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FLEXURAL DEFORMATION OF A HIGH-RISE RC BUILDING BASED ON STRONG MOTION RECORDS AND MICROTREMOR DATA

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Abstract

Over the past four decades, many high-rise buildings have been constructed in Japan. On March 11, 2011, the 2011 Great East Japan Earthquake (Mw 9.0) occurred and affected the structural responses of buildings in the eastern part of Japan. In some buildings, strong motion records were obtained and used to clarify the dynamic structural responses, including the temporal variation of dynamic properties. In high-rise buildings, flexural deformation due to overturning moment significantly impacts the lateral displacement especially in the upper floors. Flexural deformation is important because it has different dynamic characteristics from conventional equivalent multi-mass shear spring models in the higher eigen modes. However, few studies focus on flexural deformation because few strong motion records that are capable of studying. In this study, we examine the flexural properties of a 22-story reinforced concrete building located in a metropolitan area based on the recorded data of microtremor measurement as well as free vibration experiment and strong motion observation. Strong motion records were observed by four 3-axis accelerometers installed on the first floor and in three corners at the rooftop. Regarding the analysis of strong motion records, we investigated the changes in the dynamic characteristics of the building and the eigenmode at the top of the building using system identification based on the subspace method. The natural frequency of the first mode decreased by 15% after the 2011 Great East Japan Earthquake without recovering to the original condition before the earthquake. This same phenomenon was also observed in other high-rise RC buildings. For the eigenmode at the top of the building, natural vibration accompanied by rotational deformation was observed on the top floor during the earthquakes. Furthermore, we perform a nonlinear response analysis using a bending-shear model based on a three-dimensional moment-resisting frame model. The input earthquake motion was a consecutive wave that combines the 2011 Great East Japan Earthquake and the aftershock. The lateral and rotational responses at the top of the building during the mainshock and the aftershock were well reproduced by the consecutive analysis. Based on the analysis results, the ratio of the flexural deformation to the total inter-story drift during the 2011 Great East Japan Earthquake was about 59% (NS direction) and 62% (EW direction) at the top floor.

Keywords: high-rise RC building; flexural deformation; strong motion record; microtremor data

1. Introduction

In Japan, many high-rise buildings have been constructed over the past four decades. On March 11, 2011, the 2011 Great East Japan Earthquake (Mw9.0) occurred and affected the structural responses of buildings in the eastern part of Japan. In some buildings, strong motion records were obtained and used to clarify the dynamic structural responses, including the temporal variation of dynamic properties and the change of vibration characteristics such as the elongation of the natural period of the buildings had been reported [1, 2, 3]. This phenomenon indicates that the buildings showed nonlinear behavior during the earthquakes. An equivalent multi-mass shear spring model or a bending-shear model has been conventionally used to reproduce seismic response of buildings numerically. The bending stiffness (EI) and shear stiffness (GA) of the bending-shear model is set up based on static push-over analysis results for a three-dimensional frame model. In general, it is assumed that EI has a negligible nonlinearity effect [4], and, in many cases, all nonlinear behavior associated with the plasticization of columns and beam members are reflected in GA.

In high-rise buildings, flexural deformation due to overturning moment significantly impacts the lateral displacement, especially in the upper floors. The flexural deformation is evaluated based on the axial deformation of the columns and the rotational deformation of the floors. Flexural deformation is important because it has different dynamic characteristics from conventional equivalent multi-mass shear spring models in the higher eigen-modes. However, few studies focus on flexural deformation based on vibration measurements, including strong motion records and ambient data.

In this study, we examine the dynamic characteristics and flexural properties of a 22-story reinforced concrete (RC) building, using a strong motion observation system equipped with three corners at the top of the building. Furthermore, we examine the flexural deformation of the building, using a bending-shear model. First, we examine the dynamic characteristics and flexural properties at slight deformations based on the recorded data of a microtremor measurement and a free vibration experiment. The dynamic characteristics and flexural properties are then examined during earthquakes, and changes in the dynamic characteristics of the building and eigenmodes at the top of the building are investigated using system identification based on the subspace method [5]. Furthermore, we construct a bending-shear model to evaluate the response of the building to an earthquake, including the flexural deformation due to overturning moment. Additionally, a rotating ground spring is used in the analysis to take the rocking deformation of the foundation into account. We perform nonlinear earthquake analyses using the consecutive wave that combines the 2011 Great East Japan Earthquake and the aftershock, and examine the lateral and rotational responses of the top of the building. Based on the analysis results, the ratio of the flexural deformation to the total inter-story drift is discussed.

2. Outline of the building and vibration measurement

2.1 Outline of the building

The building is located in Shiki city, Saitama Prefecture, in a metropolitan area in Japan, as shown by a square in Fig. 1. The building is a moment-resisting RC frame structure constructed in 1995. Table 1 lists the information of the building. Fig. 2 shows the plan of the first floor as well as the rooftop and south cross-section, including the basement. The standard floor plan of the building is 26.8 m (NS direction) × 23.6 m (EW direction). Meanwhile, the basement floor is wider than the upper structure. The depth of the embedded basement is 9.65 m and it is supported by expanded cast-in-place RC piles. The tip position of the piles is Ground Level -36.0 m.

2.2 Strong motion observation system

This building was instrumented in 1995 with four 3-axis accelerometers for seismic observations. One accelerometer was located on the first floor and three accelerometers were located at the corners of the rooftop, as shown by the red circles with detector numbers in Fig. 2. The sampling frequency of the accelerometers was 100 Hz. We can study the flexural deformation of the building during earthquakes using vertical records obtained at three locations on the same floor.

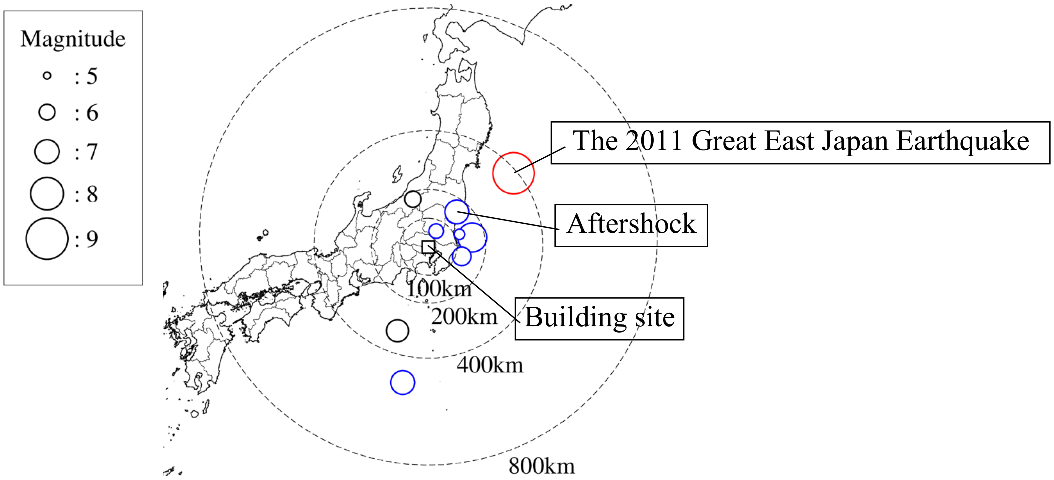
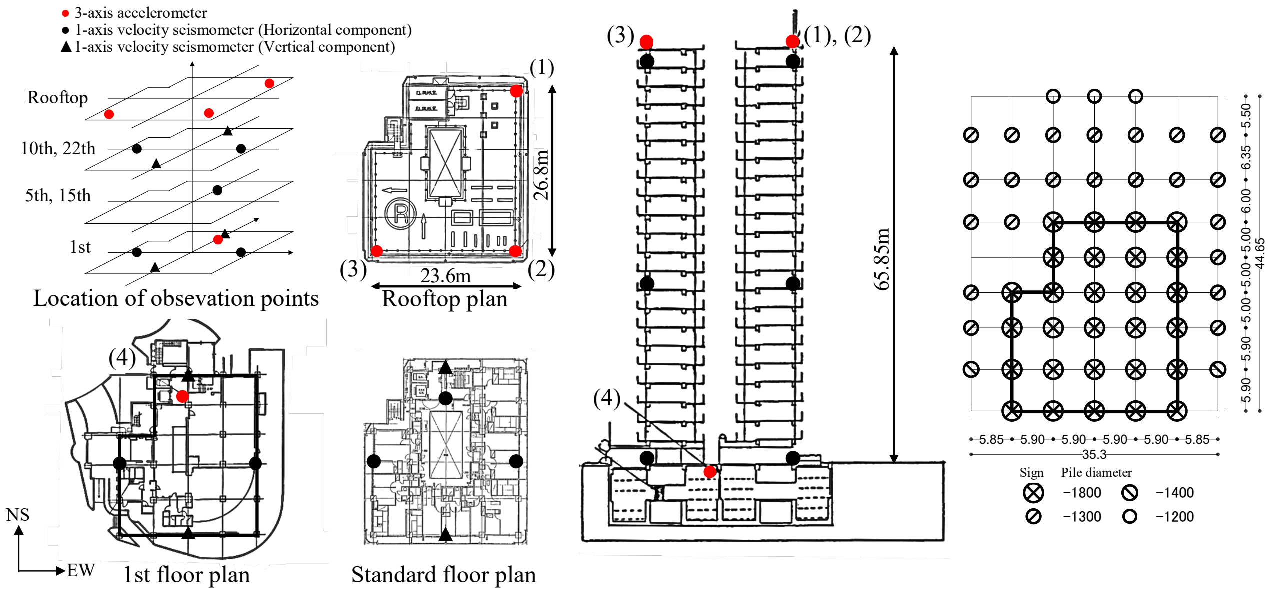


Fig. 1 – Location of the building and epicenters of the earthquakes where strong motions were recorded



(a) (b) (c)

Fig. 2 –Location of observation points at the high-rise RC building.
(a) Horizontal plan, (b) Height-wise arrangement, and (c) Plan of RC piles.

Table 1 – Information of the building

Construction region	Shiki city, Saitama Prefecture, Japan
Year of construction	1995
Building use	Residential building
Story number	1-story basement, 22-story upper structure
Eaves height	65.35 m
Structural type	Reinforced concrete (RC)
Pile type	Cast-in-place RC piles

2.3 Microtremor measurement

Microtremor measurement and free vibration experiment were conducted on the same day. At this time, the construction of columns and beams had been completed, but non-structural walls had not been installed above the 16th floor. The ambient noise was measured using velocity seismometers. The seismometers were arranged in such a way that the motions could be observed in the horizontal NS and vertical UD directions. Meanwhile, the sampling frequency of the seismometers was 100 Hz. The measurement was made on the 22nd, 15th, 10th, 5th, and 1st floors to clarify the mode shape. Figure 2 shows the observation points with black circles and triangles, where the black circle is the NS component, while the black triangle is the UD component. However, only one seismometer was placed on the 15th and 5th floors near the center of the floor. Meanwhile, the vertical components were recorded at two locations at both ends of the building.

2.4 Free vibration experiment

A Free vibration experiment was conducted on the 22nd floor using manpower excitation. About 10 people swung at the center of the 22nd floor with the excitation cycle of the first natural period obtained from the microtremor data. The number of excitation cycles was about 10 times.

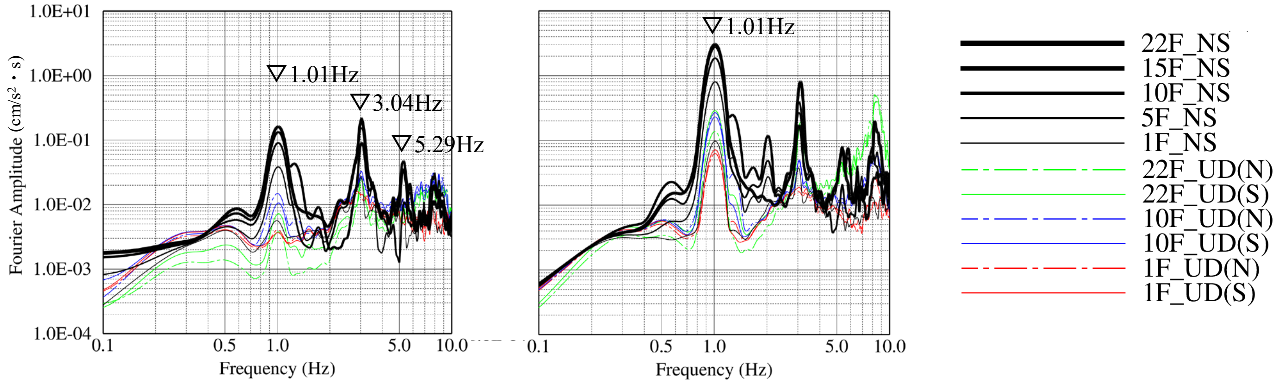
3. Dynamic characteristics and rotational deformation

3.1 Dynamic characteristics based on microtremor measurement and free vibration experiment

In a previous study, the dynamic characteristics in the horizontal direction had been reported from the microtremor measurement and free vibration experiment [6]. In this study, we investigated the overall flexural response associated with the lateral response by using vertical measurements obtained at the corners of the floors. Fig. 3 (a) shows the Fourier amplitude spectrum calculated using the acceleration data obtained from the velocity data. A Parzen window (bandwidth: 0.2 Hz) was used for smoothing. The NS direction data on the 22nd, 15th, and 1st floors were the ensemble averages of two data on the same floor. From the Fourier amplitude spectra, the predominant frequencies were observed at 1.01 Hz, 3.04 Hz, and 5.29 Hz, which correspond to the 1st, 2nd, and 3rd natural frequencies of the lateral records, respectively. In the vertical recordings, the predominant frequency is the same that of the horizontal direction. Therefore, the predominant frequency in the vertical direction is considered to be a flexural component associated with each lateral vibration. Meanwhile, the amplitude of the vertical component on the 22nd floor is significantly smaller than that on the 10th and 1st floors, due to some instrument errors.

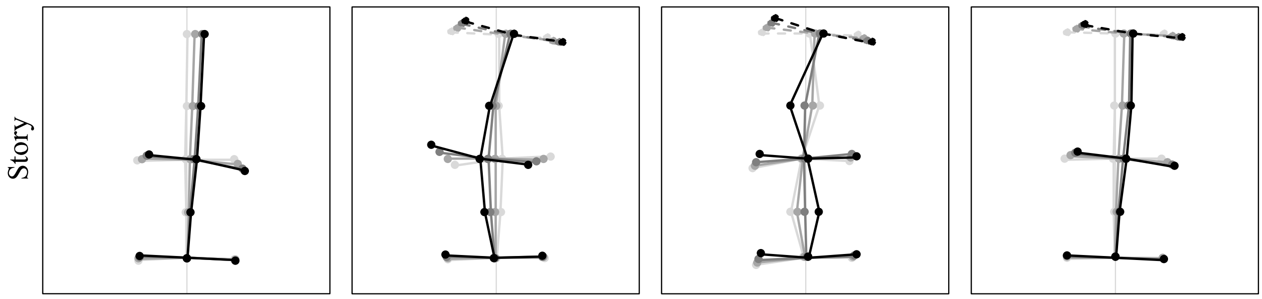
A free vibration experiment with manpower excitation was performed at the first natural period obtained from the microtremor data. In the spectra of the recorded data in Fig. 3 (b), a peak amplitude was observed in the same frequency as that of the microtremor. However, the peak amplitude was about 20 times larger than that of microtremor data.

The vibration modes from the microtremor measurement and the free vibration experiment are plotted in Fig. 4 (a)-(c) and Fig. 4 (d), respectively. The vertical displacements at the end of the building on the 22nd, 10th and 1st floors occur with the lateral displacement. The lateral amplitude was normalized by the maximum displacement at the top for each vibration mode, and the amplitude of vertical displacement was increased by 5 times that of the lateral displacement to make clear the rotational displacement in each mode.



(a) Microtremor data (b) Free vibration data

Fig. 3 – Fourier amplitude spectra from (a) microtremor data and (b) free vibration data



(a) 1.01 Hz (b) 3.04 Hz (c) 5.29 Hz (d) 1.01 Hz

Fig. 4 – (a)~(c) Vibration shapes of 1st to 3rd mode from microtremor data and (d) that of the first mode from free vibration data

3.2 Earthquakes used in this study and changes in dynamic characteristics depending on amplitude

Fig. 1 shows the relationship between the observation site and the locations of the epicenters. In the building, multiple earthquake records, including the 2011 Great East Japan Earthquake, were obtained which led to large responses in high-rise buildings in the eastern part of Japan. Previous studies had reported that the natural frequencies of the buildings changed during the earthquake due to nonlinear behavior [1, 2, 3]. Hence, we classified the earthquake records into three periods: during, before, and after the 2011 Great East Japan Earthquake. From the acceleration waveform (NS direction) observed for the building during the 2011 Great East Japan Earthquake in Fig. 5, the acceleration response in the building was amplified by about four times the input wave.

To study the temporal changes in the natural frequency and damping factor of the building, we used system identification based on the subspace method for the earthquake records shown in Fig. 1. We used the record of the 1st floor as the input data and the rooftop records as the output data, with a time interval of 20 seconds. Fig. 6 shows the relationship between the maximum relative displacement of the top floor and the 1st floor as well as (a), (b) the natural frequency and (c), (d) damping factor of the 1st mode. There was a small reduction in the natural frequency and damping factor was about 1% before the 2011 Great East Japan Earthquake. However, the natural frequency significantly decreased by about 15% after the 2011 Great East Japan Earthquake without recovering to the original condition before the earthquake. This phenomenon can also be observed in other high-rise RC buildings in the Kanto area during the 2011 Great East Japan Earthquake [2]. As the amplitude increased, the damping factor increased to about 3%. This is attributed to energy dissipation by hysteresis loop.

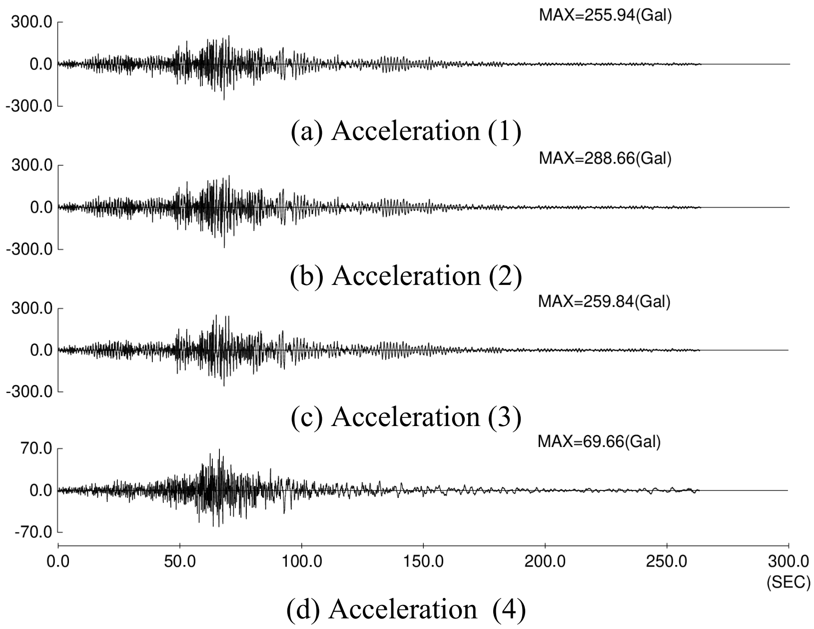


Fig. 5 – Example of acceleration waveform recorded at (a)~(c) rooftop, (d) 1st floor during the 2011 Great East Japan Earthquake (NS Direction)

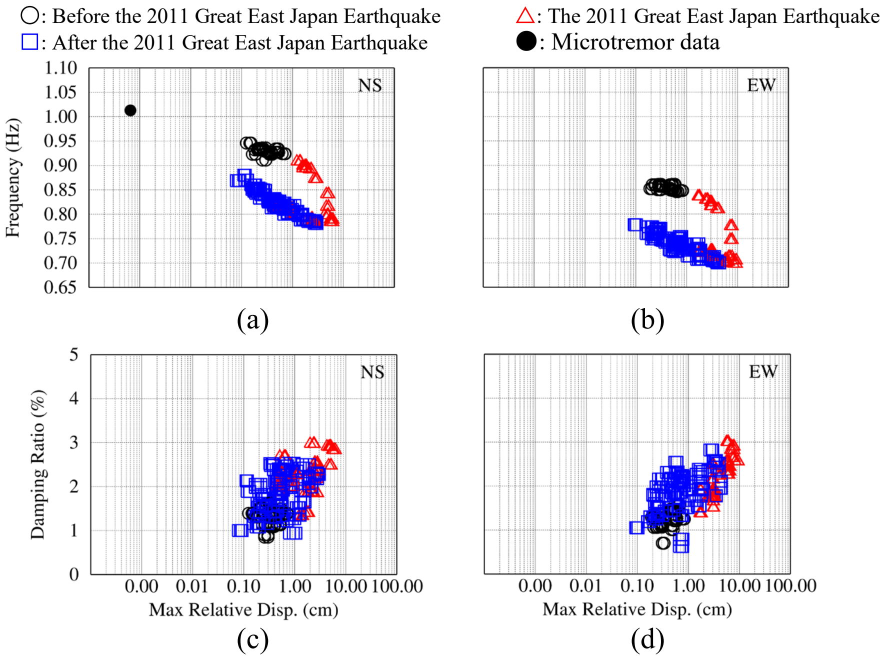


Fig. 6 – Relationship between the maximum relative displacement of the top floor and the 1st floor (a), (b) primary natural frequency and (c),(d) damping factor

3.3 Rotational deformation at the top floor during earthquakes

Fig. 7 (a) shows the Fourier amplitude spectra of the acceleration records observed by accelerometers during the 2011 Great East Japan Earthquake (NS, EW, and UD from the top). A Parzen window (bandwidth: 0.05 Hz) was used for smoothing. Peak amplitudes were observed at 0.80 Hz and 2.33 Hz in the NS direction, and at 0.71 Hz and 2.44 Hz in the EW direction, which correspond to the lateral primary and secondary natural frequencies, respectively. In the spectrum in the UD direction, the peak amplitude had the same frequency as that of the horizontal direction. This vertical displacement is attributed to rotational deformation accompanied by each natural vibration. On the other hand, the peak amplitude around 6 Hz corresponds to the 1st-order eigenmode in the vertical direction. Meanwhile, eigenmodes at the top of the building were obtained based on the system identification. Fig. 7 (b) shows the eigenmodes obtained from the main part of the records from 70 to 90 seconds during the 2011 Great East Japan Earthquake. In the figure, each accelerometer is represented by a circle. The black line indicates the original position before the earthquake, and the gray line indicates the displacement in each frequency. The values in the figure indicate the vertical displacement when the lateral displacement in each mode direction of corner (2) is normalized to 1. Moreover, rotational deformation during earthquakes was confirmed by simultaneously observing the earthquake records at multiple edge corners on the same floor.

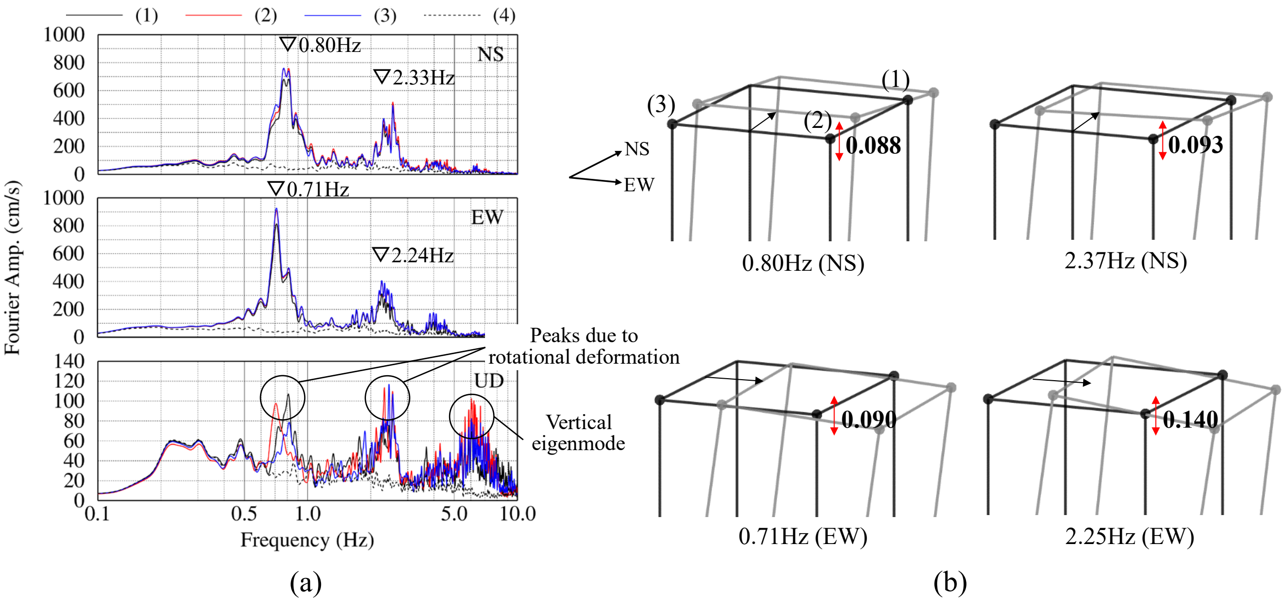


Fig. 7 – (a) Fourier amplitude spectra of the acceleration records measured by the accelerometers during the 2011 Great East Japan Earthquake
(b) Eigenmode at the top floor (numbers are the ratios of vertical to lateral displacement)

4. Seismic response analysis with special reference to rotational response

4.1 Bending-shear model

To evaluate the earthquake response and flexural deformation due to overturning moment, we first constructed a three-dimensional moment-resisting frame model. The rocking stiffness and damping coefficient in Table 2 evaluated by soil-structure-interaction analyses were added under the 1st floor to take the rocking deformation of the foundation into account. Regarding the nonlinearity of structural members, the MS model is used for columns and the elastic-plastic model is used for the beams. The restoring force characteristics are the Takeda model as a tri-linear type. Meanwhile, the rigid floor was assumed for each layer. The stiffness was adjusted so that the initial primary natural period of the three-dimensional frame model was consistent with that before the 2011 Great East Japan Earthquake. Afterward, the EI and GA of the bending-shear multiple-degree-of-freedom model were evaluated from the results of the static push-over analysis with the fixed-base condition. Bending-shear model comprise rotational and shear springs connected in series for each story. Fig. 8 shows (a) the model image and (b) bending-shear stiffness of the spring. The EI was assumed to be elastic, and all nonlinear behavior associated with the plasticization of columns and beam members were reflected in GA. In addition, the cracking capacity and second shear stiffness of the bending-shear model were adjusted so that the nonlinear response during the 2011 Great East Japan Earthquake was consistent with the observed records. Meanwhile, the damping was proportional to the instantaneous stiffness, and it was set to 1.3% of the first natural period, which is the average value of the system identification results before the 2011 Great East Japan Earthquake.

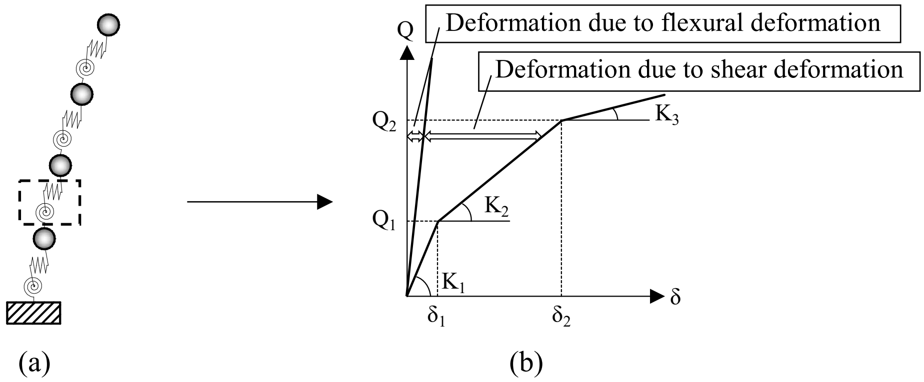


Fig. 8 – (a) Model image of the bending-shear model
(b) Tri-linear skeleton model due to flexural and shear deformation

Table 2 – Stiffness and damping of rocking springs used for analysis

Rotating ground spring		
Direction	NS	EW
Stiffness (kN·m/rad)	1.82×10^{10}	1.44×10^{10}
Damping (kN·m·s/rad)	7.35×10^{8}	5.67×10^{8}

4.2 Eigenvalue analysis

Eigenvalue analysis was performed using the constructed bending-shear model. The initial natural period of the model in Table 3 is generally consistent with the observed records before the 2011 Great East Japan Earthquake in each direction. The rocking ratio of the foundation to the total lateral displacement at the top floor is about 5 % in the 1st mode, which is relatively small.

Table 3 – Comparison of initial natural period and model rocking ratio

Natural period (s)							Rocking ratio (%)	
Mode number	1st mode		2nd mode		3rd mode		NS	EW
Direction	NS	EW	NS	EW	NS	EW	4.62	4.75
Observation record	1.08	1.17	0.36	0.38	0.21	0.22		
Bending-shear model	1.07	1.18	0.36	0.39	0.20	0.22		

4.4 Comparison of lateral and rotational response based on analysis results and observation records

The earthquakes used for the seismic response analysis are the 2011 Great East Japan Earthquake and the earthquake that occurred on April 11, 2011 in the Hama-dori of Fukushima Prefecture as one of the aftershocks. The input earthquake was a consecutive wave that combines the 2011 Great East Japan Earthquake and the aftershock in Fig. 9. Meanwhile, a zero amplitudes interval of 100 seconds was introduced between the Great East Japan Earthquake and the aftershock.

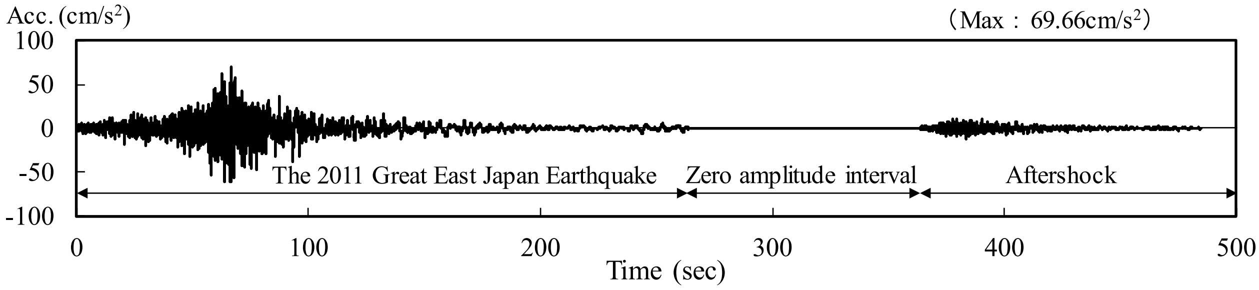


Fig. 9 – Input acceleration waveform

Earthquake response analysis was performed using the bending-shear model. Acceleration response waveforms and the pseudo-velocity response spectrum in the horizontal direction are compared in Fig. 10 (a) (b), Fig. 11 (a) (b), respectively, for each earthquake with the observation records in the NS direction. The lateral response from the observation record was evaluated from the average records at three corners of the rooftop. The calculated earthquake responses are generally consistent with the records during the 2011 Great East Japan Earthquake and aftershock in view of both the phase and amplitude of the waveforms and their spectral peaks. During each earthquake, the observed data and the analysis results of the rotational acceleration response waveform and its spectrum are compared in Figs. 12 and 13. The rotational response from the observation record was calculated from vertical acceleration waveforms obtained at the two rooftops. Since this record contains many high frequency components due to vertical vibration, a 5.0 Hz low-pass filter was applied. Meanwhile, the phase of the rotational acceleration waveform is similar to that of the horizontal waveform, implying that the rotational response is accompanied by the lateral response, although the amplitude of the response spectra of the rotational acceleration is underestimated.

The broken lines in Fig.11(b) and Fig.13(b) are spectra when the aftershock solely input to the model. They are different from the observation records in terms of the fundamental period and amplitude, implying that the structural behavior after the 2011 Great East Japan Earthquake is completely different from the original behavior.

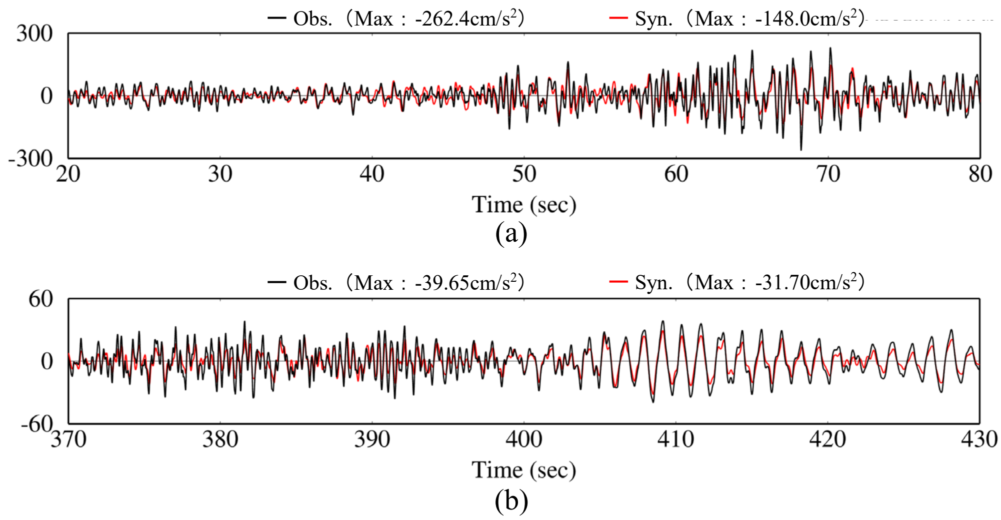


Fig. 10 – Comparison between recorded acceleration waveforms and those from analysis results at the lateral response (a) the 2011 Great East Japan Earthquake and (b) aftershock

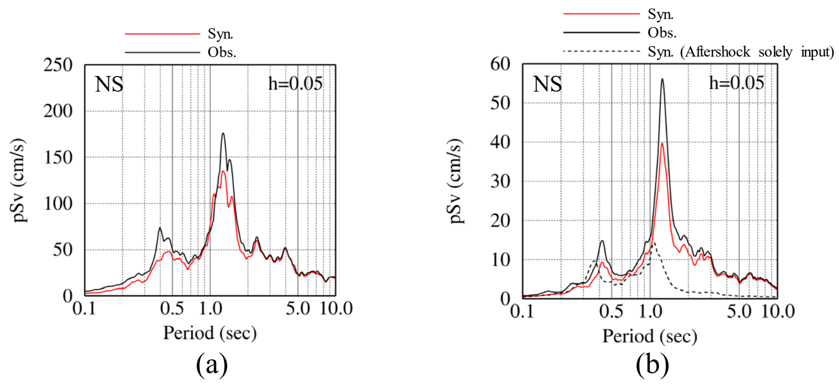


Fig. 11 – Comparison of pseudo-velocity response spectra (pSv) between recorded data and analysis results (a) the 2011 Great East Japan Earthquake and (b) aftershock (with aftershock solely input analysis result)

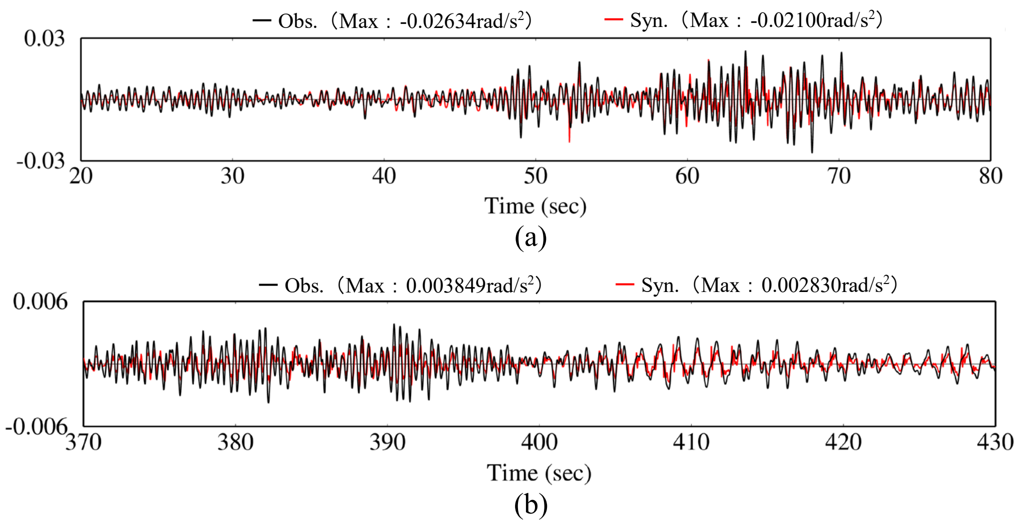


Fig. 12 – Comparison between recorded acceleration waveforms and those from analysis results at the rotational response (a) the 2011 Great East Japan Earthquake and (b) aftershock

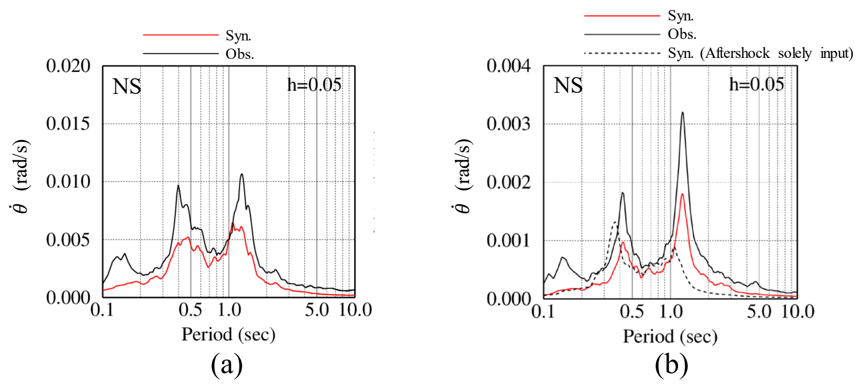
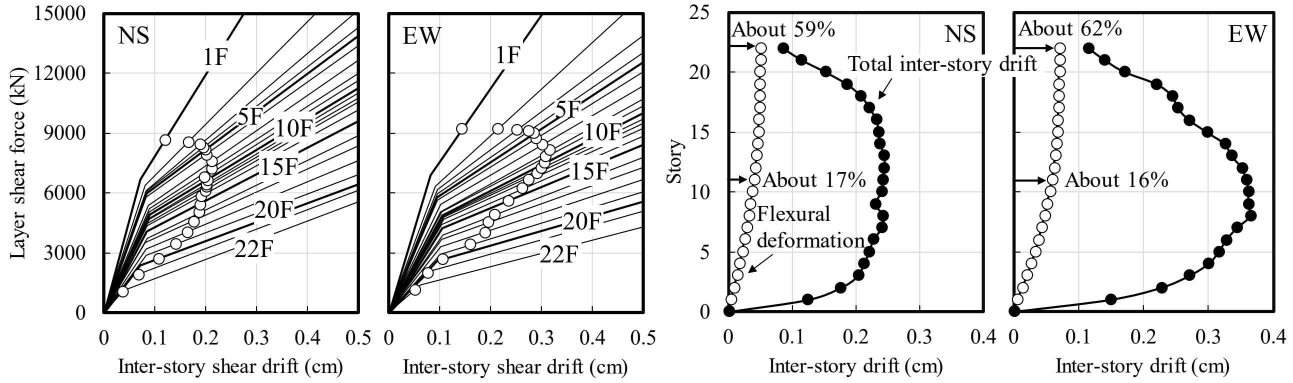


Fig. 13 – Comparison of response spectra of rotational response between recorded data and analysis results (a) the 2011 Great East Japan Earthquake and (b) aftershock (with aftershock solely input analysis result)

4.6 Maximum flexural response during the 2011 Great East Japan Earthquake

The maximum inter-story shear drift on the skeleton curve during the 2011 Great East Japan Earthquake in Fig. 14 (a) indicates that the maximum response exceeds the crack strength and is located on the second rigidity in the most layers in both directions. Meanwhile, the ratio of the flexural deformation to the total inter-story drift was examined. We extracted flexural deformation from the total inter-story drift in each story in Fig. 14 (b). The ratio of flexural deformation to total inter-story drift is about 17% (NS direction) to 16% (EW direction) in the middle floors and about 59% and 62% on the top floors.



(a) (b)

Fig. 14 – Analysis results of the 2011 Great East Japan Earthquake
(a) Skeleton curve and maximum inter-story shear drift
(b) Maximum total inter-story drift (closed circles) and flexural deformation (open circles)

5. Conclusions

This study investigated the structural responses as well as the flexural deformation of a 22-story RC building, using earthquake response records obtained at three corners at the top of the building. We also estimated the dynamic characteristics including flexural deformation due to overturning moment, and examined the ratio of the flexural deformation to the total inter-story drift based on the analysis results, using the bending-shear model. The conclusions of this study are summarized as follows.

1) In the spectrum in the UD direction, a peak amplitude was observed in the same frequency as the horizontal direction. This was attributed to rotational deformations that are accompanied by each natural vibration. Furthermore, rotational deformation was observed in each of the two lateral modes from the eigenmode diagram.
2) The natural frequency decreased and the damping factor increased as the maximum relative displacement increased during the 2011 Great East Japan Earthquake.
3) We performed earthquake response analysis using the bending-shear model and confirmed that the model is valid by comparing the observation records and analysis results
4) The ratio of the flexural deformation to the total inter-story drift became larger in the upper floors and was about 59% (NS direction) and 62% (EW direction) on the top floors.

6. Acknowledgements

The microtremor measurement and free vibration experiment were carried out by staff of Asanuma Corporation at the time of completion. Prof. Takenori Hida of the University of Tokyo provide many advices on the system identification using the MOESP. We sincerely appreciate their cooperation.

7. References

[1] Nagano M., Hida T., Watanabe K., Tanuma T., Nakamura M., Ikawa N., Yasui M., Sakai S., Morishita T. and Kawashima M. (2012): Dynamic Characteristics of Super High-Rise Residential Buildings in Kanto and Kansai Areas Based on Strong Motion Records during The 2011 Off The Pacific Coast of Tohoku Earthquake, Journal of Japan Association for Earthquake Engineering, Vol. 12, No.4, 65-79, Sep., 2012. (in Japanese)

[2] Uebayashi H., Nagano M., Hida T., Tanuma T., Yasui M. and Sakai S. (2015): Evaluation of the structural damage of high-rise reinforced concrete buildings using ambient vibrations recorded before and after damage, Earthquake Engng Struct. Dyn. 2015.

[3] Nagano M., Hida T., Tanuma T., Nakamura M., Ikawa N., Yasui M., Sakai S., Morishita T., Kitahori T. and Uebayashi H. (2016): Elucidation of Dynamic Behavior of Super High-Rise Residential Buildings during Massive Earthquake and Activities for Mitigation of Seismic Damages in Future, Journal of Japan Association for Earthquake Engineering, Vol. 16, No.5, 2-11, Apr., 2016. (in Japanese)

[4] Takahashi M., Fukuzawa E. and Isozaki Y. (2014): EARTHQUAKE RESPONSE ANALYSIS OF HIGHRISE R/C BUILDING IN CONSIDERATION OF VARYING AXIAL FORCE ON COLUMNS USING EQUIVALENT VIBRATION MODEL. Journal of structural engineering, Vol. 39B, 147-154, Mar., 1993. (in Japanese)

[5] Hida T., Nagano M. (2014): Estimation accuracy of natural frequency and damping factor of building by system identification based on three subspace methods. J. Struct. Constr. Eng., AIJ, Vol. 79, No.701, 923-932, Jul., 2014. (in Japanese)

[6] Tobita Y., Fukumoto N., Kikuchi K. and Suginouchi Y. (1995): Vibration experiments for a 22 story reinforced concrete building, Summaries of Technical Papers of Annual Meeting (Architectural Institute of Japan), 907-908, 1995. (in Japanese)

