A Study on Seismic Response of Buildings in Sendai during the 2011 Great East Japan Earthquake

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SUMMARY:
This paper presents seismic performance of buildings based on observation records during the 2011 Great East Japan earthquake. The intended buildings are located about 170 km away from the epicentre. One is a structural control building, which provided a high damping performance. Another is an earthquake resistant building, which received little visible damage on structural components. These two buildings are equipped with accelerometers, which have produced a number of records since the buildings completion. The continuous seismic observation is very important for evaluation of seismic excitation, response performance and damage of buildings. The purpose of this research is figuring out building response from observation records of large earthquake, and evaluating safety of buildings after the earthquake with accuracy. In this paper, the vibration characteristics and the damping capacity of buildings are clarified by wave analysis and seismic response analysis using observation records.

Keywords: the 2011 Great East Japan earthquake, observation record, seismic response, natural period

1. INTRODUCTION

The authors have continued seismic observation in nationwide since 1956. As of April 2012, 69 buildings throughout Japan are subject to seismic observation, and configuring the seismic observation network mainly with the structurally-distinctive buildings. Each building is equipped with accelerometers on the bottom, intermediate and top floor. In this network, not only ground shaking but also shaking at multiple points in buildings is simultaneously observed, so this allows obtaining estimation of vibration characteristics of buildings and vibration evaluation of equipment, which are based on seismic observation records.

In the 2011 Great East Japan 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 epicentre is located more than 1250 km away (Figure 1.1.). The maximum acceleration of over 500 gal was observed in a building in Sendai which is the closest to the epicentre. It was also confirmed that a high-rise building in Tokyo located about 400 km away from the epicentre was swaying for more than 10 minutes with the maximum amplitude of over 100 cm on the top.

This paper focuses on two buildings in Sendai, which are located about 170 km away from the epicentre. Observation records in these buildings are valuable for evaluation of various phenomenons during large earthquakes. In this paper, vibration characteristics and seismic performances of these buildings are evaluated using observation records.

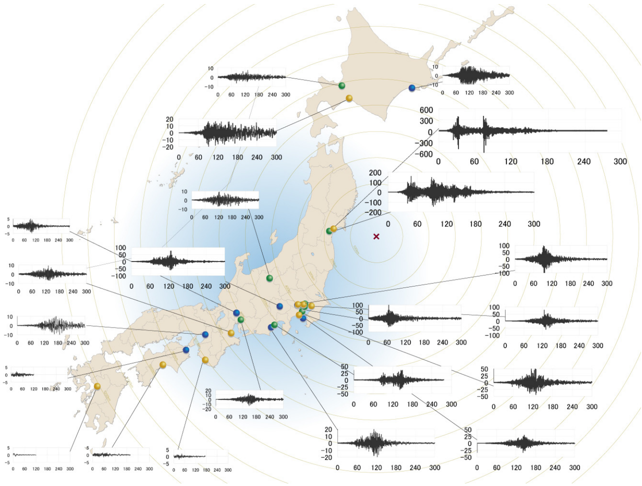

Figure 1.1. Observation records of the 2011 off the pacific coast of Tohoku Earthquake

2. OVERVIEWS OF THE BUILDINGS

Both of the intended buildings are located about 170 km away from the epicentre. But, the distance between two buildings is about 5 km. One is a high-rise steel building with damper (hereinafter referred to as "building A"). The other is an earthquake resistant low-rise building (hereinafter referred to as "building B"). Both buildings differ from one another in many distinctions, including ground conditions, structure types, scales and equipments. And, both have experienced the Miyagi-ken-oki earthquakes in 2003 and 2005, the Iwate-Miyagi-Nairiku earthquake and the Iwate-ken-Engan-Hokubu earthquake in 2008. In this section, overviews of the intended buildings are shown.

2.1. High-rise Steel Building with Damper (Building A)

The building A is a high-rise steel building equipped with the RDT (Rotary Damping Tube) and LED (Lead Extrusion Damper) as dampers, and with a steel tower. And, the building is constructed on firm ground with spread foundation. Figure 2.1. shows a structural drawing and locations of accelerometers. The building is equipped with accelerometers for the purpose of figuring out seismic response, which have produced a number of records since the building completion in 2004. Servo-type accelerometers that enable measurement in three directions are installed on the second basement, the ground and the 22nd floor as well as on the top of the steel tower. The data observed during the 2011 Great East Japan earthquake were recorded for more than one hour continuously.

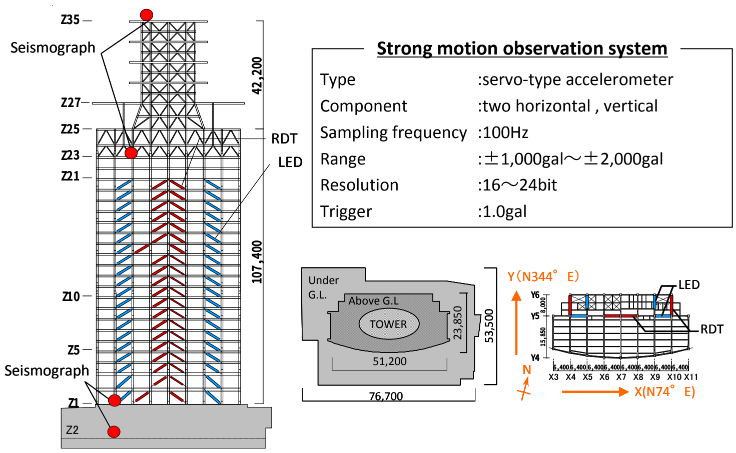

Figure 2.1. Overview of the building A

2.2. Low-rise Reinforced Concrete Building (Building B)

The building B is a low-rise RC building with shear wall. The building is supported by pile foundation. Figure 2.2. shows a structural drawing and locations of accelerometers. The building was designed after the 1978 Miyagi-ken-oki earthquake. So, the building is given consideration to provide sufficient seismic capacity during large earthquakes. The building is also equipped with accelerometers which are analog type (SMAC). The accelerometers have been installed on the ground floor and the top floor since 1982.

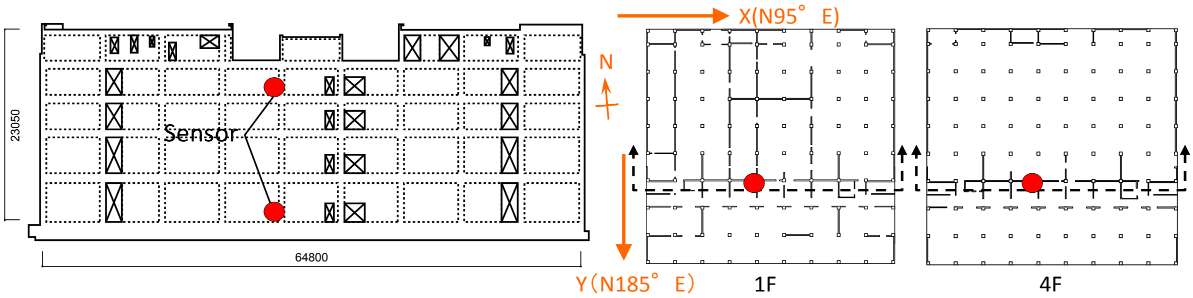

Figure 2.2. Overview of the building B

3. ANALYSIS OBSERVATION RECORDS

3.1. Observed Seismic Waves

Figure 3.1. shows the comparison of the observation records at the second basement in the building A and the ground floor in the building B with the records observed on a building in Kobe, which is subject to author's seismic observation network, during the Southern Hyogo prefecture earthquake in 1995. The maximum acceleration is 158.4 gal in the building A (X dir.), and 586.3 gal in the building B (Y dir.). Both seismic waves contain two peaks, because seismic shift have occurred in two areas, both of them are located in off Miyagi prefecture. The comparison in Figure 3.1. shows that big shakes during the 2011 Great East Japan earthquake continued for a surprisingly long time.

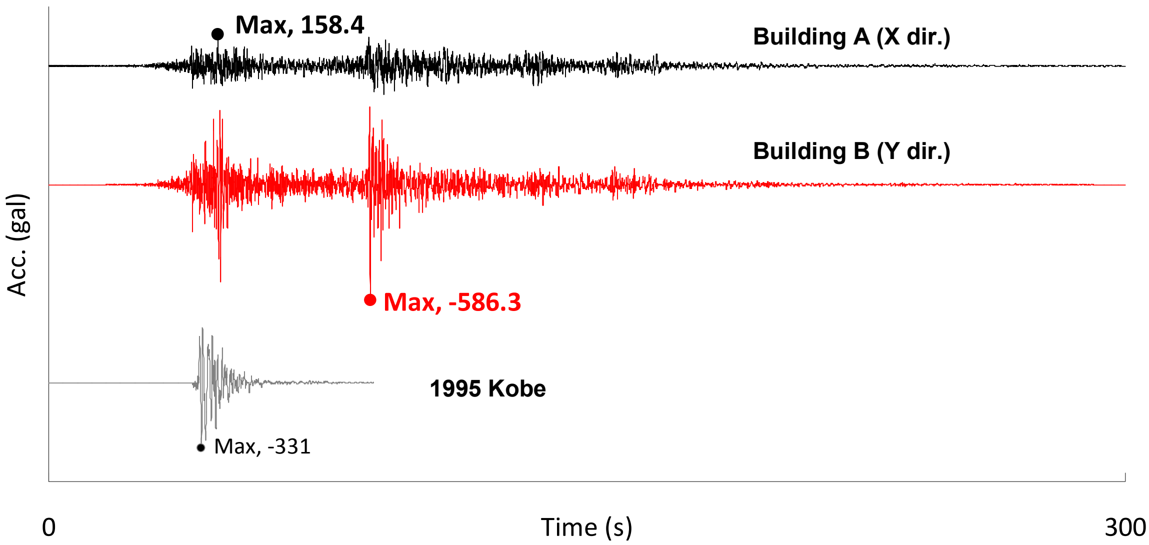

Figure 3.1. Observed Seismic Waves

3.2. Spectral Analysis

Using the records of the 2011 Tohoku earthquake, the response spectrum was calculated. Figure 3.2. shows the comparison of the response spectrum of the Southern Hyogo prefecture earthquake in 1995, and the design basis spectrum on engineering bedrock defined in Japan (Level 2). As seen in Figure 3.2., the spectrum of the building A is slightly smaller than the design basis spectrum, but it exceeds in about 3.0 periods. And, the building A is generally smaller than that of the 1995 Hyogo earthquake, and this difference is remarkably seen in around the periodic band from 1.0 second to 2.0 seconds, which may cause particularly building damage. Otherwise, as for the building B, the observation wave contains very large components with 1.0 second and under, that far exceeds the building A and the design basis. The ground condition of the building A is relatively suitable, and it is considered that the difference from the building B is caused by the difference of ground conditions.

Also, Figure 3.3. shows the comparison of the response spectrum with records of K-NET on free field in Sendai located about 250 m away from the building B. The building B is generally smaller than that of K-NET. It is considered that the difference is cased by the effect of input loss.

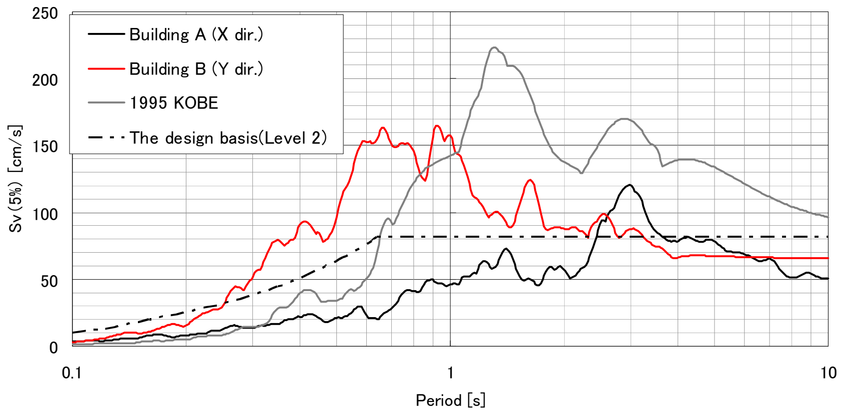

Figure 3.2. The comparison of the response spectrum with other earthquakes

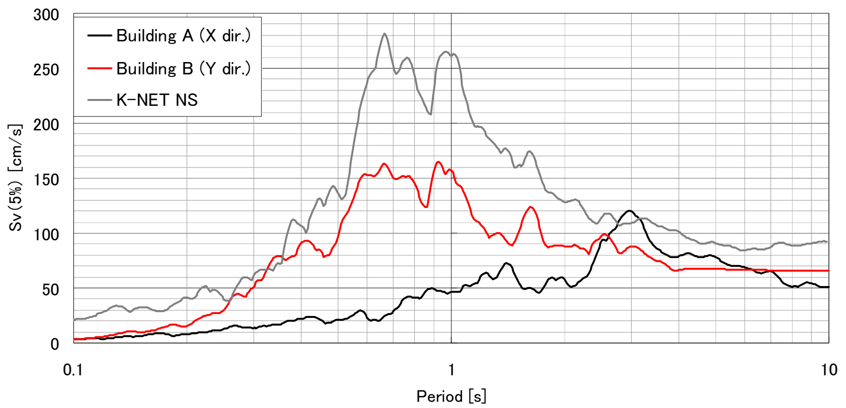

Figure 3.3. The comparison of the response spectrum with records of K-NET

4. NATURAL PERIODS OF STRUCTURAL CONTROL BUILDING

Based on the records of observation multiple points in the building A, vibration characteristics are identified. And the effects that may influence the vibration characteristics of structural control building are considered. This section considers changes in natural periods over time.

4.1. Estimation of Natural Periods

At first, this section describes differences of transfer functions between the main shock, a historical record, and records obtained from before and after the main shock. The specifications of intended records are shown in Table 4.1. The building transfer function was calculated using the records of the ground floor and the 22nd floor. A peak of the calculated transfer function is defined as the estimated building natural period. The calculated transfer function from each earthquake record is shown as overlaid curves in Figure 4.1. As well, the design natural periods at the 1st-mode of the building are 2.97 seconds on the X direction. As shown on Figure 3.2., the seismic wave of the X direction contains many components with around a period of 3.0 seconds, and it is thought that a slightly severe seismic force works on the X direction of the building.

In the 2011 Tohoku earthquake, the natural period is equivalent to the design value of about 2.8 seconds in the X direction. And, the natural period is also about 2.8 seconds in the aftershock. On the other hand in the foreshock, this is about 2.4 seconds, which becomes rather small. In the earthquake in 2004, it is about 2.2 seconds, which become much smaller than those. As shown in Table 4.1., the acceleration levels of the earthquake in 2004 and the foreshock are very small compared with those of the main shock and the aftershock. So, the amplitude dependence of the natural periods of the building estimated from the observation records was confirmed.

Table 4.1. 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

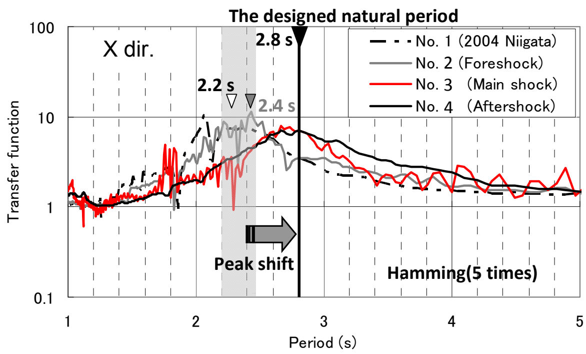

Figure 4.1. The comparison of transfer function from each earthquake

4.2. Chronological Change in Natural Period

The vibration characteristics of the 2011 Tohoku earthquake (the main shock) and those before and after the main shock are arranged in chronological order, and the tendency is considered.

Figure 4.2. shows the vibration characteristics of the 2011 Tohoku earthquake and those before and after the main shock in chronological order. In building A, microtremor records are observed periodically since more than 3 years from before the main earthquake, and so the natural periods estimated from the microtremor records are also shown. The figure presents the increased natural periods in the main shock and the maximum aftershock both in the X directions which returned to the original values. And, it is confirmed that the average of the natural periods estimated from the records obtained from before the main shock are slightly smaller than that of after the main shock. This tendency is similar to the natural periods estimated from the microtremor records. It is considered that one of the reasons for that is decreasing the apparent stiffness of the building by dampers working

effectively. And, the difference of the average of the natural periods between before and after the main shock is caused by the effects of non-structural components loosing and so on.

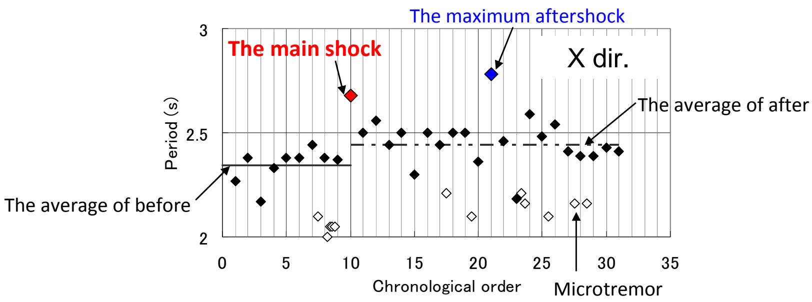

Figure 4.2. The natural periods in chronological order

5. NATURAL PERIODS OF EARTHQUAKE RESISTANT BUILDING

This section evaluates changes in natural period before and after the 2011 Tohoku earthquake for an earthquake resistant building in the area where suffered severe ground motion. The building B, as previously described, is given consideration to provide sufficient seismic capacity during large earthquakes. So, the building received little visible damage on structural components in the 2011 Tohoku earthquake. But, damages on non-structural components and exterior of the building were confirmed by field survey. In this section, the effects of these damage or invisible damages on the vibration characteristics are shown.

5.1. Comparison of Natural Periods

The natural periods in the main shock are compared with that of before and after the main shock. The transfer functions were calculated using the records of the ground floor and the 4th floor. The intended earthquakes are shown in Table 5.1. The calculated transfer functions from each earthquake records are shown as overlaid curves in Figure 5.1. At first, the transfer functions of before the main shock (No.1, 2) are dominated in about 0.35 seconds. In the main shock, two predominant periods are seen in about 0.55 seconds and 0.80 seconds. And, after the main shock (No.4, 5), the dominant periods is about 0.65 through 0.70 seconds. The natural periods of building B increase after the main shock, so it is considered that the vibration characteristics change during the main shock.

Table 5.1. The specifications of earthquakes

No.	Seismic source information					Epicenter location	Max. Acceleration (gal) (The G.L. floor)	
	Date and Time of occurrence	Northern latitude	East longitude	Depth (km)	Mj		X	Y
1	2005/8/16 11:46	38.15	142.28	41.6	7.2	Off Miyagi Prefecture	109.2	108.6
2	2008/7/24 0:26	39.44	141.38	108.0	6.8	North Shore of Iwate Prefecture	187.3	121.8
3	2011/3/11 14:46	38.10	142.86	23.7	9.0	Off the Pacific coast of Tohoku	496.4	586.3
4	2011/3/22 18:19	37.32	141.91	43.0	6.4	Off Fukushima Prefecture	17.0	12.0
5	2011/7/10 9:57	38.03	143.51	34.0	7.3	Off the Coast of Sanriku	13.5	12.8

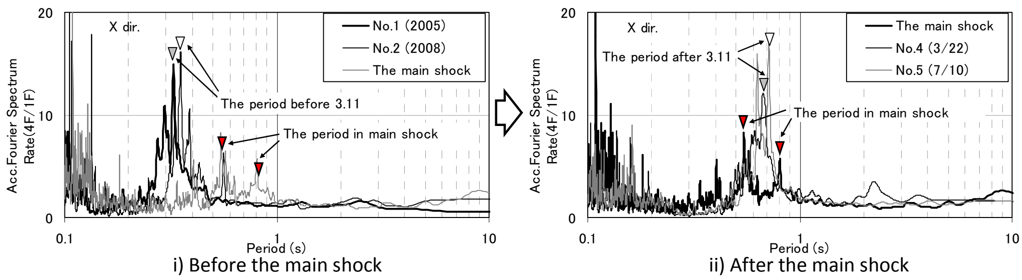

Figure 5.1. The comparison of transfer function from before and after the main shock

5.2. Time History Change of Natural Periods

The observation records are split at regular interval, the transfer functions were calculated in each time section for analyzing about the changes of the vibration characteristics during the 2011 Tohoku earthquake in detail. Figure 5.2. shows the time history change of the transfer functions in the X direction. The predominant period was about 0.3 through 0.4 periods in first arrival, but increased to about 0.8 through 0.9 periods in the 1st wave group (around 30 seconds) and the 2nd wave group (around 75 seconds), and slightly returned back after the 2nd wave group, and end up about 0.6 through 0.7 seconds, which accord with the estimated value after the main shock.

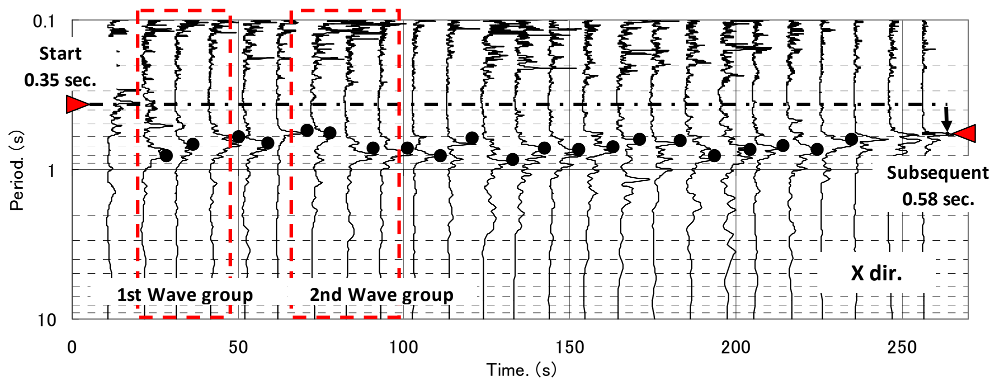

Figure 5.2. The time history change of the transfer functions

There are several reasons why the natural period is increased. In general, one of them is the effect of cracked concrete. But as previously described, it is confirmed that visible damages on structural components are little by field survey. So, it is also considered that there is possibility that the vibration characteristics of soil-pile-building interaction have changed.

6. SEISMIC RESPONSE OF STRUCTURAL CONTROL BUILDING IN SENDAI

Using the records of the 2011 Tohoku earthquake, the earthquake response was analyzed with a space frame elasto-plastic model of the building A. The vibration characteristics of the building A was adjusted by the superimposed load or the member stiffness, based on the building conditions and the observation records. Table 6.1. shows analytical parameters of the building and dampers. The observation records from the second basement are used as the input wave.

Figure 6.1. 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. Figure 6.2. shows the comparison of the displacement response waveforms on the 22nd floor and the top of the steel tower with the observation records. Looking at the time history of the displacement response shown in Figure 6.2., the waveforms as the analysis result roughly represented the observation records and ensured the analysis model could reproduce the actual phenomenon. Figure 6.3. 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. Figure 6.4. shows the time history of absorption energy obtained from analysis. The absorption energy of dampers consists about 73 percent in the total. It is made sure that the absorption energy becomes 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 A is safeguarded against the earthquake.

Table 6.1. 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)

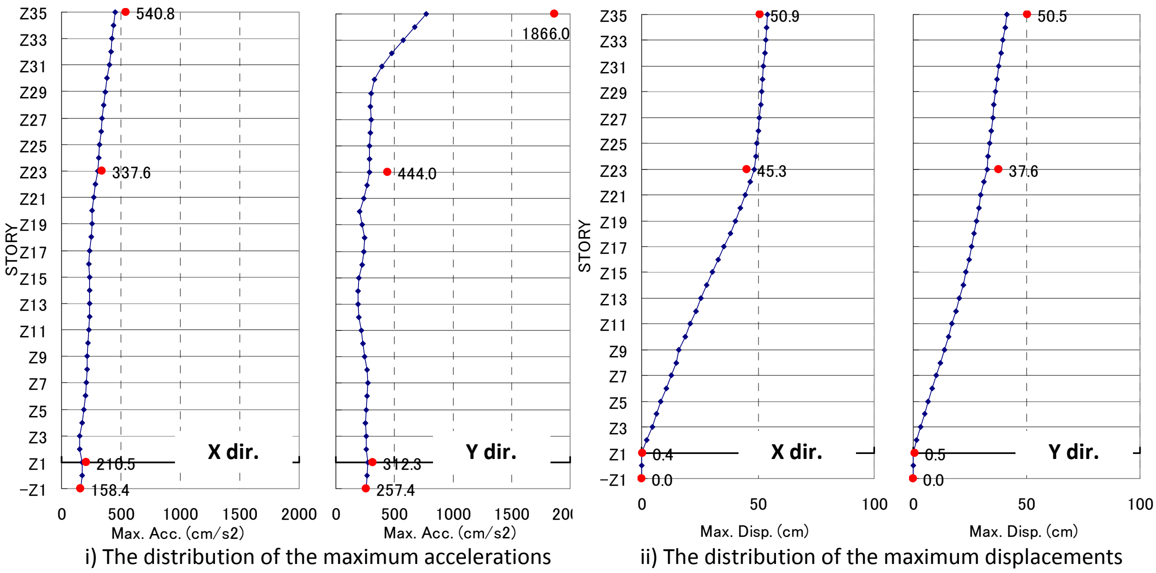

Figure 6.1. The comparison of the maximum response

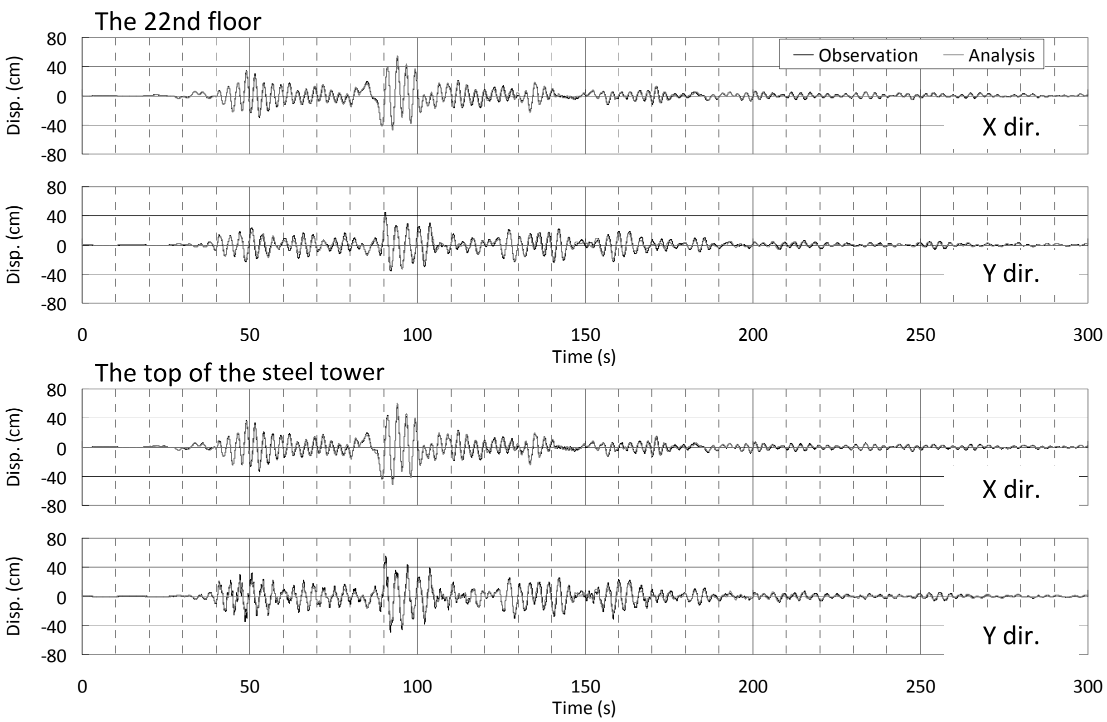

Figure 6.2. The comparison of the displacement response

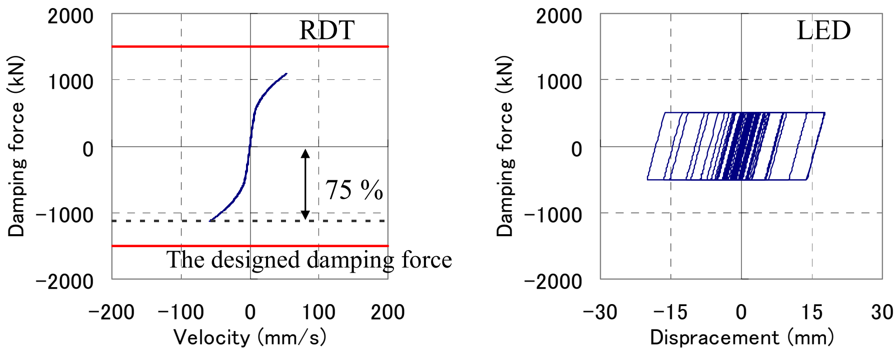

Figure 6.3. The damping force

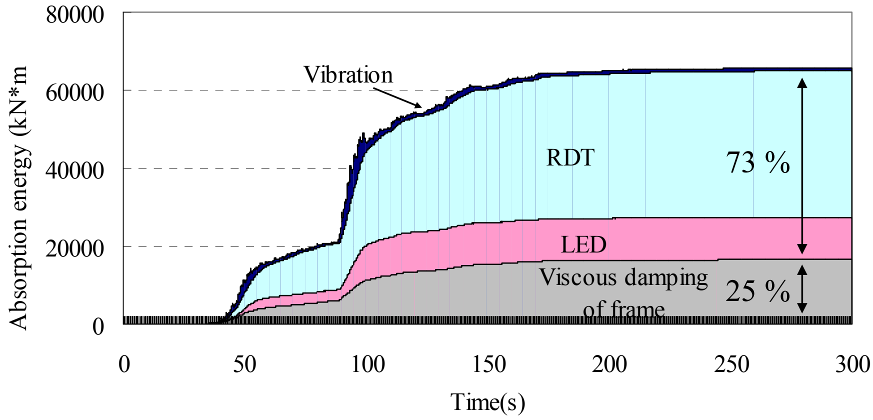

Figure 6.4. The time history of absorption energy

7. CONCLUSIONS

In this paper, the vibration characteristics and the seismic responses of a structural control building and an earthquake resistance building are evaluated using observation records during the 2011 Great East Japan earthquake. The result obtained about the vibration characteristics and the seismic responses are summarized as the following.

The natural periods of both buildings are increased during a large earthquake. In the building A, it is considered that one of the reasons for that is decreasing the apparent stiffness of building by dampers working effectively. Otherwise in the building B, the natural periods haven't returned to before the main shock. So, there are possibilities of the effect of cracked concrete, change in the characteristics of soil-pile-building interaction and so on.

The analysis result of the building A verified that the dampers provided the sufficient damping performance, and the structural control building is safeguarded against the large earthquake. But effects of higher-order modes and the difference of the natural periods between before and after the main shock haven't been figured out in this paper.

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

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