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EVALUATION OF EARTHQUAKE RESPONSE OF HIGH-RISE BUILDING WITH DAMPERS IN SENDAI DURUING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

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ABSTRACT: In the 2011 off the pacific coast of Tohoku Earthquake (M9.0) which occurred on March 11, the strong shaking in buildings were observed in wide range areas of the whole country. In this paper, vibration characteristics and seismic performance of building are evaluated using observed strong motion records in a high-rise building in Sendai, which is the closest to the epicenter. And, vibration control effect with dampers and damping capacity of the building are confirmed.

Key Words: the 2011 off the pacific coast of Tohoku Earthquake, observed strong motion, microtremor, seismic response, natural period, damper

INTRODUCTION

The authors have continued seismic observation in nationwide since 1956. As of February 2012, 69 buildings throughout Japan are subject to seismic observation (Fig. 1), configuring the seismic observation network mainly with the structurally-distinctive buildings including those located in the increased risk of earthquakes, base-isolated buildings or structural control buildings, and buildings in which a high iron tower is incorporated. Each building is equipped with accelerometers on the bottom, intermediate and top floors as well as on the iron tower. Using this seismic observation network, strong motion records have been observed including records of the Southern Hyogo prefecture earthquake in 1995, Miyagi earthquakes in 2003 and 2005, the Mid Niigata Prefecture Earthquake in 2004. In this network, not only ground shaking but also shaking at multiple points in buildings are simultaneously observed, so this allows to obtain estimation of vibration characteristics of buildings and vibration evaluation of equipment, which are based on seismic observation records. And, by observing not only huge earthquakes but also small and medium earthquakes and microtremor, changes in vibration characteristics by differences in level of amplitude and across ages are evaluable.

In the 2011 off the pacific coast of Tohoku Earthquake (M9.0) which occurred on March 11, the strong shaking were observed in wide range areas of the whole country. At that time, 64 buildings are operated in this network. Main shock records are observed on 29 buildings, and a building furthest to this quake's epicenter is located more than 1250 km away (Fig. 2). The maximum acceleration of over 500 gal is observed in the building in Sendai which is the closest to the epicenter. It is also confirmed that high-rise buildings in Tokyo located about 400 km away from the epicenter are swaying for more than 10 minutes with the maximum amplitude of over 100 cm on the top. These seismic response records are considered valuable for evaluation of not only seismic performance and damage of buildings in a huge earthquake but also vibrations of buildings in long-period ground motion.

This reports focus on a high-rise building in Sendai. In this earthquake, this building which is equipped with dampers has been undamaged, but provided useful data indicating the building behavior during a huge earthquake. In this paper, this building is showed as an example that the damper functions effectively, and vibration characteristic and seismic performance of building is evaluated using observed strong motion records in a high-rise building in Sendai. And, vibration control effect with damper and damping capacity of the building is confirmed.

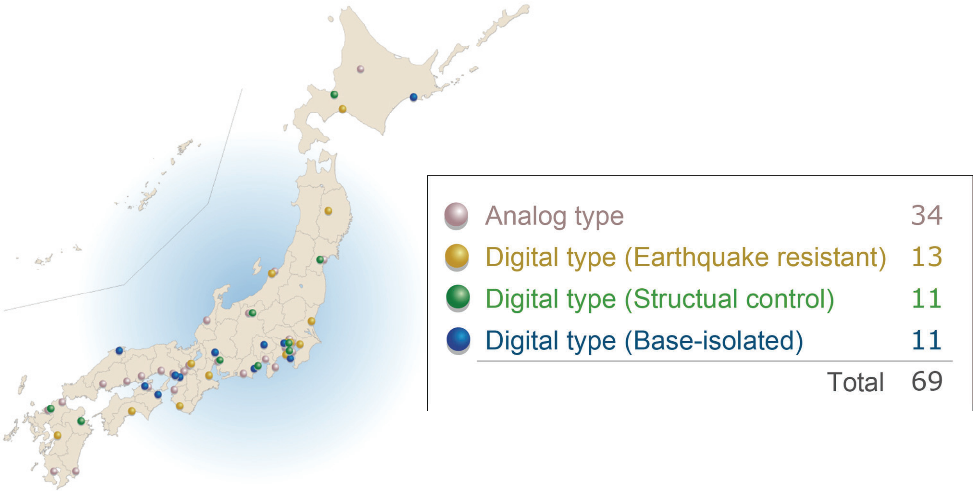

Fig. 1 The seismic observation network

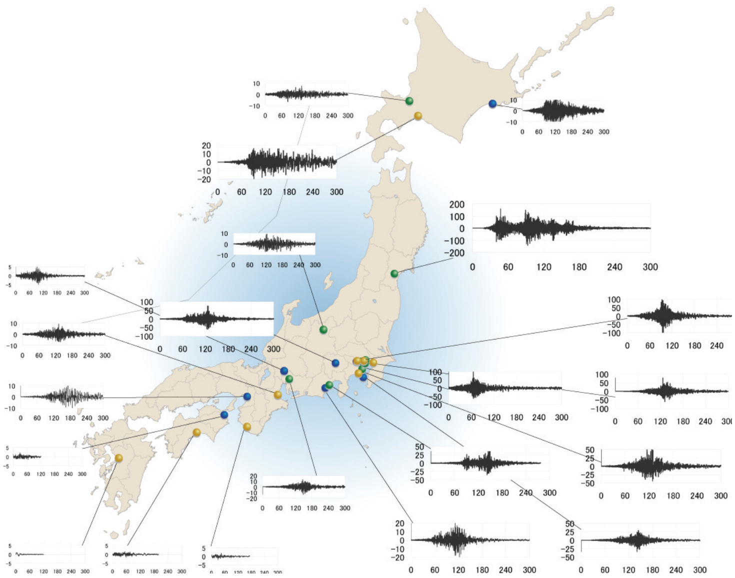

Fig. 2 Observation records of the 2011 off the pacific coast of Tohoku Earthquake

OVERVIEW OF THE BUILDING

The intended building is located about 175 km from the epicenter. This building is a high-rise building equipped with the RDT (Rotary Damping Tube) and LED (Lead Extrusion Damper) as dampers, and has an iron tower. Additionally, the building is equipped with accelerometers for the purpose of figuring out building behavior at time of earthquakes, which have produced a number of records since the building completion in 2004. Servo-type accelerometers (resolution of 24 bit) that enable measurement in the three directions of X, Y and Z are installed on the second basement, ground and 22nd floors as well as on the top of the iron tower. The X direction is the longitudinal beams, and the Y direction is the transverse beams. Fig. 3 shows the locations of accelerometers in the building.

Triggered by the accelerometer on the second basement floor, seismic observation starts simultaneously with the accelerometers installed on the relevant floors when the second basement floor exceed 1.0 gal. The sampling frequency and range of measurement are set to 100 Hz and ±2,097 gal, respectively. The data observed during the 2011 Tohoku earthquake were recorded for more than one hour.

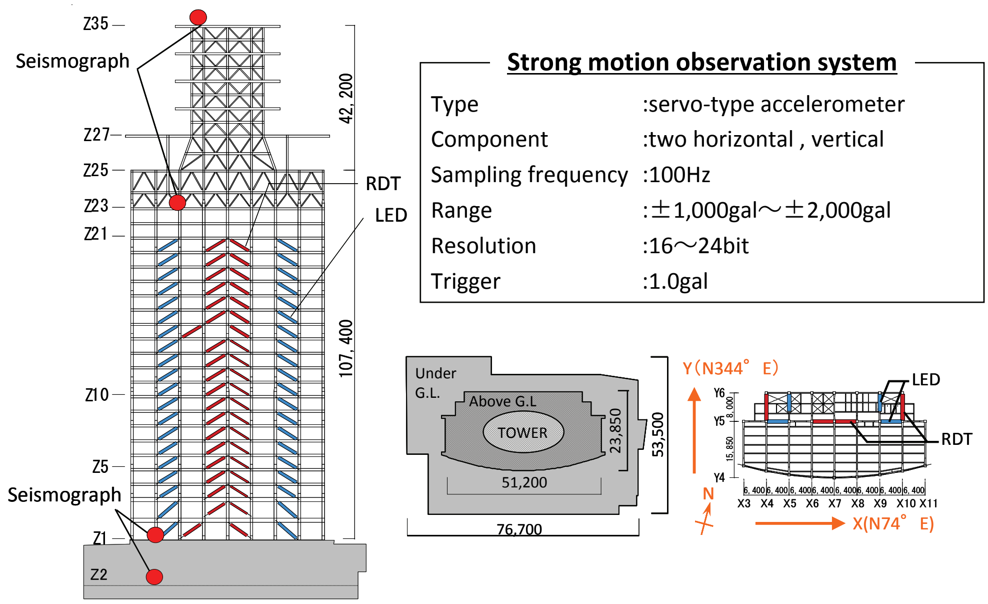

Fig. 3 The locations of accelerometers in the building

ANALYSIS OF OBSERVATION RECORDS

In this section, the characteristic of observed seismic waves is analyzed by comparing the records obtained from before and after the earthquake and from near buildings.

Observed seismic waves

Fig. 4 shows the observation record at the second basement. The maximum acceleration in the X direction is 158.5 gal, and that in the Y direction is 257.5 gal. The seismic wave contains two peaks, and this has the reason that seismic shift have occurred in two area, both of them are located in off Miyagi prefecture. Fig. 5 shows the records observed in Kobe city during the Southern Hyogo prefecture earthquake in 1995. The comparison between Fig. 4 and Fig. 5 shows that big shakes during the 2011 Tohoku earthquake continue for a surprisingly long time.

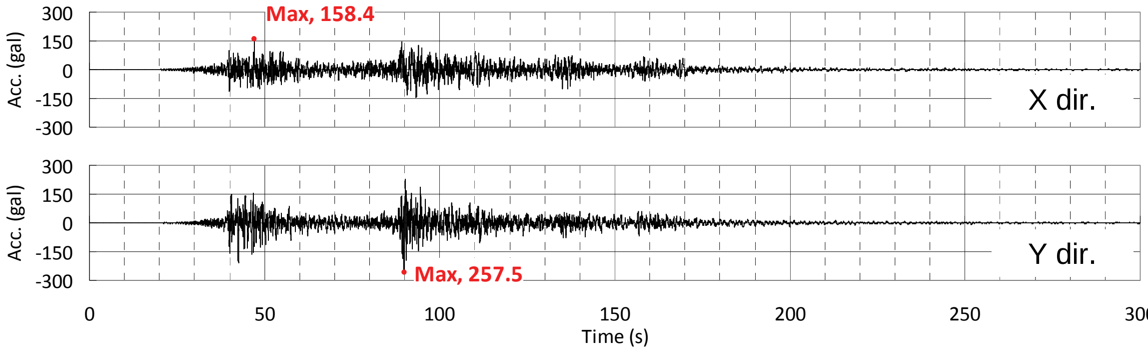

Fig. 4 The observation record at the second basement

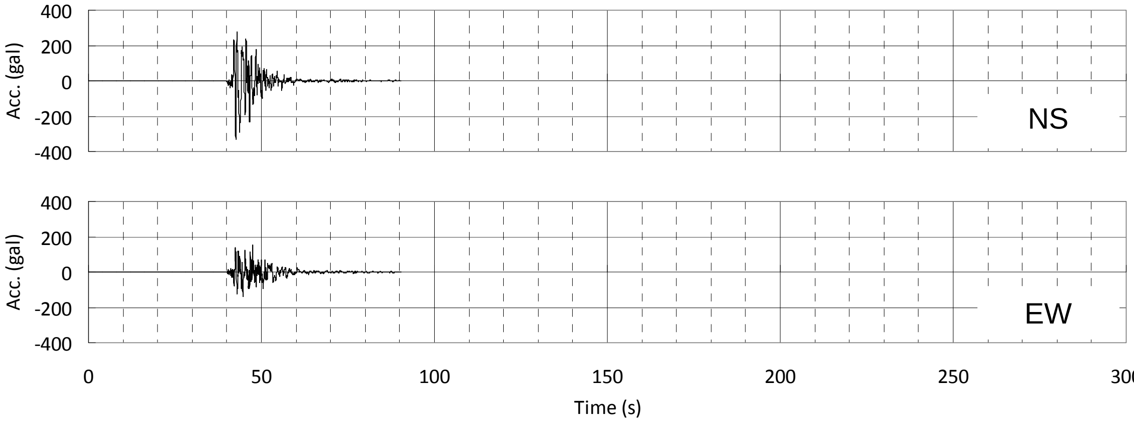

Fig. 5 the records observed in Kobe city during the Southern Hyogo prefecture earthquake in 1995

Spectral analysis

Using the records of the 2011 Tohoku earthquake, the response spectrum was calculated. Fig. 6 shows the comparison of the response spectrum of the largest earthquake ever observed in the building before the 2011 Tohoku earthquake (the Miyagi earthquakes in 2005) and the Southern Hyogo prefecture earthquake in 1995, and the design basis spectrum in Japan (Level 2). As seen in Fig. 6, the 2011 Tohoku earthquake is much larger than the earthquake ever observed, and this is slightly smaller than the design basis spectrum in Japan, but it exceeds in some periodic bands. Otherwise, the spectrum is generally smaller than that of the 1995 Hyogo earthquake, and this difference is remarkably seen in around the periodic band from 1.0 seconds to 2.0 seconds, which may cause particularly building damage.

Also, Fig. 7 shows the comparison of the response spectrum of the intended building with records of K-NET on free field in Sendai and BRI located about from 250 m away from the building. The ground condition of the intended building is relatively suitable, and it is considered that the difference from the record of K-NET is caused by the difference of ground conditions. The record of the intended building is well accorded with BRI.

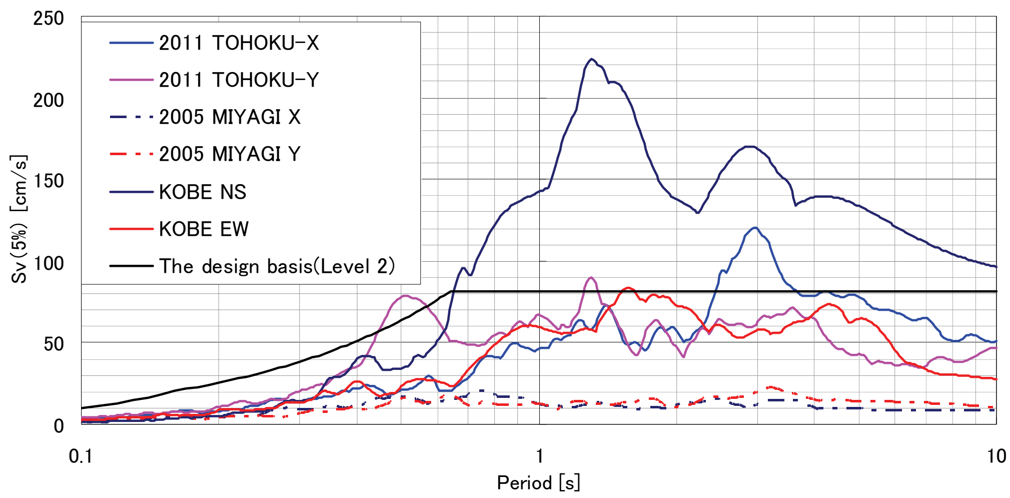

Fig. 6 The comparison of the response spectrum with other earthquakes

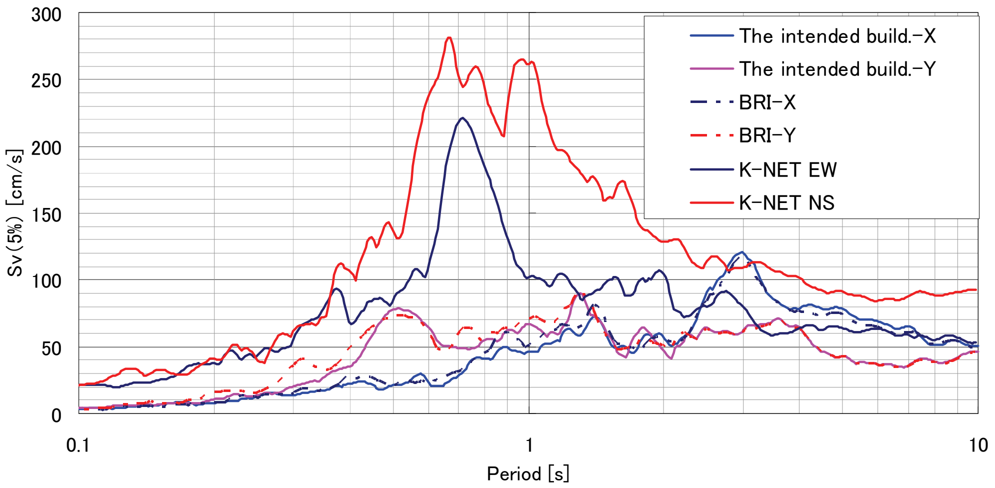

Fig. 7 The comparison of the response spectrum with other points

VIBRATION CHARACTERISTICS OF A BUILDING

Based on the records of observation multiple points in the intended building, vibration characteristics are identified. And the effects that may influence vibration characteristics are considered. This section presents a comparison of the records with 3 seismic observation records of a foreshock on May 9 in 2011, the maximum aftershock on April 7 in 2011 and the Mid Niigata Prefecture Earthquake in 2004. The specifications of earthquakes are shown in Table 1.

Table 1 The specifications of earthquakes

No.	Seismic source information					Epicenter location	Maximum Acceleration (The second basement)	
	Date and Time of occurrence	Northern latitude	East longitude	Depth (km)	Mj		X	Y
1	2004/10/23 17:56:00	37.29	138.87	13.08	6.8	the Mid Niigata Prefecture	5.4	5.7
2	2011/03/09 14:45:12	38.20	143.17	8.00	7.3	Off the Coast of Sanriku	15.3	18.2
3	2011/03/11 14:46:18	38.10	142.86	23.74	9.0	Off the Pacific coast of Tohoku	158.4	257.5
4	2011/04/07 23:32:43	38.20	141.92	65.89	7.1	Off Miyagi Prefecture	131.8	186.0

The design natural frequency

The design natural periods of the building are 2.97 seconds on the X, and 3.26 seconds on the Y direction, which is shown as Table 2. Then Fig. 8 shows the relations of the response spectrum and natural frequency of the 2011 Tohoku earthquake. In this earthquake, the seismic wave of the X direction contains many components with around a period of 3 seconds, and it is thought that a slightly severe seismic force works on the X direction of the building. As for the wave in the Y direction, it contains many components with a period of 2 seconds and under, and it is considered that the seismic wave is excited in higher-order modes.

Table 2 The design natural periods of the building (sec)

Direction	1st.	2nd.	3rd.
X	2.973	1.012	0.606
Y	3.260	1.110	0.678

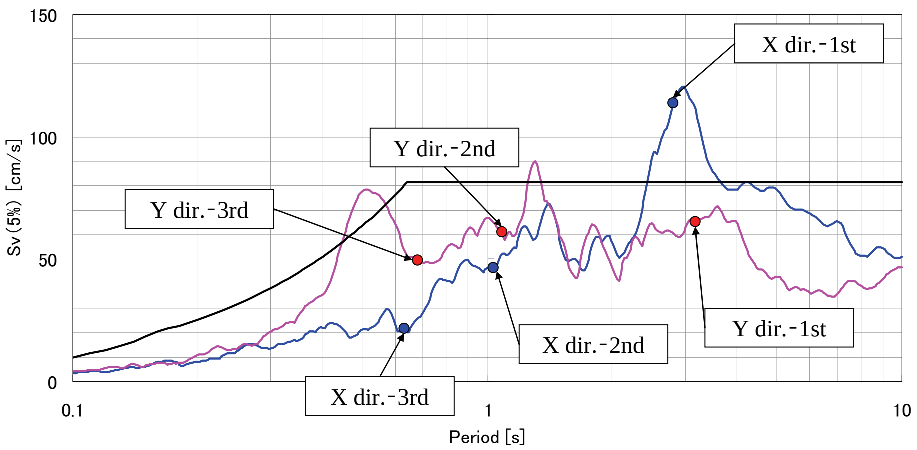

Fig. 8 The relations of the response spectrum and natural frequency

Estimation of the natural frequency

The building natural frequency is estimated based on the seismic observation record. The building transfer function is calculated using the records of the ground floor and the highest floor (22F). A peak of the calculated transfer function is defined as the estimated building natural frequency. The calculated transfer function from each earthquake record is shown as overlaid curves in Fig.9. In The 2011 Tohoku earthquake, the natural periods are equivalent to the design value of about 2.8 seconds in the X and about 3.2 seconds in the Y direction. In the aftershock, the natural periods are about 2.8 seconds in the X and about 3.2 seconds in the Y direction, on the other hand in the foreshock, they are about 2.4 seconds in the X and about 2.9 seconds in the Y direction, which become rather small. In the earthquake in 2004, they are about 2.2 seconds in the X and 2.7 seconds in the Y direction, which become much smaller than those. As shown in Table 1, the acceleration levels of the earthquake in 2004 and the foreshock are very small compared with those of the main shock and the aftershock. The amplitude dependence of the natural periods of the building estimated from seismic observation records has been confirmed.

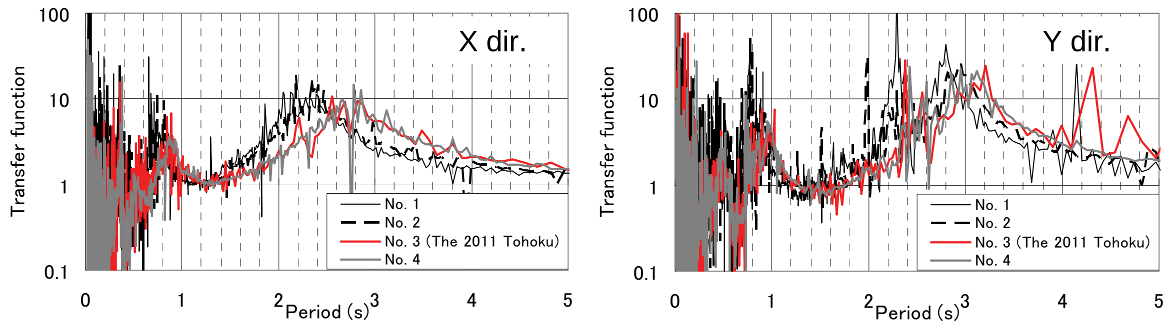

Fig. 9 The comparison of transfer function from each earthquake

TIME-SERIES EVALUATION OF THE NATURAL PERIOD

This section considers considered changes in the natural periods focusing on vibration characteristics over time. Vibration characteristics of the 2011 Tohoku earthquake (the main earthquake) and those before and after the main earthquake are arranged in chronological order, and the tendency is considered.

Evaluation in chronological order

Fig. 10 shows vibration characteristics of the 2011 Tohoku earthquake (the main earthquake) and those before and after the main earthquake in chronological order. In the intended building, microtremor records are is observed periodically since more than 3 years from before the main earthquake, and so the natural periods estimated from the microtremor observation records are is also shown. The figure presents the increased natural periods in the main earthquake and the maximum aftershock both in the X and Y directions which returned to the original values. And, it is confirmed that the average of the natural periods estimated from observation records observed of before the main earthquake are slightly larger than that of after the main earthquake. This tendency is similar to the natural periods estimated from microtremor observation records.

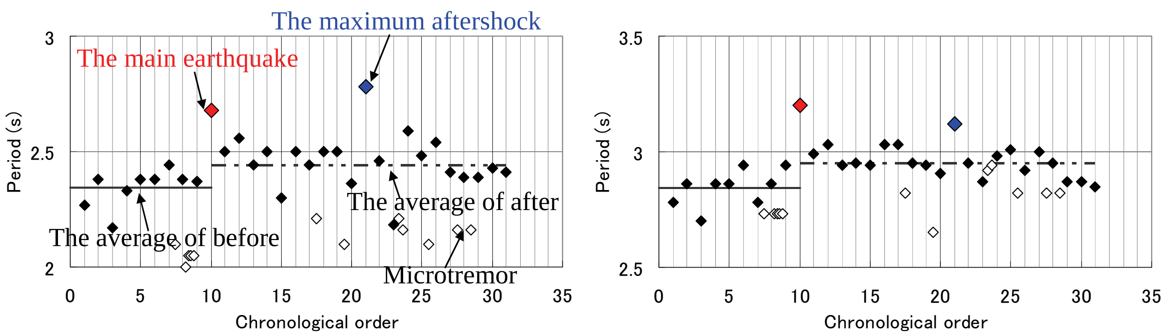

Fig. 10 The natural periods in chronological order

SEISMIC RESPONSE ANALYSIS

Using the records of the 2011 Tohoku earthquake, the earthquake response is was analyzed with a the space frame elasto-plastic model of the intended building. The natural periods of the building is was adjusted by the superimposed load or the member stiffness, based on the natural periods and building conditions estimated from observation records. Table 3 shows analytical parameters of the building and dampers. The observation records from the second basement are were used as the input wave.

Fig.11 shows the comparison of the maximum response of each floor based on the observation records and the analysis. In the X direction, the acceleration and the displacement generally agree with both responses. But in the Y direction, the responses of the analysis result become smaller than the observation record. Fig. 12 shows the comparison of the displacement response waveforms on the 22nd floor and the iron tower top with the observation records. Looking at the time history of the displacement response shown in Fig. 12, the waveforms as the analysis result roughly represented the observation results and ensured the analysis model could reproduce the actual phenomenon. Fig. 13 shows relations between the velocity and the damping force of RDT, and between the displacement and the damping force of LED in the story where the maximum relative story displacement is the largest. It is apparent that RDT provided the sufficient damping performance up to 75 percent of the designed damping force and LED provided the sufficient damping performance by becoming plastic. Fig. 14 shows the time history of absorption energy obtained from analysis analyzed. The absorption energy of dampers consists about 73 percent in the total. It is confirmed made sure that the absorption energy become greatly enlarged just before about 100 seconds when the building amplitude is increased, and also at the same time the building vibration amplitude is dampened. The analysis result verified that the dampers provided the sufficient damping performance, and the building is safeguarded against the earthquake.

Table 3 Analytical parameters of the building and dampers

Analysis Model		Space frame elasto-plastic analysis model
Layer Number		36 layered (Above G.L. = 34, Under G.L. = 2)
Member Model	Column & Beem	Beam element with rigid-plastic edge
	Damper	Lead extrusion damper -> Elasto-plastic spring model
		Rotarydamping tube -> Maxwell model
Viscous damping factor of frame		h = 1.0 % (Proportion to instantaneous stiffness)

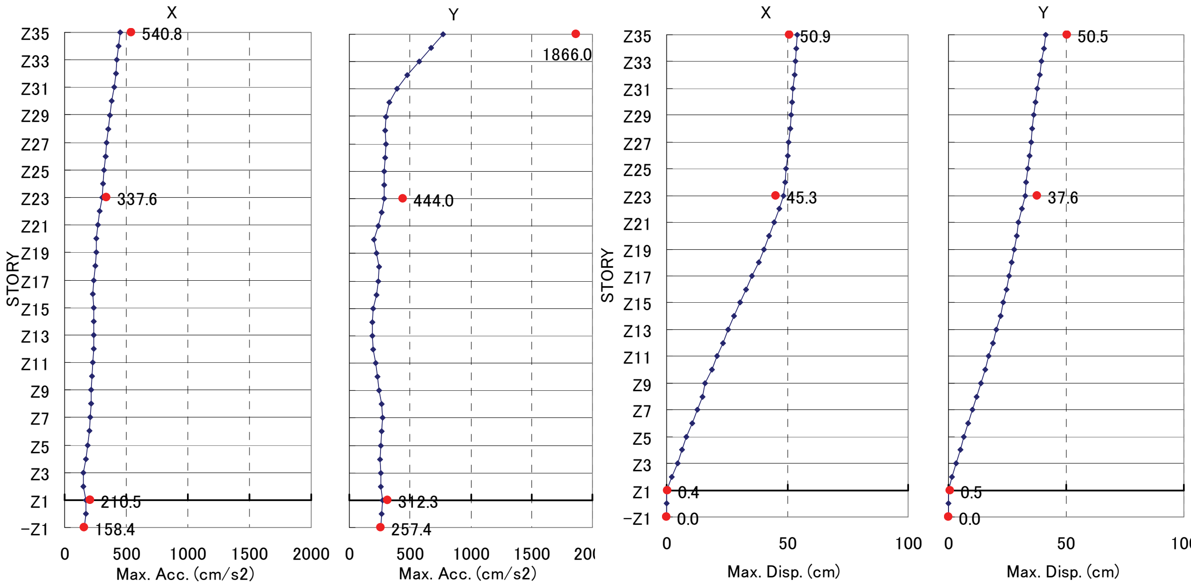

Fig. 11 The comparison of the maximum response

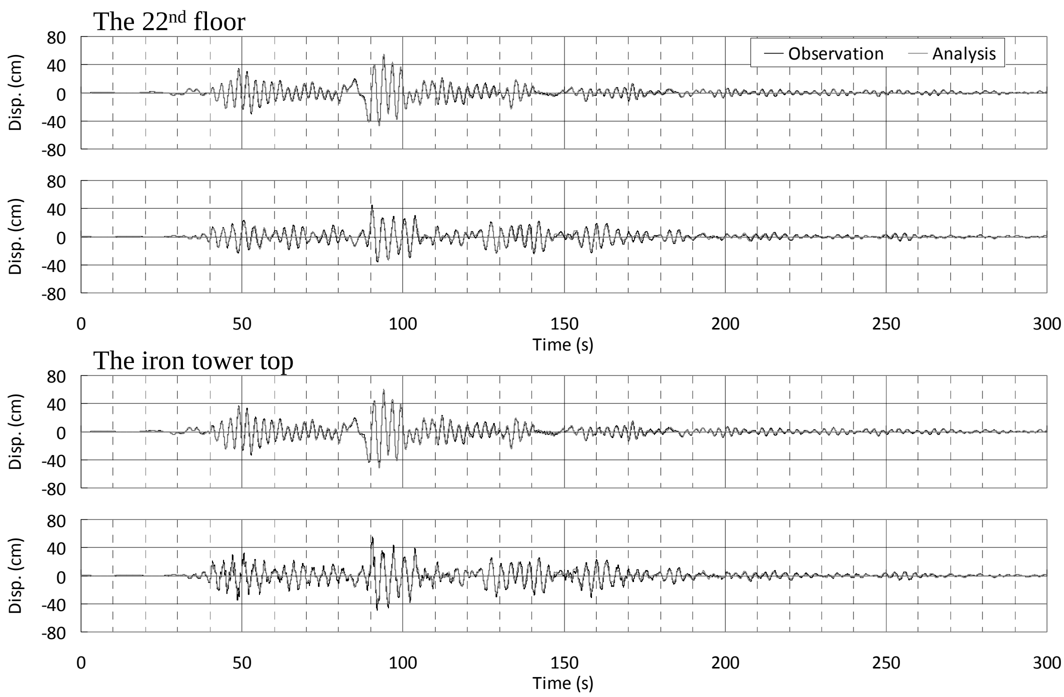

Fig. 12 The comparison of the displacement response

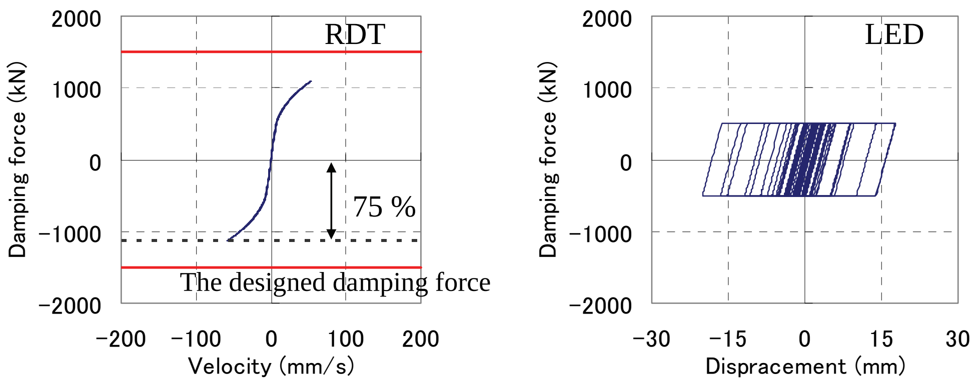

Fig. 13 The damping force

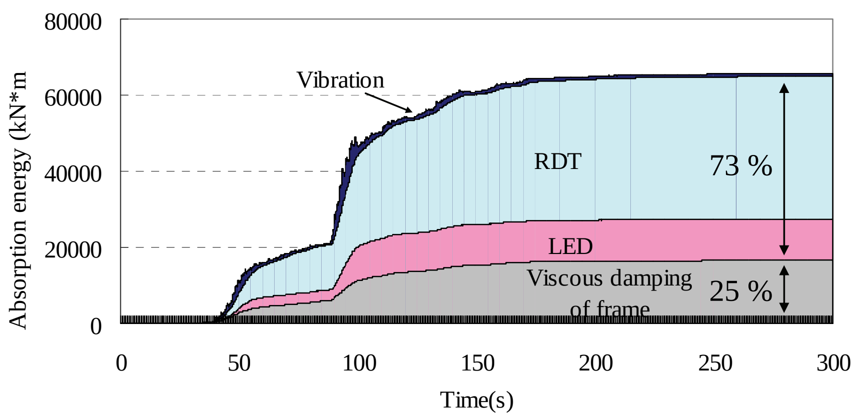

Fig. 14 The time history of absorption energy

CONCLUSIONS

In this report, vibration characteristics and seismic performance of building are evaluated using observed strong motion records in a high-rise building in Sendai during the 2011 off the pacific coast of Tohoku earthquake. The result obtained about the seismic excitation and seismic response is be summarized the following.

1) The seismic motion is slightly smaller than the design basis spectrum in Japan, but it exceeds in some periodic bands, and this is characterized by the long earthquake duration.

2) The natural periods estimated from the main earthquake are larger than ever observed, and these periods are close to the design natural periods.

3) As a result of using the parameters based on observation records, the building response during the large earthquake was simulated. The analysis result verified that the dampers provided the sufficient damping performance, and the building is safeguarded against the earthquake.

But effects of higher-order modes and the difference of the natural periods between before and after the main earthquake hasn't been figured out in this report.

So, the further study must verify possible causes that could affect the vibration characteristics and clarify them through analyses or other means in order to establish how to accurately estimate the safety of buildings after the large earthquake.

ACKNOWLEDGMENTS

Strong motion observation records of National Research Institute for Earth Science and Disaster Prevention, and Building Research Institute are used as records around the intended building. The authors gratefully acknowledge for NIED and BRI.

REFERENCES

Toyota, K. et al. (2001). "Dynamic Loading Experiment and an Application to a High-rise Building of Large-scale Lead Hysteretic Damper. (Part1 to 2)" *Summaries of technical papers of annual meeting Architectural Institute of Japan*, Vol. B-2, pp385-386

Saito, K. et al. (2004). "Application of Hybrid Damping System using Hysteresis Damper and Viscous Damper in Multistory Building." *AIJ Journal of Technology and Design*, Vol. 19,pp95-100

Akagi, H. et al. (2004). "Earthquake Observation System for Telecommunication in Japan." *The 13th WCEE*

Tsukuda, S. et al. (2006). "Seismic Response of the Buildings during the Miyagi-ken-Oki Earthquake. (Part1 to 3)" *Summaries of technical papers of annual meeting Architectural Institute of Japan*, Vol. B-2, pp7-12

Goto, W. et el. (2009). "Analysis of Strong-motion Records during the Iwate-Miyagi-Nairiku Earthquake and Iwate-ken-Engan-Hokubu Earthquake" *Summaries of technical papers of annual meeting Architectural Institute of Japan*, Vol. B-2, pp549-550

Nagashima, S. et el. (2011). "Evaluation of Earthquake Response of High-rise Building with Damper in the 2011 off the Pacific coast of Tohoku Earthquake." *Summaries of technical papers of annual meeting Architectural Institute of Japan*, Vol. B-2, pp313-316