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EARTHQUAKE RESPONSE CHARACTERISTICS OF A 30-STORY RC BUILDING BASED ON OBSERVED RESPONSE RECORDS

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Abstract

Structural damage to high-rise buildings caused by a long-period ground motion during a severe earthquake has been reported recently in Japan. Vibration behaviors of an existing high-rise building are discussed on the basis of response observation and measurements. The seismic performance is analytically investigated assuming severe earthquakes in the future.

The investigated building is a 30-story RC rahmen structure constructed in 1988 at the site of 17km to the south-southwest from Tokyo. Structural damage to the building caused by ground motions had not been observed during 19 years of the earthquake response observation since the completion of the building. However, it was confirmed that fundamental periods of the building elongated with the passage of time.

A slight damage to non-structural walls of the building caused by the Great East Japan Earthquake 2011 has been observed. The results of microtremor measurement show that any damage might have occurred to the structural members of the building because of the elongation of the fundamental periods, which was caused by the earthquake. The non-linear response analyses indicate that any damage might have also been generated in the structural members.

The largest story drift angle will be approximately 1/100rad. according to the analyses using the assumed ground motion obtained by amplifying the long-period component.

Keywords: Earthquake Response Characteristics; 30-story RC Building; Non-linear Analysis

1. Introduction

Structural damages to high-rise buildings caused by long-period ground motion during a severe earthquake have been reported recently in Japan [1-3]. The countermeasure for the long-period ground motion to high-rise buildings is not sufficient yet, and the verification of the seismic performance is an urgent issue.

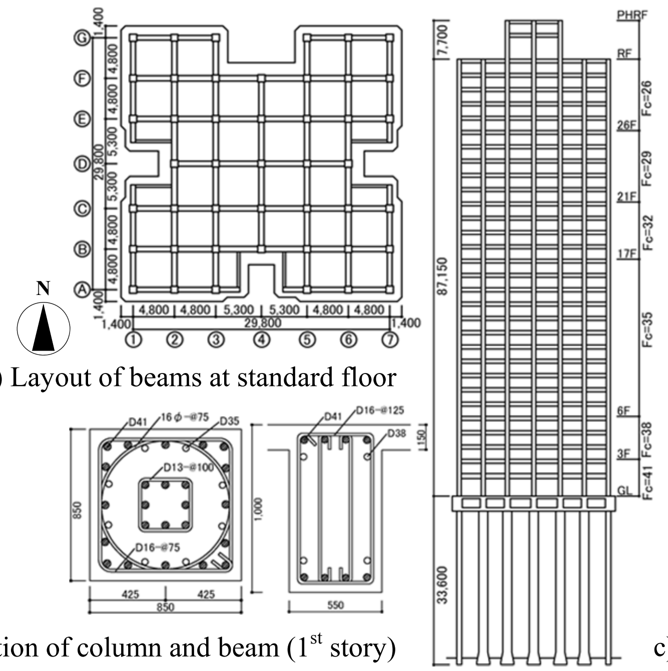
Vibration behaviors of an existing 30-story RC building are discussed on the basis of the results of microtremor measurements and earthquake response observation. And the seismic performance is analytically investigated against assumed severe earthquakes in the future [4].

2. Investigated building

The investigated building is a 30-story RC rahmen structure with approximately 100m high and constructed in 1988 at the site of 17km to the south-southwest from Tokyo. It is designed to yield in flexure at beams. The outline and the shape of the building is shown in Table 1 and Fig. 1, respectively. The building was constructed at the site of 400km from the epicenter of the Great East Japan Earthquake occurred on 11 March 2011 (hereafter "3.11EQ"). Slight damages to non-structural walls and joints of stair-slabs caused by 3.11EQ have been observed, but no damage to structural members has been observed.

Table 1 – Outline of investigated building

Construction year	1988
Building area	949m^2 (Total floor area : 24,400m^2)
Number of stories	30 stories (2 stories for penthouse)
Story height	4.00m for the 1st story, 2.85m for the other stories
Structure type	Reinforced concrete rahmen structure
Foundation type	Underground continuous wall and cast-in-place concrete bell pile



a) Layout of beams at standard floor

b) Cross section of column and beam (1st story)

c) Elevation of C-frame

Fig. 1 – Shape of investigated building

3. Microtremor measurement and earthquake response observation

3.1 Microtremor measurement

Microtremor measurements on the building were carried out annually from 2010 to 2015 except 2011. Sensors for the measurements were set at every 5 floors from the 1st floor to the roof floor. The time interval for data sampling was 0.01s, and the duration time was 300s for the measurements in 2010 otherwise 1,000s. Fourier's spectrum ratios of the records measured at the roof floor to the 1st floor, the ratios of RF/1F, are calculated to classify the fundamental periods. The periods measured in 2012 are approximately 1.2 times longer than the values measured in 2010 as shown in Table 2. It is assumed that the building received some sort of structural damages by 3.11EQ.

Two moderate earthquakes, which maximum ground acceleration are approximately 80cm/s^2 in the vicinity of the investigated building, occurred after 3.11EQ until the beginning of 2015. However, elongation of the periods caused by the attacks in those earthquakes is not confirmed as shown in Fig. 2.

Table 2 – Fundamental periods of investigated building [NS direction] (s)

	Fundamental period		Elongation of period [Ratio of elongation]
Year	2010	2012	
1st	1.63	1.95	0.32 [1.20]
2nd	0.513	0.605	0.092 [1.18]
3rd	0.287	0.345	0.058 [1.20]

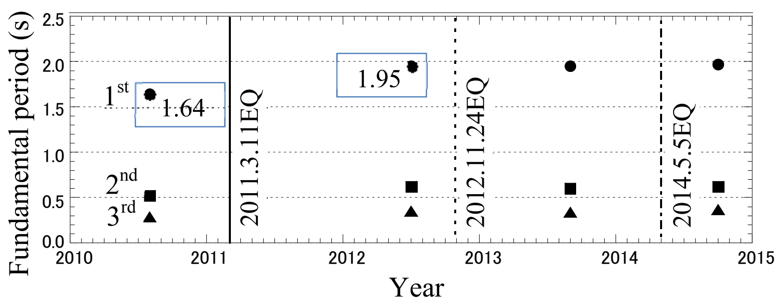


Fig. 2 – Transition of fundamental periods of investigated building [NS direction]

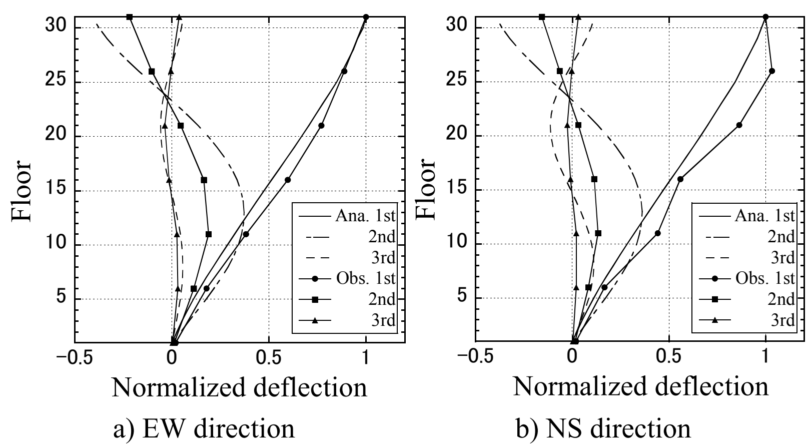


Fig. 3 – Vibration mode of investigated building [2014]

Shape of vibration mode of the building calculated on the basis of the results of microtremor measurements conducted in 2014 is shown in Fig. 3 with the analytical shape of the mode. The microtremor measurements and the modal analyses show the similar pattern.

The damping factors for the 1st, 2nd and 3rd vibration modes were determined by approximation using the least-squares method to RD waves which were evaluated using random decrement technique. The factors for the 1st, 2nd and 3rd modes are approximately 1-2%, 2-3% and 3-4%, respectively.

3.2 Earthquake response observation

Earthquake response observation on the building was conducted for 19 years from 1987, and there were 210 sets of data observed at the 1st and the roof floors during the period. Fourier's spectrum ratios are calculated to classify the fundamental periods of the building. The change of the periods is shown with approximate lines calculated in the least-squares method in Fig. 4. It is confirmed that the fundamental periods are elongated gradually with the passage of time.

Relationships between fundamental periods and maximum response acceleration observed at the roof floor are shown in Fig. 5. The number of observed data is reduced as the maximum response acceleration increases, and the periods are also elongated as the acceleration increases.

The elongation of fundamental periods obtained by microtremor measurements in 2010 and 2012 is too big to be regarded as the influence of the passage of time. This shows a possibility of structural damage on the investigated building by 3.11EQ occurred in 2011.

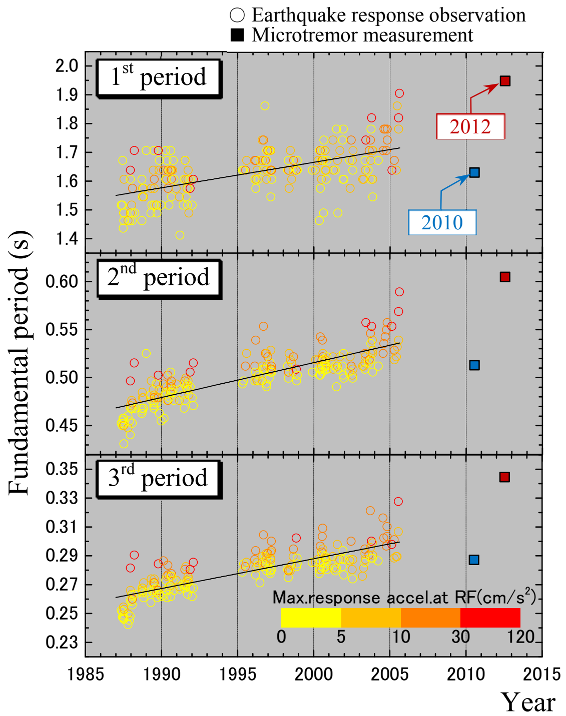


Fig. 4 – Change of fundamental periods [NS direction]

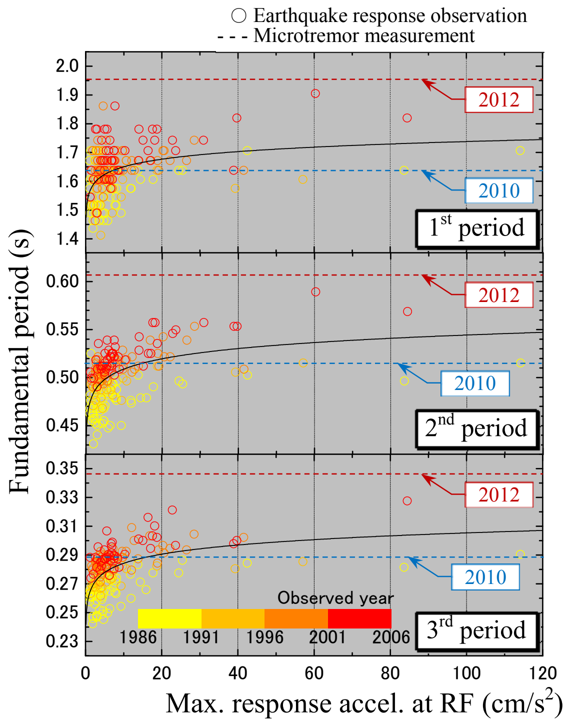


Fig. 5 – Fundamental periods vs. max. response accel. [NS direction]

4. Non-linear analyses

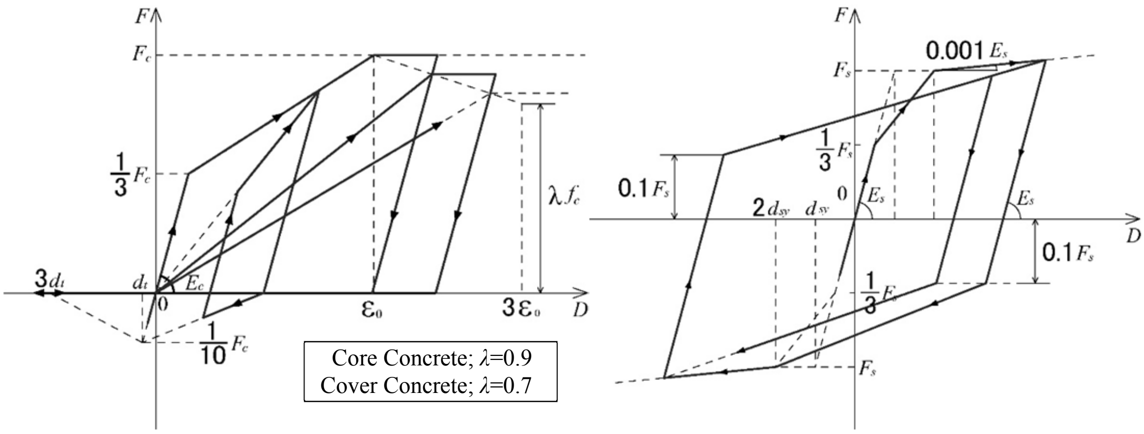
A three-dimensional non-linear analytical model for the building was made to conduct earthquake response analyses using SNAP ver.6. The model aims to simulate the response of the building to 3.11EQ and to confirm the seismic performance to severe ground motions during the assumed earthquakes that the Central Disaster Prevention Council, the Cabinet Office in the Government of Japan, press released.

4.1 Analytical model

Columns and beams are substituted for single wire for the analytical model, and weight of the building is intensively given at each node of the structural frame. The bottoms of columns on the 1st floor are fixed to the ground, and shear deformation of each floor is assumed to be negligible.

Flexural springs, a shear spring, and a torsional spring are given to every beam in order to represent deformation characteristics, and every column has an axial spring in addition to those springs. However, the axial and flexural characteristics of all columns on the 1st floor and outer columns on the 2nd-3rd floors are represented using multi-spring system in order to consider the influence of variable axial force. Flexural and shearing hysteresis models for the structural models are defined as the Takeda model and the origin-oriented model, respectively. Torsional and axial springs are also elastic model. Hysteresis loops of concrete and steel elements used for the multi-spring model are defined as Fig. 6. Joint zone of columns and beams is assumed rigid.

The damping factor for response analyses is considered as 3% in proportion to tangent stiffness.



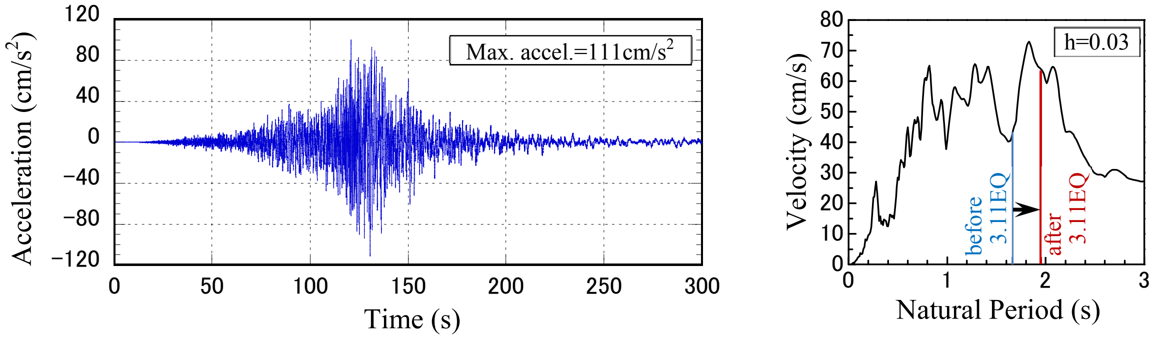
a) Concrete element b) Steel element

Fig. 6 – Hysteresis loops for multi-spring model

4.2 Analytical results on the Great East Japan Earthquake

Ground motion data recorded in the strong motion seismograph networks, which were named as KiK-net promoted by NIED, the National Research Institute for Earth Science and Disaster Resilience in Japan, was used for response analyses in 3.11EQ. The KiK-net Yokohama is the nearest station from the site of the investigated building. Accelerogram at the building site during 3.11EQ was calculated in consideration of the surface soil on the basis of accelerogram recorded at 2km underground of Yokohama station. The maximum acceleration of the calculated ground motion is 111cm/s^2. The accelerogram in NS direction and the response velocity spectrum is shown in Fig. 7. The response velocity of the predominant period of the investigated building during 3.11EQ is obviously predominated.

Elongation of fundamental periods of the investigated building caused by 3.11EQ is shown in Table 3. The natural periods of the analytical model are satisfied in 8% of precision according to the results of microtremor measurement in 2010 before 3.11EQ. The natural periods of the model after non-linear response by 3.11EQ are also corresponding to the results of microtremor measurement in 2012 after 3.11EQ with almost the same accuracy. The building property seems to be able to have been reproduced by the analyses.



a) Accelerogram b) Response velocity spectrum

Fig. 7 – 3.11EQ at the site of the investigated building [NS direction]

Table 3 – Elongation of fundamental periods of the investigated building by 3.11EQ [NS direction]

	Analyses (s)		**Microtremor (s)**		**Ana. / Microtremor**	
	before	after	2010	2012	before	after
1st	1.701	2.048	**1.63**	**1.95**	1.04	1.05
2nd	0.556	0.671	0.513	0.605	1.08	1.11
3rd	0.304	0.374	0.287	0.345	1.06	1.08

Note; "before" in column "Analyses" means condition before 3.11EQ.
"after" in column "Analyses" means condition after response against 3.11EQ.
"before" in column "Ana./Microtremor" means values of "before" in column "Analyses" divided by values of "2010" in column "Microtremor", and "after" is also based on "2012".

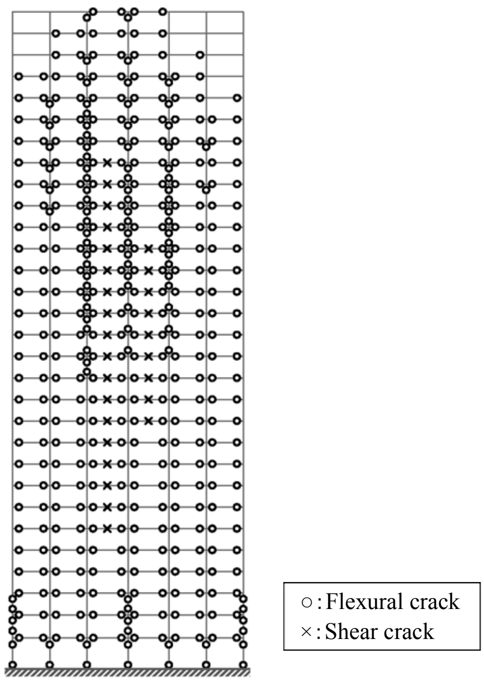


Fig. 8 – Crack pattern due to 3.11EQ (2-frame)

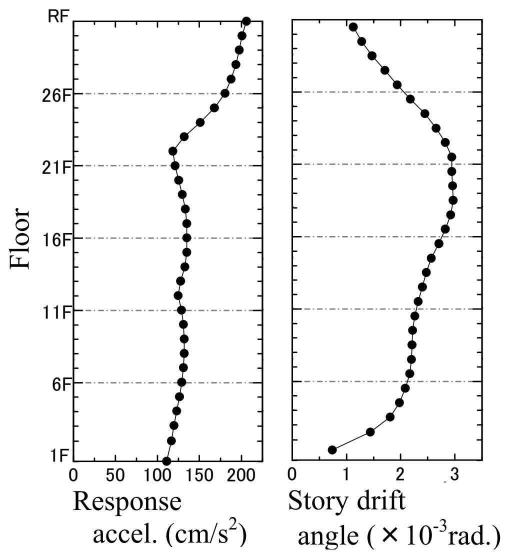


Fig. 9 – Maximum distribution on response analyses by 3.11EQ [NS direction]

Table 4 – Number of damaged structural members

	Column	Beam
Flexural crack	291 [0.22]	2,049 [0.94]
Shear crack	0 [0.00]	126 [0.06]
No damage	1,059 [0.78]	126 [0.06]
Total number	1,350	2,175

Note;
Values in brackets mean ratios of numbers of damaged members to total members.

Crack pattern of 2-frame with the most severe damage by 3.11EQ is shown in Fig. 8, and numbers of damaged columns and beams of the building are shown in Table 4. Nearly all the beams show flexural cracks. Flexural cracks on the columns and shear cracks on the beams occurred with large story drift angle on the intermediate floor. The maximum story drift angle is a little less than 1/330rad. on the 17^{th}-21^{st} floors as shown in Fig. 9.

4.3 Response to the assumed severe earthquake

Many waves on engineering foundations underground during severe earthquakes assumed in the future were shown by the expert committee, the Central Disaster Prevention Council, the Cabinet Office in the Government of Japan [4]. We chose several events which may influence the investigated building greatly Tokai-Tonakai-Nankai linked earthquake, Tama plate-boundary earthquake, and North of Tokyo Bay earthquake. The outline of ground motion at the site of the investigated building by the assumed earthquakes is shown in Table 5, and the response velocity spectra are shown in Fig. 10.

Tokai-Tonankai-Nankai linked earthquake is one of massive earthquakes around Japan assumed in the near future. The earthquake will occur along Nankai Trough, which is located in the Pacific Ocean near the southwestern part of Japan and is corresponding to a subduction zone of the Philippine Sea plate. However, the assumed maximum ground acceleration at the site of the building caused by the linked earthquake is not large because of the long distance to the site from the trough.

Table 5 – Ground motion at the investigated building site by assumed earthquakes

Name of earthquake	Max. accel. (cm/s^2)	Duration time (s)
Tokai-Tonankai-Nankai	66	176
Tama plate-boundary	374	33
North of Tokyo Bay	429	36

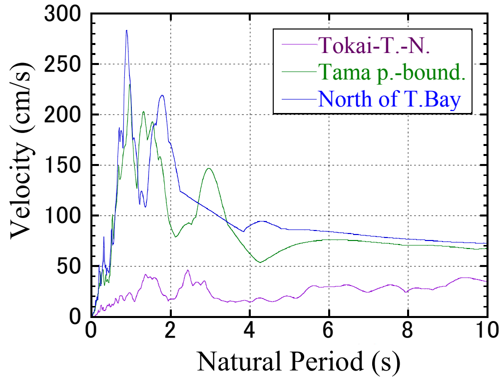


Fig. 10 – Response velocity spectra of assumed earthquakes [h=0.03]

Table 6 – Outline of spectrum fit waveforms

Name of waveform	Max. accel. (cm/s^2)	Duration time (s)
Fit waveform A	525	400
Fit waveform B	51	400
Fit waveform C	516	400

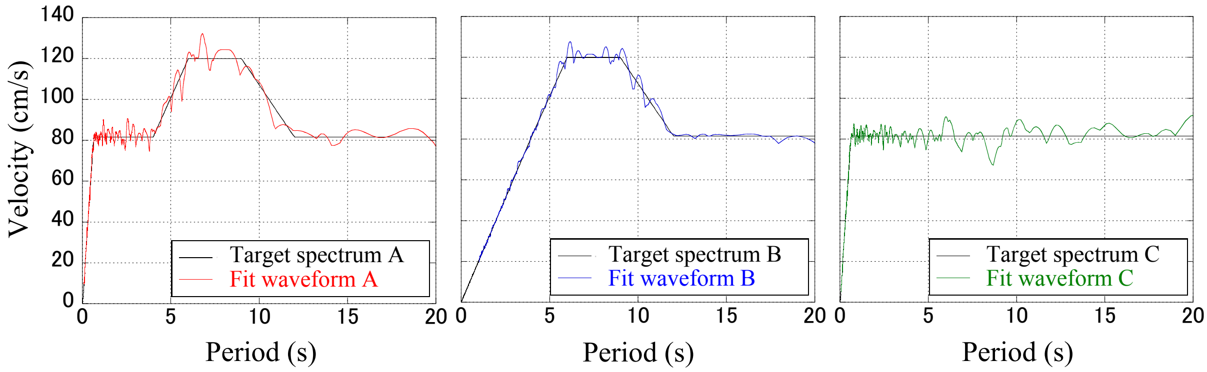


Fig. 11 –Response velocity spectra of spectrum fit waveforms [h=0.05]

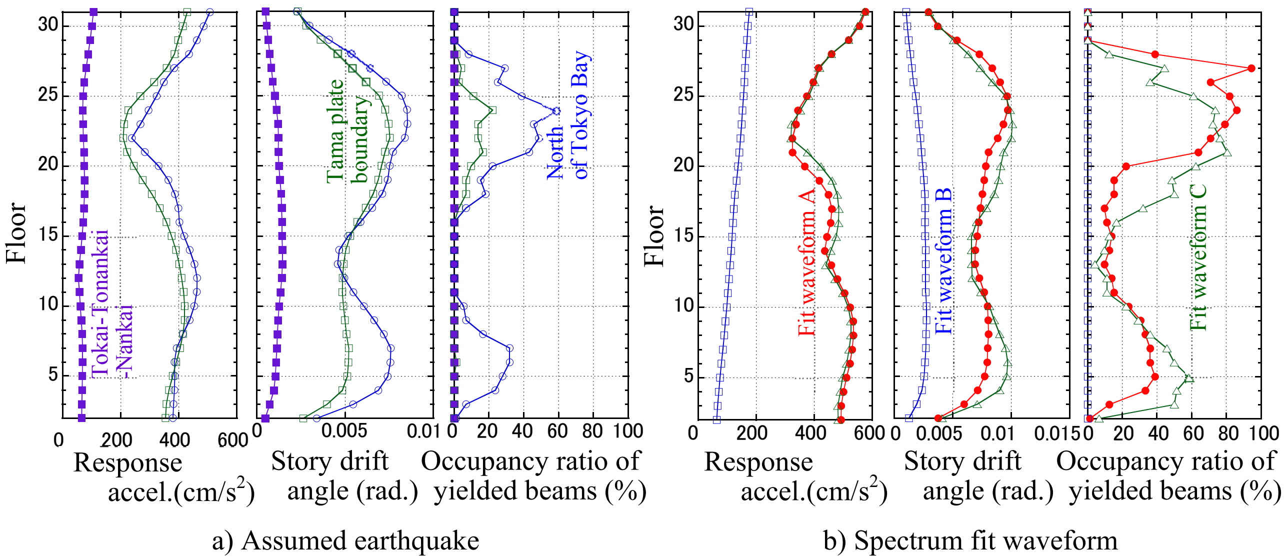


Fig. 12 – Maximum distribution on response analyses

Assumed ground motion obtained from response spectrum shown in a public notice of the Ministry of Land, Infrastructure, Transport and Tourism in Japan, is also used for the analyses. The ground motion is created by amplifying the long-period component with the response spectrum fitting method proposed in Ref. 5. The outline of the spectrum fit waveforms at the site is shown in Table 6, and the response velocity spectra are shown in Fig. 11.

The target spectrum C is the response velocity spectrum of level 2 defined in a public notice, of which maximum velocity is 50cm/s on the subsurface ground. The investigated building is located on the Kanto Plain, which is the widest plain including Tokyo area in Japan. The amplifying method for long-period component is proposed to make the target spectra intended for the Kanto Plain in Ref. 5. The target spectrum B shows the response velocity spectrum for amplification of the long-period component. And the target spectrum A is obtained by the combination of the long-period component in the target spectrum B and the short-period component in the target spectrum C.

All assumed accelerograms are used for response analyses, continuing after the accelerogram during 3.11EQ with the consideration of the deterioration of stiffness due to 3.11EQ.

Fig. 12a) shows distribution of the maximum responses by the assumed earthquakes, Tokai-Tonakai-Nankai linked earthquake, Tama plate-boundary earthquake, and North of Tokyo Bay earthquake. Fig. 12b) shows the distribution by the spectrum fit waveforms.

The maximum values of response acceleration, story drift, and occupancy ratio of yielded beams, are the largest in the analytical case in North of Tokyo Bay earthquake among the assumed earthquakes as shown in Fig. 12a). The values of story drift on the 5th-7th and 22nd-25th floors are large. The maximum story drift angle is a little more than 1/120rad. The degree of structural damage is not serious.

Time history of relative displacement during the earthquake is shown in Fig. 13. It seems that the higher vibration mode is predominant around the time of the maximum story drift. Relative displacement distribution at the time of the maximum story drift is shown in Fig. 14. The shape is similar to the 2nd vibration mode, and is also corresponding to the distribution of occupancy ratios of yielded beams.

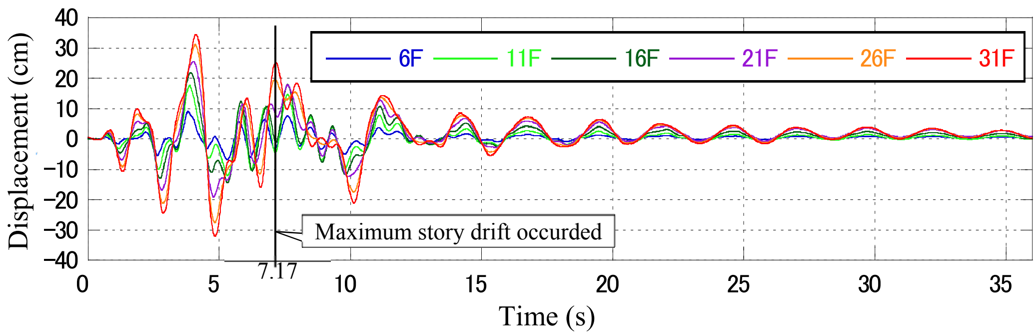


Fig. 13 – Time history of relative displacement caused by North of Tokyo Bay earthquake

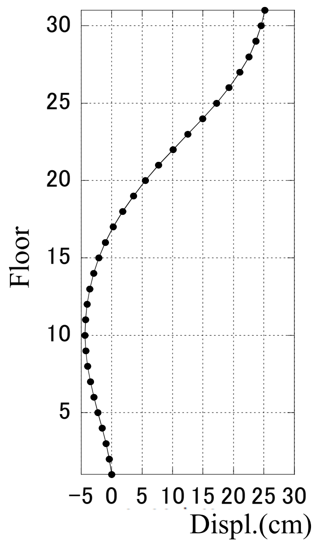


Fig. 14 – Distribution of relative displacement caused by North of Tokyo Bay earthquake (at the time with the maximum story drift)

The maximum response values are the smallest in the analytical case using the spectrum fit waveform B among the waveforms as shown in Fig. 12b). The maximum response values of story drift are obtained on the lower floors, 4th-8th, and the upper floors, 18th-26th. This tendency is similar to the case of North of Tokyo Bay earthquake. The maximum story drift angle is approximately 1/100rad. And the occupancy ratios of yielded beams more than 80% are obtained on the upper floors, 21st-27th. Although structural damages cannot be avoided during severe ground motions, excessive story drift will not occur on any floor.

Fig. 15 shows time histories of relative displacement on the roof floor caused by the spectrum fit waveforms A and C. The duration time of vibration caused by the fit waveform A is longer than the time caused by the fit waveform C. The influence on the degree of damage caused by amplifying the long-period component is not remarkable in the case of the investigated building. However, the duration time of vibration becomes longer by amplifying long-period component.

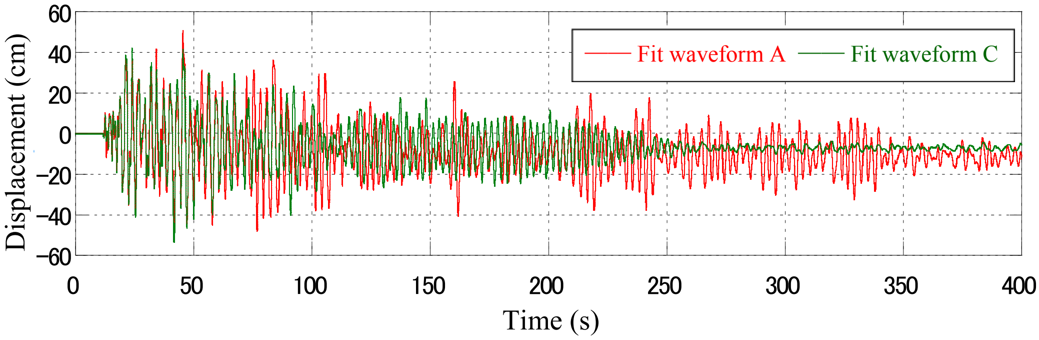


Fig. 15 – Time history of relative displacement at RF caused by spectrum fit waveforms A & C

5. Conclusions

Response characteristics of a 30-story RC building designed to yield in flexure at beams are discussed on the basis of the results of microtremor measurements, earthquake response observation, and response analyses.

Fundamental periods of the building tend to be elongated with the passage of time. Structural damages caused by 3.11EQ, the Great East Japan Earthquake 2011, are not observed. However, comparison of the results of microtremor measurements before and after 3.11EQ suggested that the building to be structurally damaged. Flexural cracks at nearly all the beams occurred in non-linear response analyses using 3.11EQ.

The results of response analyses using the assumed ground motion at the site of the investigated building show that the 2nd vibration mode is predominant. The maximum story drift angle is a little more than 1/120rad. in the case of North of Tokyo Bay earthquake. The degree of structural damage is not serious.

The 2nd vibration mode is also predominant in the analytical case using the waveforms amplified the long-period component. To amplify the long-period component from 4s to 12s contributes to longer duration time of response of the investigated building. The maximum story drift angle is approximately 1/100rad. Although structural damages cannot be avoided, excessive story drift will not occur on any floor.

6. Acknowledgments

The authors used the response observation data have been obtained by Kajima Corporation at the time of the earthquakes for 19 years since 1987. We received a great deal of cooperation from the members of the management association of the investigated building to conduct microtremor measurements and to use the detailed information about the building. We were able to gratitude toward them.

We used recorded data of the strong motion seismograph networks named as Kiban-Kyoshin Net promoted by NIED, the National Research Institute for Earth Science and Disaster Resilience in Japan.

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