily wind velocity of 19.5m/s, which was recorded at Niigata Local Meteorological Observatory. This was the maximum daily wind velocity in 2004 in Niigata, and it continued for about 2 hours. Damping in the transverse direction during strong wind blow with this typhoon was also estimated by an RD technique as 5.3%. And building response was greatly reduced and improved the habitability under strong wind blow.

6. CONCLUSION

Four large earthquake records were obtained from a high-rise building equipped with semi-active oil dampers in the transverse direction and conventional passive oil dampers in the longitudinal direction. Estimated damping verified the high damping property of the building with oil dampers. Equivalent damping ratios were from 6.4% to 6.7% in the transverse direction and from 4.3% to 4.8% in the longitudinal direction. The effect of the dampers was also discussed with reference to a seismic design model. By comparing the damping ratio added by the dampers estimated from the earthquake records with that estimated from the seismic design model with passive oil dampers, it was verified that the passive oil dampers showed almost the same results as expected, and the semi-active oil dampers showed high performance in adding damping, which was about 1.7 times as large as that expected by a passive oil damper.

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