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A Change in Dynamic Characteristics of High-Rise Buildings due to the 2011 Great East Japan Earthquake

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ABSTRACT: On 11 March, 2011, a massive earthquake occurred off the Pacific coast of north-eastern Japan. The earthquake (Tohoku Earthquake) brought extremely severe shaking in the eastern half of Japan. The most of buildings, in the strong motion network operated by the Building Research Institute, had never experienced such a severe disaster.

High-rise buildings in Tokyo and its surrounding areas suffered intense long-period, long-duration earthquake motion. In this study, a change in dynamic characteristics of ten high-rise buildings in the BRI strong motion network during the Tohoku Earthquake is investigated through the analysis of strong motion data. The natural periods of two concrete buildings obviously increased during the earthquake, and were not recovered even after the shaking. On the other hand, a change in natural periods of eight steel buildings was comparatively small.

Amplitude dependence of the dynamic characteristics of two buildings was examined in detail. In the case of a concrete building, the dependence on the response amplitudes of the natural periods was clearly recognized and the trend was different between before and after the Tohoku Earthquake.

1 INTRODUCTION

The Building Research Institute (BRI) of Japan is a national institute engaged in research and development in the fields of architecture, building engineering, and urban planning. The BRI operates the strong motion network that covers buildings in major cities across Japan, as part of its research activities.

On 11 March, 2011, an enormous earthquake with a moment magnitude (Mw) of 9.0 occurred off the Pacific coast of north-eastern Japan. The earthquake, known as the Great East Japan Earthquake (hereafter, simply referred to as the Tohoku Earthquake), caused a monstrous tsunami and massive damage to eastern Japan. Seventy-nine stations of the BRI strong motion network were running at the time of the earthquake. Among them, 61 stations were triggered (Kashima et al. 2012 and Okawa et al. 2013).

Tokyo and its surrounding areas suffered severe long-period, long-duration earthquake motion even though being nearly 400 kilometres away from the epicentre. The structural damage to the super high-rise buildings has not been reported, but some damage was observed in the non-structural elements and the facilities.

There are 10 high-rise buildings in the metropolitan area in the BRI strong motion network. This paper discusses actual seismic response of the high-rise building to the severe earthquake motion of the Tohoku Earthquake using strong motion data.

2 A CHANGE IN DYNAMIC CHARACTERISTICS DURING THE TOHOKU EARTHQUAKE

2.1 *Target buildings*

Target buildings of the analysis are listed in Table 1. The buildings A and B are apartment buildings, of which structures are the steel framed reinforced concrete (SRC) and the reinforced concrete (RC), respectively. The buildings C to J are steel constructed office buildings. In addition, some seismic control systems are installed in the buildings F, H, I and J. Although the buildings D and E are twin buildings having the same basement and lower floors, they are treated separately.

These ten buildings are equipped with strong motion instruments having two or more acceleration sensors. The uppermost and lowermost sensor mounting places in each building are indicated in Table 1. Strong motion data recorded in these sensors are adopted as input and output motions in the analysis. On the right hand side of the table, maximum accelerations during the Tohoku Earthquake are listed. A_B is the maximum acceleration sensed by the sensor at the base and A_T is that on the top. The maximum accelerations at the building base were nearly 1 m/s^2 in those buildings and those on the top were strengthened by a factor of 2 to 7.

Table 1 Target buildings

#	Ward or City	Str.*	Floors	Comp. Year**	Top/Base***	A_B (m/s^2)*****		A_T (m/s^2)*****	
						L	T	L	T
A	Koto	SRC	32F+B1F	1995	32F/B1F	0.69	0.63	2.83	2.49
B	Chuo	RC	37F+B1F	1988	37F/01F	0.87	0.98	1.62	1.98
C	Sumida	S	19F+B2F	1990	20F/B1F	0.66	0.69	2.90	3.85
D	Chiyoda	S	20F+B3F	1994	20F/01F	0.91	0.85	2.10	1.50
E	Chiyoda	S	20F+B3F	1994	19F/01F	0.91	0.85	1.73	1.77
F	Chiyoda	S+	21F+B4F	2000	21F/B4F	0.75	0.71	1.21	1.31
G	Yokohama	S	23F+B3F	1996	23F/B2F	0.60	-	1.62	-
H	Saitama	S+	26F+B3F	2000	27F/B3F	0.74	0.63	2.65	6.86
I	Chiyoda	S+	32F+B2F	2007	32F/B2F	0.52	0.67	1.79	1.91
J	Chuo	S+	33F+B4F	2001	33F/B4F	0.53	0.50	1.63	1.46

* Structure (RC: reinforced concrete, SRC: steel-framed RC, S: steel, S+: steel with seismic control system)

** Completion year

*** Floors with the uppermost and lowermost sensors placed.

****Maximum accelerations at base (A_B) and on top (A_T) of building

2.2 *Analytical method*

Fundamental natural periods and damping ratios in both horizontal directions of each building are identified in the following three parts of seismic response;

- Initial part: time period of 40 seconds after the building response initially exceeds 0.1 m/s^2
- Main part: time period of 40 seconds before and after the peak time of the acceleration response
- Coda part: time period of 40 seconds till the building response lastly exceeds 0.1 m/s^2

Figure 1 illustrates the definition of the three parts. As the fundamental natural period and damping ratio of the building, a natural period and a damping ratio of a single-degree-of-freedom system, which allows an actual response with the best fitness to be simulated, are searched by the grid search method (Kashima et al. 2006a). The relative displacement of the building top to the building base is selected as the response to be fitted.

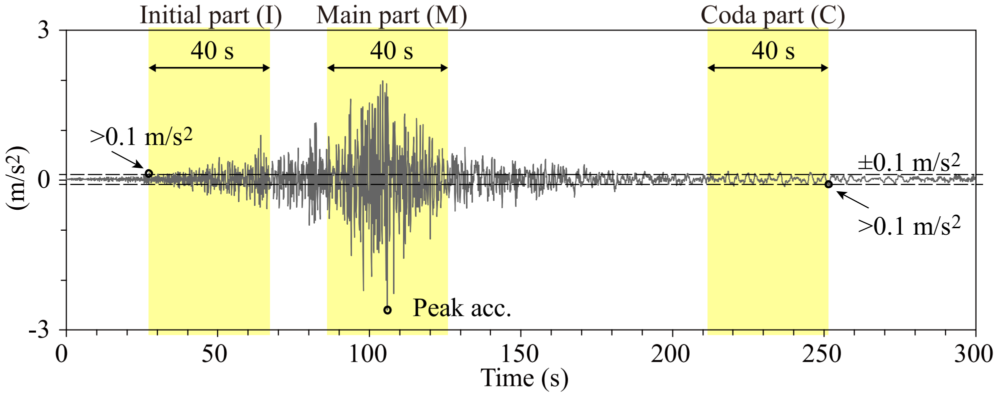


Fig.1 Definition of initial, main and coda parts of seismic response

2.3 *Dynamic characteristics of buildings before the Tohoku Earthquake*

Firstly, basic dynamic characteristics of the target buildings are examined. The dynamic characteristics in the initial part may indicate the original characteristics of the buildings before suffering intense earthquake shaking; therefore the initial natural periods (T_I) and damping ratios (h_I) are dealt with in this section. Figure 2(a) shows the relationship between the heights and the natural periods of the buildings. In the figure, circles (● and ●), hollow triangles (△ and △) and solid triangles (▲ and ▲) indicate the natural periods of concrete (SRC and RC) structures, ordinary steel structures (S) and steel structures having seismic control systems (S+), respectively. Red and blue symbols represent the results in the longitudinal and transverse directions, respectively. The higher the height of the building is, the longer the natural period of the building is.

The relationship between the building height and its natural period is commonly explained using Eq. (1).

$$T = \alpha H \tag{1}$$

where T is the natural period of the building in seconds, H is the building height in metres, and α is a constant.

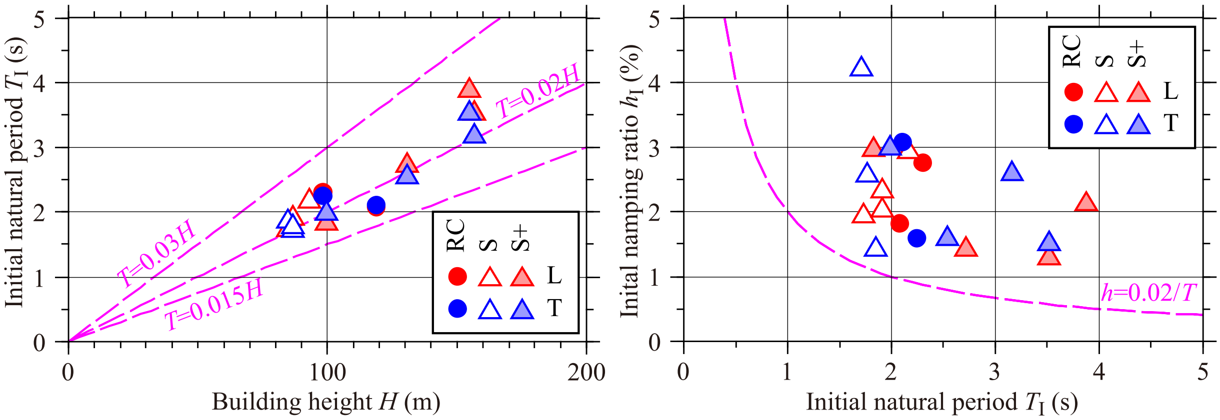
The Architectural Institute of Japan (AIJ) proposed α=0.015 for concrete structures and α=0.02 for steel structures based on the experimental results in low amplitude range (the Architectural Institute of Japan. 2000). Ministry of Construction of Japan recommends α=0.02 for concrete structures and α=0.03 for steel structures as rough estimation of the natural period in the structural design (Ministry of Construction. 1980). Dashed lines in Fig. 2(a) indicate Eq. (1) for α=0.015, 0.02 and 0.03. Our results distribute along the line of $T = 0.02H$ and a difference caused due to structure types is not clear.

Relationship between natural periods and damping ratios of the buildings are plotted in Fig. 2(b). The symbols have the same meanings as those in Fig. 2(a). Although the tendency that with the longer natural period, the damping ratio decreases is generally recognized, values vary somewhat. The relationship between the natural period and damping ratio is sometimes expressed by Eq. (2).

$$h = \beta T \tag{2}$$

where h is the damping ratio of the building and β is a constant.

The authors introduced β=0.01 to 0.02 for concrete structures and β=0.02 for steel structures based on the analysis of strong motion data in low- and middle-rise buildings (Kashima et al. 2006a). The Architectural Institute of Japan indicates β=0.014 for concrete structures and β=0.013 for steel structures in low amplitude range (the Architectural Institute of Japan. 2000). The results in Fig. 2(b) show larger damping ratios than the relationship of $h = 0.02T$.



(a) H vs. T_I

(b) T_I vs. h_I

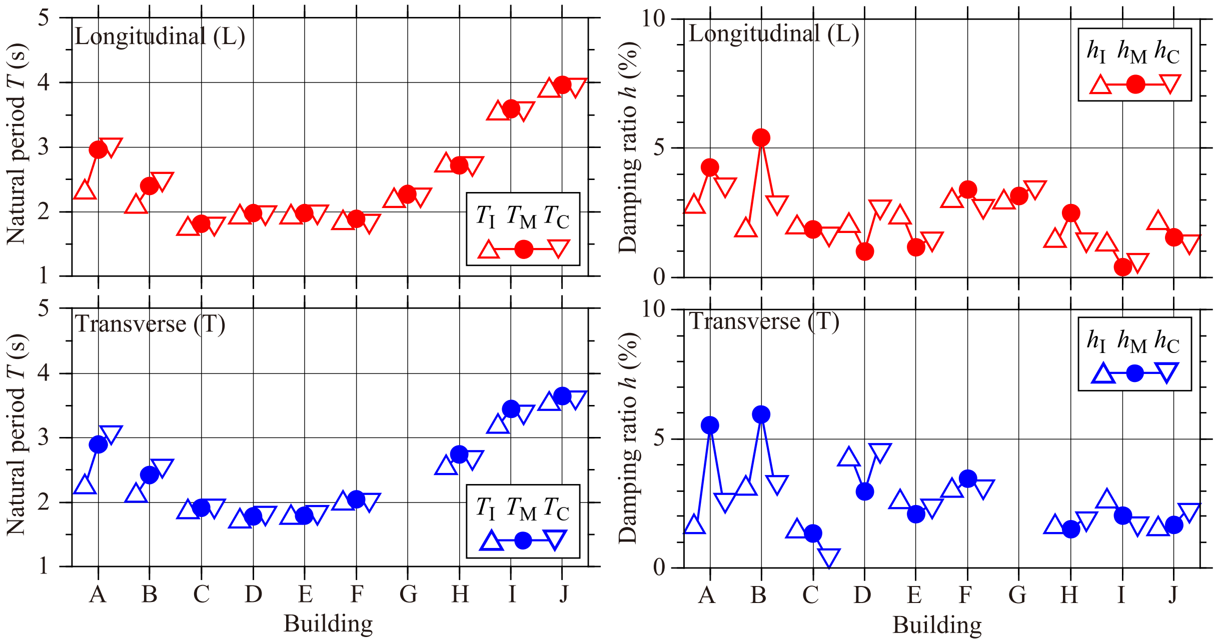
Fig.2 Relationship among building heights (H), initial natural periods (T_I), and initial damping ratios (h_I)

2.4 *Dynamic characteristics of buildings during the Tohoku Earthquake*

The identified natural periods in the initial, main and coda parts (T_I, T_M and T_C) of each building are plotted in Fig. 3(a). Triangles (△ and △), circles (● and ●) and inverted triangles (▽ and ▽) represent the natural periods in the initial, main and coda parts, respectively. The natural periods in the longitudinal direction are plotted in the upper graph and those in the transverse direction are plotted in the lower graph.

The main natural periods (T_M) of the concrete buildings (A and B) are 1.2 to 1.4 times longer than the initial natural periods (T_I). The coda natural periods (T_C) of those buildings do not return to the initial values (T_I). An increase in natural period represents a deterioration in stiffness caused by inelastic seismic response of the building.

In contrast, the change in natural periods of the steel buildings (C to J) during the Tohoku Earthquake seems to be small in general. A little increase in the natural period from the initial part (T_I) to the main part (T_M) can be observed in the transverse directions at the buildings H and I.



(a) Natural period

(b) Damping ratio

Fig.3 Changes in natural periods and damping ratios of each building during the Tohoku Earthquake.

Figure 3(b) shows the identified damping ratios of the initial, main and coda parts (h_I, h_M and h_C) of each building. The same symbols as those in Fig. 3(a) are used. In the case of the concrete buildings (A and B), the initial damping ratios were 1.6% to 3.1% and increased to 4.3% to 6.0% in the main part. In the code part, the damping ratios again decreased to 2.6% to 3.6%. It is supposed that seismic response of the building A to the Tohoku Earthquake exceeded the elastic range (Nakamura et al. 2013); therefore the increase of the damping ratio in the main part would be caused by the hysteretic damping. The damping ratios of the steel buildings (C to J) are comparatively small. No clear trend is observed in transition of the damping ratios in the initial, main and code parts. Any effect of the seismic control systems in the buildings (F, H, I and J) is not obvious on the graph.

3 A CHANGE IN DYNAMIC CHARACTERISTICS WITH LAPSE OF TIME AND AMPLITUDE DEPENDENCE

3.1 *Target buildings and analytical method*

The buildings B and F are taken up for detailed analysis. The building B is a 37-storey apartment building of reinforced concrete framed structure. The building F is a 21-storey office building of steel structure, which is equipped with viscous damping walls and low yield strength steel walls as the seismic control system.

In order to examine a time-lapse change in dynamic characteristics and amplitude dependence of the dynamic characteristics, strong motion data from various earthquakes are dealt with in this chapter. The natural periods and damping ratios in the main part of each strong motion data are identified by the same method as in the previous chapter.

3.2 *A time-lapse change in dynamic characteristics*

Figure 4 shows a time-lapse change in natural periods (upper) and damping ratios (lower) of the building B for seven years from 2007 to 2013. Seventy-three strong motion records having the building displacement (relative displacement of the building top to the building base) of over 2 mm are selected to plot. Circles (●) and triangles (△) indicate values in the longitudinal and transverse directions, respectively.

Before 11 March, 2011, when the Tohoku Earthquake attacked, the natural periods in both directions showed stable values of about 2 seconds. During the Tohoku Earthquake and the following aftershocks, the natural periods varied in the range between 2.3 seconds and 2.6 seconds. From late 2011, the natural periods seem to have been settled down to about 2.4 seconds. Looking at the damping ratios in the lower plot, these were 1% to 2% before the Tohoku Earthquake. After the quake, the damping ratios have shown larger values and varied widely.

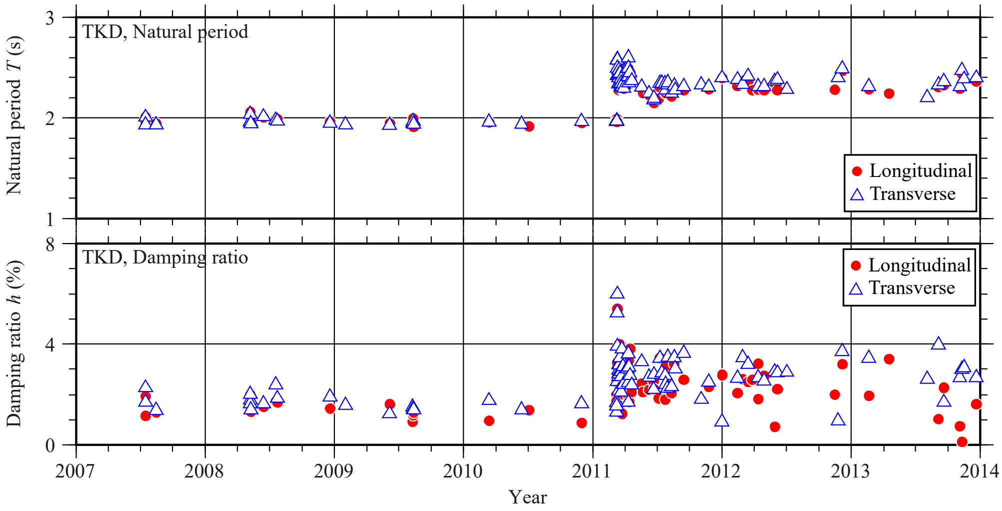


Fig.4 Annual changes in natural periods (upper) and damping ratios (lower) of building B.

Slight damage to the building B, i.e. damage of exterior tiles, fissures on wallpaper and separation of mortar on exterior walls, were reported after the 2011 Tohoku Earthquake (Midorikawa et al. 2011). According to the seismic response analysis of the building B using a lumped mass system having the degrading tri-linear hysteresis model, it is estimated that storey displacements at the lower and middle floors exceeded the cracking points (Tanaka et al. 2014). Therefore it can be supposed that the nonlinear behaviour of the concrete structure and the non-structural elements caused the change in the dynamic characteristics of the building B.

The upper and lower plots of Fig. 5 show annual changes in natural periods and damping ratios of the building F from 2007 to 2013, respectively. Seventy-nine strong motion records having the building displacement of over 2 mm are used. The symbols have the same meanings as those in Fig. 4. Before the Tohoku Earthquake attack, the natural periods in the longitudinal and transverse directions were about 1.8 seconds and about 1.9 seconds, respectively. A change in natural periods caused by the Tohoku Earthquake is too small to be recognized on the plot. The damping ratios show values of about 3% over the entire period and the influence of the Tohoku Earthquake is small as well.

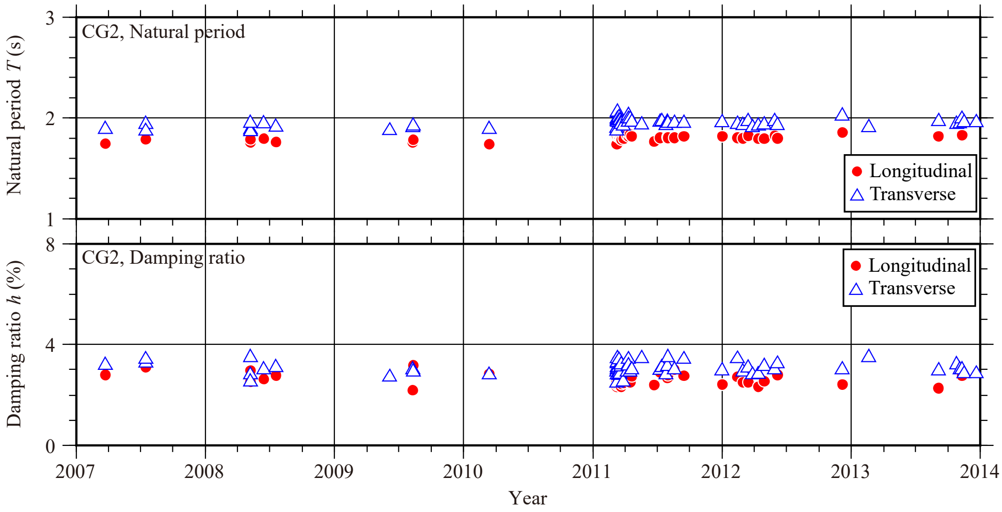


Fig.5 Annual changes in natural periods (upper) and damping ratios (lower) of building F.

3.3 *Amplitude dependence of dynamic characteristics*

It is known that the natural periods (and probably damping ratios) of buildings vary depending on response amplitudes (e.g. The Architectural Institute of Japan. 2000 and Kashima et al. 2006a). Therefore it is important to consider the amplitude dependence in order to discuss a change in dynamic characteristics of buildings.

To represent response amplitude, the maximum building displacement angle ($\theta_{\max}$) is defined as follows.

$$\theta_{\max} = |\delta_{\mathrm{TOP}}(t) - \delta_{\mathrm{BASE}}(t)|_{\max} / H_{\mathrm{S}} \qquad (3)$$

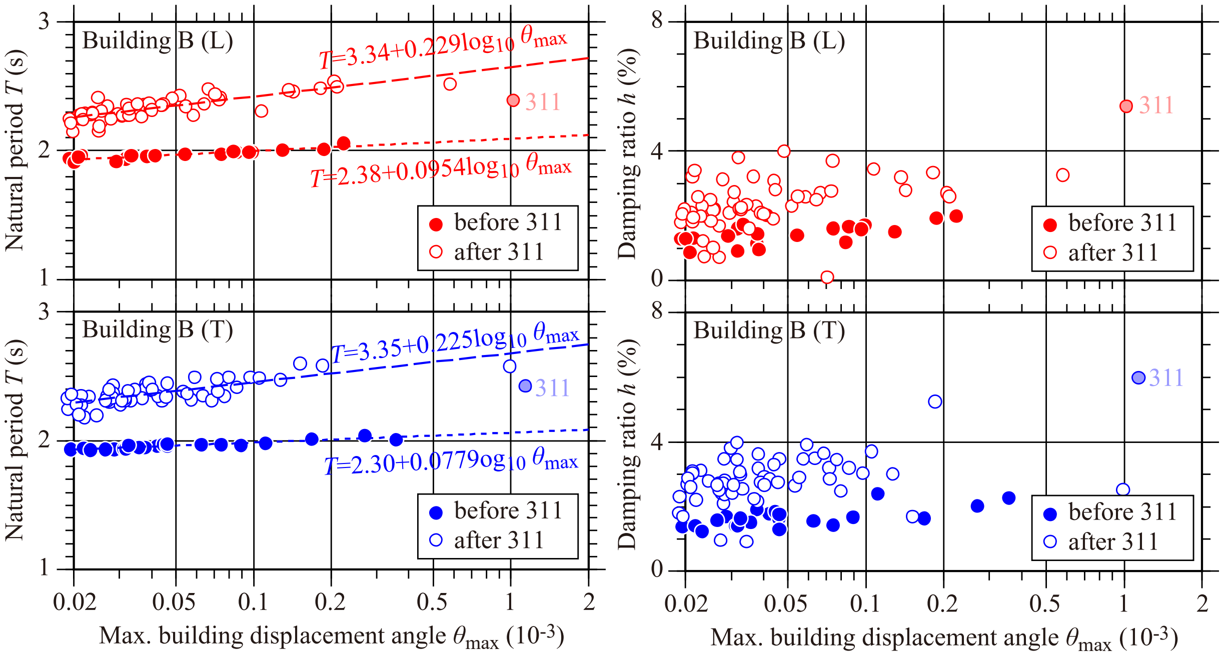
where $\delta_{\mathrm{TOP}}(t)$ and $\delta_{\mathrm{BASE}}(t)$ are the time histories of displacement at the building top and building base, respectively. H_{S} is the height from the first floor to the sensor installed at the building top.

The displacement is calculated by the integration using the Fast Fourier Transform (FFT) applying the low-cut filter with a cut-off frequency of 0.2 Hz.

Figure 6(a) indicates the relationship between the maximum building displacement angles ($\theta_{\max}$) and the natural periods of the building B. The results in the longitudinal and transverse directions are plotted in the upper and lower graphs, respectively. Solid circles (● and ●) and hollow circles (○ and ○) represent the natural periods estimated from the strong motion records before and after the Tohoku Earthquake, respectively. The small but stable amplitude dependence appears in the result before the Tohoku Earthquake. After the Tohoku Earthquake, the amplitude dependence is apparent and becomes strong. There is no significant difference between the results in the longitudinal and transverse directions. Dotted and dashed lines in the graph show the regression analysis results using the data before and after the Tohoku Earthquake, respectively. The natural periods estimated from the strong motion data of the Tohoku Earthquake is not included in either of the regression analysis. The dependence of the natural periods on the response amplitudes has increased more than twice after the Tohoku Earthquake.

The relationship between the maximum building displacement angles and the damping ratios of the building B is shown in Fig. 6(b). While it shows wide variation, general tendency is similar to that in Fig. 6(a). The dependence on the amplitudes of the damping ratios can be recognized and the damping ratios after the Tohoku Earthquake are larger than those before.

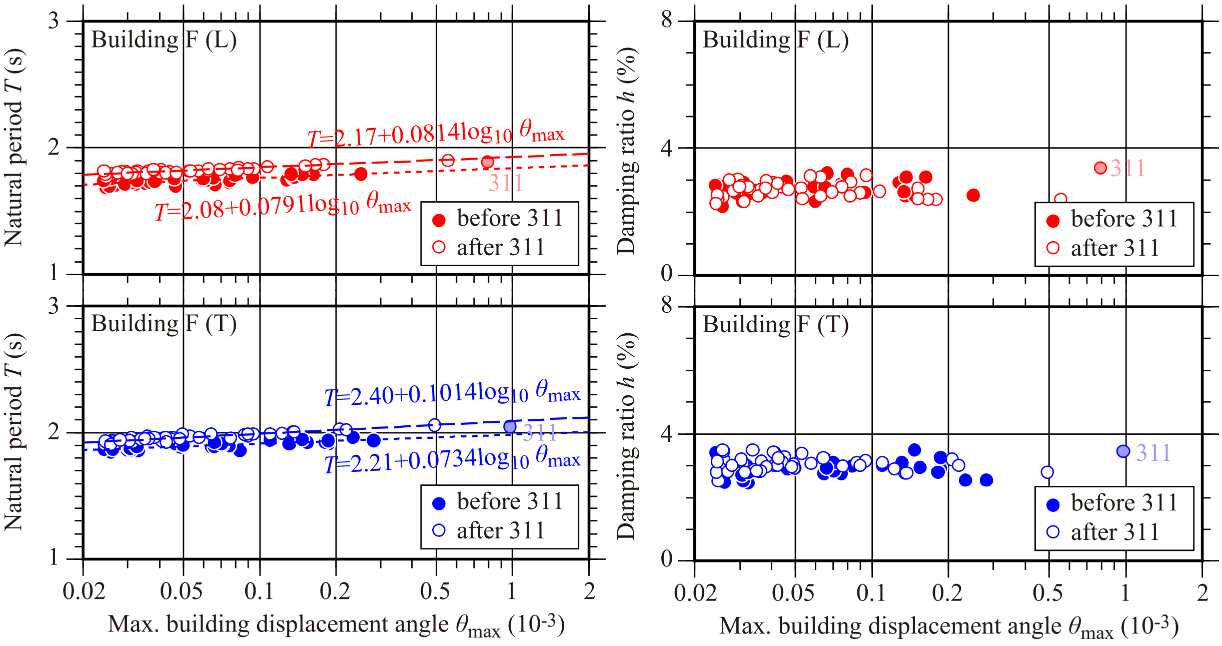
Figure 7(a) indicates the relationship between the maximum building displacement angles and the



(a) Natural period

(b) Damping ratio

Fig.6 Relationship between natural periods and building displacement angles of building B



(a) Natural period

(b) Damping ratio

Fig.7 Relationship between natural periods and building displacement angles of building F natural periods of the building F. Differences in the natural periods between before and after the Tohoku Earthquake clearly appear if the amplitude dependence is considered. The natural periods of the building F became about 0.1 seconds longer after the Tohoku Earthquake. The amplitude dependence can be obviously recognized as well. The relationship between the maximum building displacement angles and the damping ratios of the building F is shown in Fig. 7(b). The estimated damping ratios are stable, but it is difficult to confirm the difference between values before and after the Tohoku Earthquake and the amplitude dependence.

4 **CONCLUSIONS**

Seismic response of high-rise buildings in Tokyo and its surrounding areas during the 2011 Tohoku Earthquake was discussed through the analysis of strong motion data. In the case of the concrete buildings, an increase in natural periods due to the response reaching inelastic range were clearly recognized. Changes in dynamic characteristics of steel buildings were relatively small.

Amplitude dependence of the dynamic characteristics of concrete a building and a steel building was examined in detail. A change in the natural periods depending on the response amplitude was recognized in both types of buildings. In the concrete building, the dependence of the natural periods on the response amplitudes has increased more than twice after the Tohoku Earthquake. The consideration of the amplitude dependence is essential to discuss a subtle change in dynamic characteristics of building structures.

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