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EVALUATION OF EXISTING BUILDING DYNAMIC CHARACTERISTICS BASED ON MICRO-TREMOR MEASUREMENTS AND STRONG MOTION OBSERVATIONS

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Abstract

In Japan, huge earthquakes such as the Tokyo inland earthquake and the Tokai-Tonankai-Nankai earthquake are predicted to occur in the near future. For earthquake-induced damage estimation and seismic performance evaluation of buildings, it is important to understand the dynamic characteristics of buildings. A large number of studies have employed practical observations to investigate the dynamic characteristics of super high-rise buildings and quake-absorbing structures; however, there is currently a lack of studies focusing on low- and medium-rise buildings. To address the lack of research on such structures, the authors installed seismometers in an existing steel-frame reinforced concrete (SRC) building in Tokyo, and conducted long-term-observations. After several years, during which time the 2011 Off the Pacific Coast of Tohoku Earthquake occurred, the dynamic characteristics of this building based on the observation records were investigated. Micro-tremor measurements of this building were also acquired on several occasions, and the dynamic characteristics from these measurements were investigated. Additionally, vibration analysis of a three-dimensional frame model was performed, and the differences between the observations and the analysis were investigated.

The building adopted in this study was a nine-story SRC residential building located on the alluvium ground in Tokyo and built in September 1978. Micro-tremor measurements were acquired in September 2007, and strong motion observations were continuously taken beginning in May 2008. The building experienced the 2011 Off the Pacific Coast of Tohoku Earthquake in March 2011, and micro-tremor measurements were acquired again in October 2012 and October 2013. The strong motion observations were recorded using a small-sized strong-motion-seismograph with semiconductor sensors at a sampling rate of 100 Hz. The measurement points were located at the first floor and the roof floor of the building in order to record the acceleration in three dimensions on each floor. The micro-tremor measurements were recorded using servo-type speedometers at a sampling rate of 200 Hz. The analysis model consisted of line elements comprising the three-dimensional frame. Eigenvalue analysis was performed using a three-dimensional structural analysis software, and the vibration mode and natural frequency of the frame model were calculated.

As for the strong motion observations, 36 records excluding incomplete or incorrect data were obtained. The changes in the dynamic characteristics of the building during the course of the long-term observations were investigated through analysis of the strong motion data. The natural period of the building was found to be substantially longer during the 3.11 earthquake, and gradually reduced over time following the event. The comparison between the analyses of the micro-tremor measurements and the frame model analysis revealed nearly identical results for the vibration mode and natural frequency.

Keywords: strong motion observation, micro-tremor measurement, modal analysis, vibration mode

1. Introduction

In recent years, there has been growing concern for huge earthquakes such as the Tokyo inland earthquake and Tokai-Tonankai-Nankai earthquake predicted to occur in Japan in the near future [1]. To evaluate the earthquake-induced damage and seismic performance of buildings, it is critical to understand the vibrational properties of buildings accurately. Although several studies have explored the vibrational properties of specific buildings such as high rise buildings and seismically isolated buildings, few have focused on medium- to low-rise buildings which comprise a large percentage of all buildings [2] [3]. Fukuwa et al.[3] conducted the seismic responce observations of several ordinary buildings. They examined some analyses of these observation data.

The present study aimed to investigate vibrational characteristics using micro-tremor measurements of a medium-rise residential building made of steel-frame reinforced concrete (SRC) in Chiyoda Ward, Tokyo. The vibrational properties were obtained using artificial excitation and strong motion observation records. The results were compared to an analysis performed using a three-dimensional frame model to determine the differences between the analysis and the observations.

2. Overview of the building

The building used in the study was located in Chiyoda Ward, Tokyo. The building had nine stories and was made of steel-frame reinforced concrete (SRC). An overview and history of the target building are presented in Tables 1 and 2. The elevation and plan view are shown in Figs. 2 and 3.

The building was built in September 1978, and seismic reinforcement work was carried out in December 2002 to build shear walls on the first floor in the longitudinal direction. Slit renovation was carried out in August and September 2011 to install a slit on the south end of the first floor in the span direction.

Micro-tremor measurements were acquired in 2007 to determine the vibrational properties of the building. In addition, micro-tremor measurements were acquired in 2012 and 2013 following the 2011 Off the Pacific Coast of Tohoku Earthquake (hereafter, referred as "the 3.11 earthquake"). Furthermore, free vibration measurements by artificial excitation were acquired in 2013.

Table 1 – Overview of the building

Scale	Ground 9-story and penthouse 1-story		
Completion year	1978		
Structure format	Steel-frame reinforced concrete structure		
Construction area	167.63m^2	Total area	1158.47m^2

Table 2 – Building history

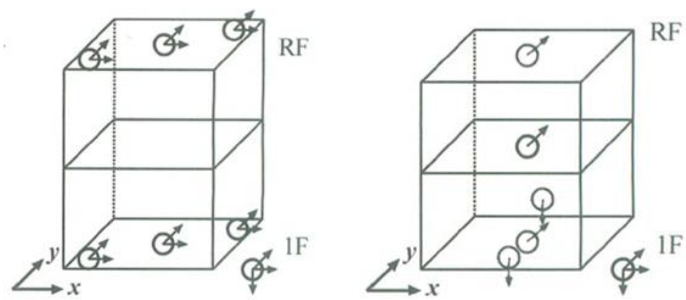
Date	History
Sep 1978	Construction completed
Dec 2002	Seismic strengthening work
Sep 2007	Micro-tremor measurement
Mar 2011	Tohoku Pacific Ocean Earthquake
From Aug to Sep 2011	Slit renovation work
Oct 2012	Micro-tremor measurement
Oct 2013	Micro-tremor measurement, Artificial excitation

3. Micro-tremor measurements

3.1 Measurement overview

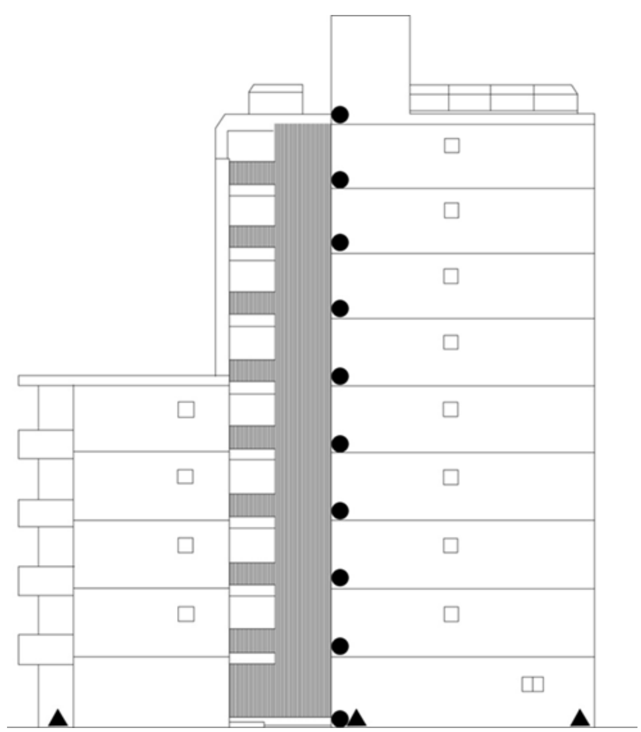
A schematic diagram of the micro-tremor measurements is shown in Fig. 1. The measuring devices included servo-type speedometers VSE-15D and a small vibration-measuring device SPC-51 as a recording machine. The data measured in this study and in 2007 were obtained through repeating each measurement four times at a recording sampling frequency of 200 Hz for 5 min each.

At some point of the first floor and the roof is in a state of torsion, and at the same time measuring in the micro-tremor of span and longitudinal directions. The shape of the mode of a floor was measured in one direction for each floor. The measurement locations are shown in Figs. 2 and 3.



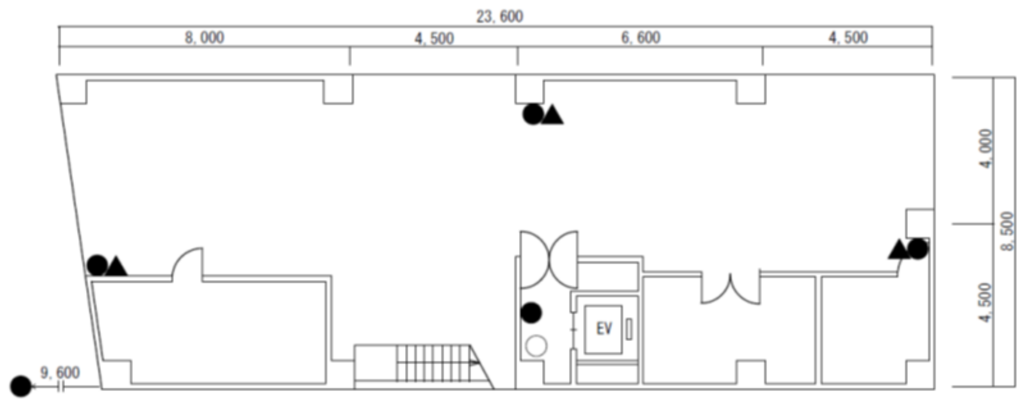
(Torsional Vibration) (Horizontal Vibration)

Fig. 1 – Overview of micro-tremor measurements

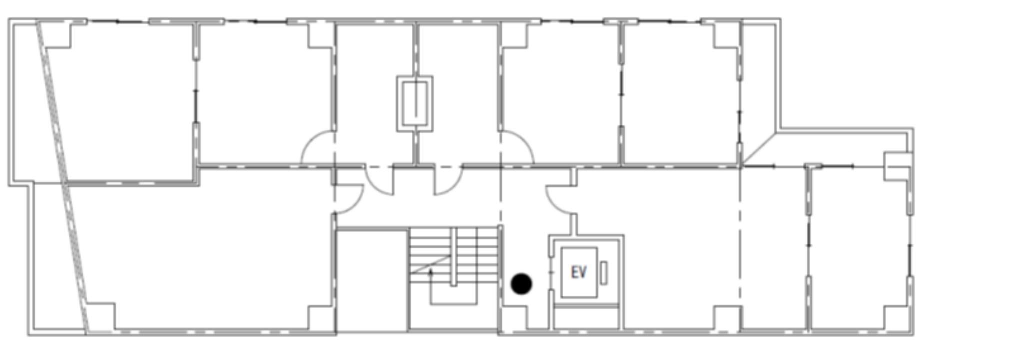


▲Vertical motion measurement location ●Horizontal motion measurement location

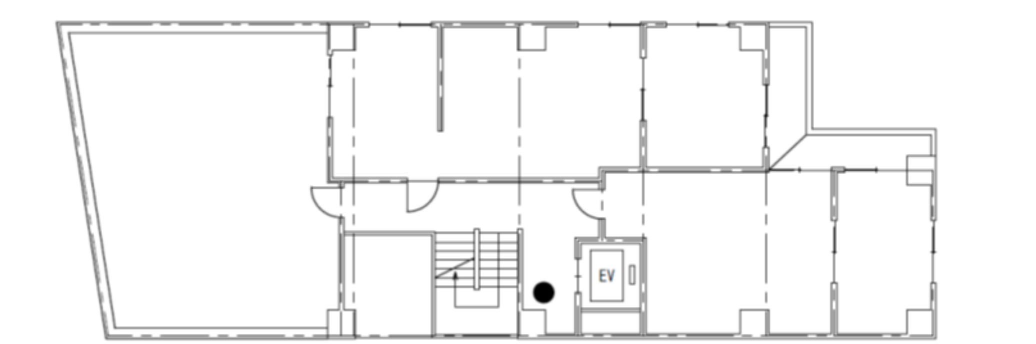
Fig. 2 – Measurement locations (Elevation)



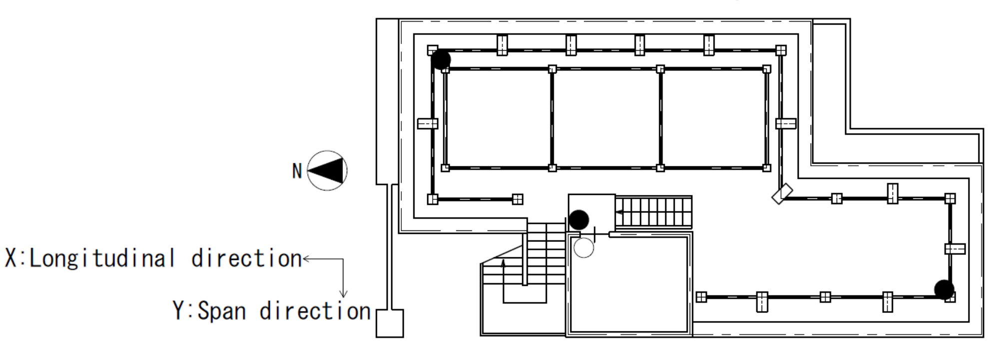
Measurement locations on the first floor



Measurement locations on the second through fifth floors



Measurement locations on the sixth through ninth floors



Measurement locations on the roof

▲, ● (See Fig. 2) ○Seismograph installation locations

Fig. 3 – Measurement locations (Plan)

3.2 Transfer function and natural period

For the frequency analysis of the micro-tremor measurements, 15 waves were extracted from the 5 minute velocity wave (60000 points) as a single 20.48 s unit (4096 points), and analyzed using fast Fourier transform to obtain the Fourier spectra.

To determine the natural frequency and the natural period of the building, the transfer function, coherence, and phase angle were computed from the Fourier spectra as shown in Eqs. (1)–(3).

Transfer function
$$H(\omega) = \frac{S_{io}(\omega)}{S_{ii}(\omega)} \tag{1}$$

Coherence
$$\{coh(\omega)\}^2 = \frac{|S_{io}(\omega)|^2}{\{S_{ii}(\omega) \cdot S_{oo}(\omega)\}} \tag{2}$$

Phase angle
$$\theta_{io}(\omega) = \tan^{-1}\left\{\frac{\mathrm{Re}\, S_{io}(\omega)}{\mathrm{Im}\, S_{io}(\omega)}\right\} \tag{3}$$

Where,

$S_{io}(\omega)$: Cross spectrum of the building foundation and top

$S_{ii}(\omega)$: Power spectrum of the building foundation

$S_{oo}(\omega)$: Power spectrum of the building top

$\mathrm{Re}\, S_{io}(\omega)$: Real part of the cross spectrum

$\mathrm{Im}\, S_{io}(\omega)$: Imaginary part of the cross spectrum

The natural periods in the span and longitudinal directions were determined using the transfer function, coherence, and phase angle of the rooftop and first floor. The results are shown in Table 3.

Table 3 – Natural period

Mode	Microtremor measurement		Modal analysis	
	Frequency (Hz)	Period (s)	Frequency (Hz)	Period (s)
Span	2.295	0.436	2.222	0.450
Longitudinal	4.053	0.247	4.238	0.236
Tortion	4.395	0.228	4.538	0.220
Secondary span			6.601	0.151
Secondary longitudinal			10.075	0.099

3.3 Primary translational mode

The shape of the primary translational mode of the building was estimated from the velocity waveform and the transfer functions of the micro-tremor.

The ensemble average of the Fourier spectra of the velocity waveform at each floor was taken, and a rectangular band-pass filter of bandwidth 0.8 Hz around the primary natural frequency was applied to the spectrum. Thereafter, the inverse transform of the spectrum was used to obtain the velocity waveform of each floor for the primary translational mode. The normalized results for the top floor are shown in Fig. 4 as a solid line with circular markers.

The primary translational mode was also estimated from the transfer function. The response magnification was determined from the transfer function of each floor to the first floor. The average of the primary translational mode was obtained by repeating the measurement four times. The normalized results are shown in Fig. 4 as a broken line with square markers.

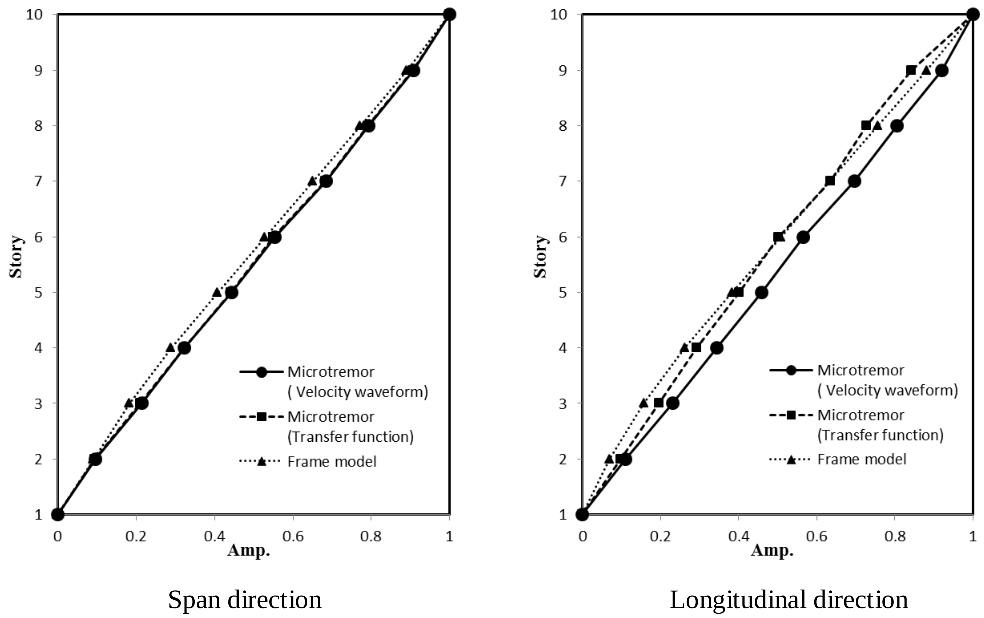


Fig. 4 – Primary translational mode (Average of four measurements)

Both the span and longitudinal primary translational modes demonstrated a linear distribution. Differences were observed in the longitudinal direction, while the in the span direction, the mode shape remained almost the same as that determined by the transfer function obtained from the velocity waveform.

3.4 Torsional vibration mode

The location of the center of rigidity was evaluated using the micro-tremor results.

Around the natural frequency of torsional vibration, an inverse Fourier transform was performed using a band pass filter having a bandwidth of 0.5 Hz. The Fourier spectrum of the velocity waveform in the span direction was used; the values at the three measurement points on the rooftop and the ensemble average were used to obtain the velocity waveform of the torsional vibration mode. By extracting the twisted portion from the waveform, and plotting cycles with periods of $\pi/4$, the mode of torsional vibration was determined. Fig. 5 shows a plot obtained with the arithmetic mean of four measurements.

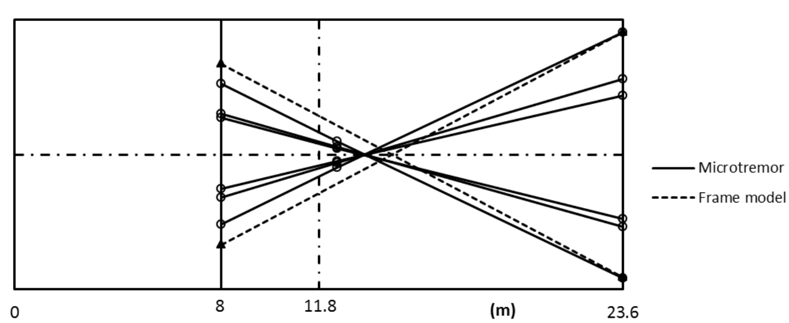


Fig. 5 – Torsional vibration mode

The intersection of the graph in Fig. 5 indicates the position of the center of rigidity. It can be seen that only the wave of the torsional vibrations could be sampled from the micro-tremor results because the points of the intersection overlapped neatly. The center of gravity of the building was located near the elevator (shown as "EV" in Fig. 3), and was near the measurement point of the center. In this analysis, since the location of the center of rigidity was near the elevator, the eccentricity of this target building was determined to be small.

4. Artificial excitation

The free vibration was measured using the artificial excitation method.

Measurement instruments with the same servo-type speedometer as that employed in the micro-tremor measurements were used. Vibrational measurements were carried out three times for each recording waveform with a 200 Hz sampling rate. Two waves in the Y-direction (the span direction) and one in the X-direction (the longitudinal direction) were measured. Furthermore, measurement data were obtained from the first floor and rooftop of the building.

Human power excitation was carried out using a weight-shifted procedure to press the side of the penthouse with four or five persons. The period of the vibration was adjusted to the natural period (X-direction: 0.25 s, Y-direction: 0.45 s) of the target building.

An example of the measured free vibration waveform is shown in Fig. 6. Using the amplitude decrement ratio shown in Eq. (4), the natural period and damping factors were derived.

$$h \approx \frac{(d-1)}{2\pi} \tag{4}$$

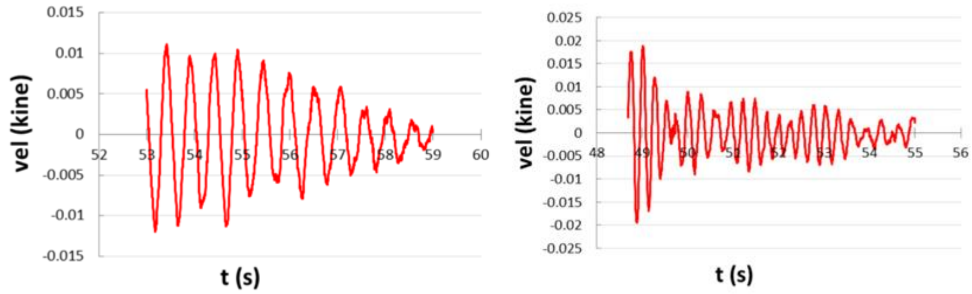
Where, *d*: Amplitude decrement ratio

h: Damping factor

The results of the analysis are listed in Table 4.

Table 4 – Analysis of artificial excitation

Direction	No.	Natural period (s)	Damping factor (%) From Eq.(4)
Y	1	0.511	2.35
Y	1	0.508	2.13
Y	1	0.519	1.95
Y	Ave	0.513	2.14
Y	2	0.519	2.52
Y	2	0.522	1.75
Y	2	0.506	2.28
Y	Ave	0.516	2.18
X	1	0.304	2.51



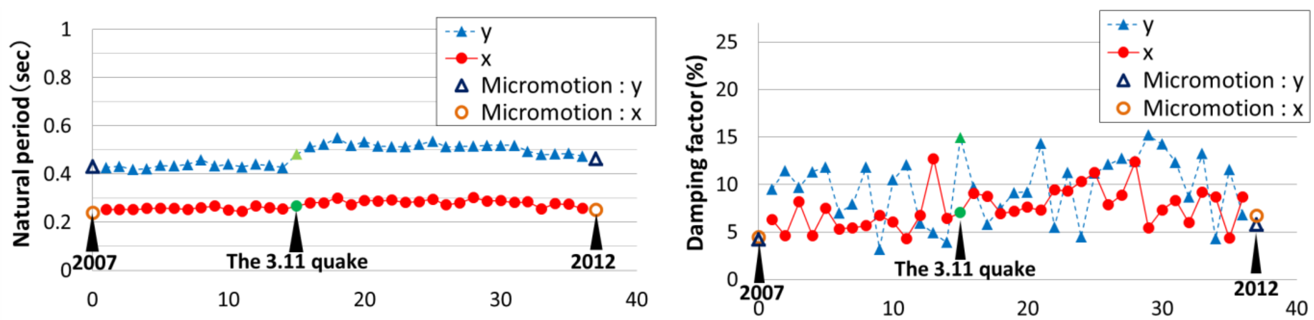
(a) Y-direction (b) X-direction

Fig. 6 – Sampled portion from the recording waveform

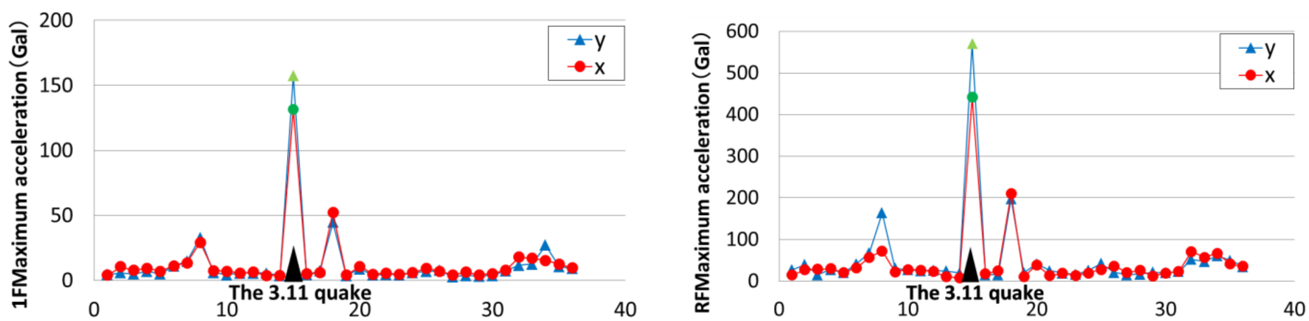
5. Strong motion observation

Strong motion observation was conducted using a small seismograph with a semiconductor acceleration sensor at a 100 Hz sampling rate. The installation locations of the seismographs are shown in Fig. 3. Strong motion observation records were obtained to yield a total of 36 pieces of records, excluding incomplete or incorrect data for the five years spanning 2008 to 2012.

Fig. 7 shows the natural period, damping factor, and maximum acceleration in the time series of the 36 pieces of observation data collected from 2008 to 2012. With regard to changes of the natural period in both X (longitudinal) and Y (span) directions, the natural period of the building was substantially longer during the 3.11 earthquake. Following this event, a gradual reduction with the passage of time was observed.



(a) Natural period (b) Damping factor



(c) 1F Maximum acceleration (d) RF Maximum acceleration

Fig. 7 – Strong motion analysis values (in Time series)

6. Three-dimensional frame analysis

A three-dimensional model was employed to analyze the vibrational properties of the building using Multiframe Advanced Ver.16.02. The analysis model is shown in Fig. 8. The dimension in the span direction was 8.5 m, and that of the longitudinal direction was 23.6 m; the height was 25.6 m. There were 502 members and 123 nodes. The floor and shear walls had brace replacements.

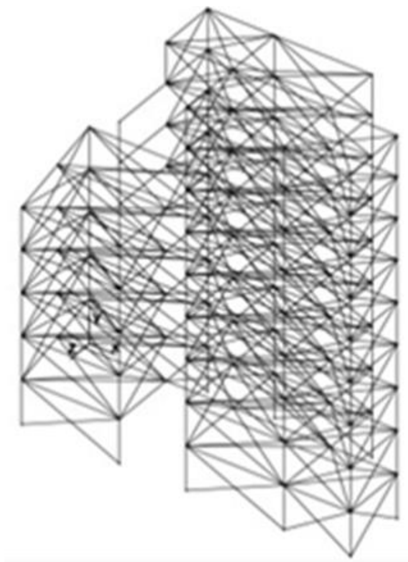
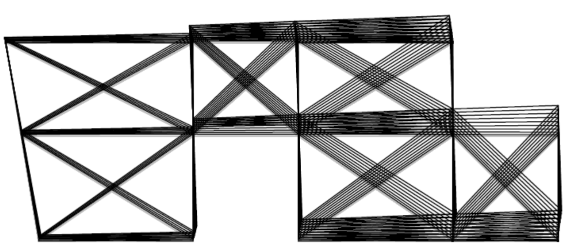


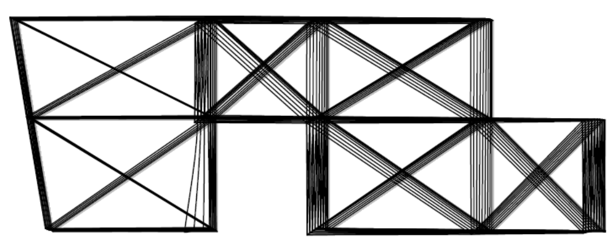
Fig. 8 – Analysis model

Modal analysis was conducted to determine the natural period. The analysis method was a sub-space iteration method. Modal computation was performed up to 50-order modes. The results of the modal analysis are shown in Fig. 9. Table 3 presents the results of the natural period.

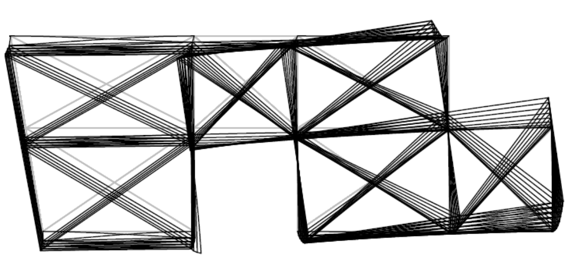
The modal analysis results show that the natural period in the span direction was 0.450 s, that in the longitudinal direction was 0.236 s, and that of the torsional vibrations was 0.220 s.



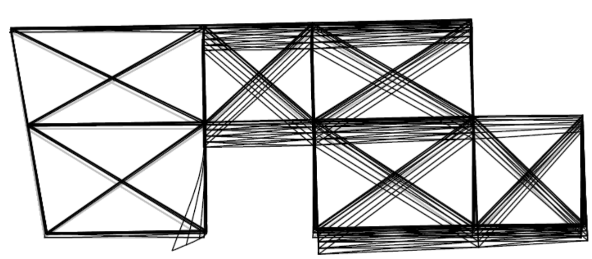
Primary mode (Span direction)



Secondary mode (Longitudinal direction)



Third-order mode (Torsion)



Fifth-order mode (Secondary Span direction)

Fig. 9 – Modal shapes

7. Consideration

To compare the natural period results of mode analysis using micro-tremor measurements and the frame model (shown in Table 3). Regarding the micro-tremor measurements, the higher-order modes could not be obtained because the noise was larger than that of the torsional mode. With regard to the primary mode of span and longitudinal directions and the torsional mode, the natural periods of the results of the micro-tremor measurements and the modal analysis demonstrated highly similar values. Errors of the first to third order modes were 3.1 to 4.1%.

The primary translational mode obtained from the velocity waveform and the transfer functions of the micro-tremor and the modal analysis of the frame model for the node in the vicinity of the staircase of each floor are shown in Fig. 4. The results of the scaled mode for each floor were used as normalization values. The values corresponding to the mode shape of the primary translational mode of the rooftop are also shown in Fig. 4. In the span direction, the micro-tremor waveform and transfer function of the frame model demonstrated good agreement. In the longitudinal direction, the transfer function and the frame model results also demonstrated similar values, but the micro-tremor results differed slightly. This could be attributed to the period of the torsion being similar to the period of the longitudinal direction when applying the band pass filter.

Fig. 5 shows the torsional vibration mode obtained from the mode analysis of frame models overlaid on the resulting torsional vibration mode from the micro-tremor measurements. Here, the torsional vibration mode was used as the normalization value to be normalized by the maximum value of the positive side at the upper right. In the figure, the solid line corresponds to the micro-tremor results, and the broken lines represent the frame model results. The location of the center of rigidity as obtained by the mode analysis was at a position slightly south of that estimated by the micro-tremor results.

8. Conclusion

To investigate the dynamic characteristics of an existing building, micro-tremor measurements, artificial excitation, strong motion observation, and frame model vibration analysis were performed. The vibrational characteristics of the building determined by the study are summarized as follows.

1) The natural periods of the span and longitudinal directions and the torsion calculated using the micro-tremor measurements were very close to the results from the modal analysis of the frame model.

2) In terms of the primary translational mode derived from the micro-tremor measurements and from the modal analysis results of the frame model, the vibration mode shape from the velocity waveform and the transfer functions of the micro-tremor and the modal analysis of the frame model were highly similar for the longitudinal direction.

3) The difference between the torsional vibration mode obtained from the modal analysis of the frame model and the torsional vibration mode obtained from micro-tremor measurements was small.

4) With regard to artificial excitation, the free vibration waveform demonstrated good results in the span direction.

5) The strong motion observation results show changes in the natural period of the building. The natural period was significantly longer during the 3.11 earthquake, but demonstrated a gradual recovery with the passage of time following the event.

9. Acknowledgments

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10. References

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