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DYNAMIC RESPONSE CHARACTERISTICS OF SUPER HIGH-RISE RESIDENTIAL BUILDINGS IN KANTO AND KANSAI AREAS DURING THE GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT: During the main shock of the 2011 Great East Japan Earthquake, long-period ground motions were observed in the Kanto and Kansai areas, far from the epicenter, which must have influenced the dynamic behavior of the long-period structures. This paper describes the dynamic response characteristics of 14 super high-rise residential buildings in the Kanto and Kansai areas on the basis of the recorded motions. In addition, we examine the psychological condition of residents and actual damage caused to household property during the main shock through a questionnaire survey.

Key Words: the Great East Japan Earthquake, super high-rise residential buildings, recorded motions, dynamic characteristics, predominant period, questionnaire survey

INTRODUCTION

A massive earthquake, the 2011 Great East Japan Earthquake (off the Pacific coast of Tohoku Earthquake, Mw9.0), shook the eastern part of the Japanese mainland and led to devastating damage to buildings along the coastal area, mainly due to the immense force of the resultant tsunami (Architectural Institute of Japan, 2011). Because of the rupture of a large area of the seismic fault, ground motions of large amplitude and long duration were observed in not only the Tohoku area near the epicenter but also the Kanto area. Serious soil liquefaction also occurred in landfilled areas and throughout the alluvial land along the Tone River in Chiba Prefecture (Tokimatsu et al., 2011). Despite being the largest recorded earthquake (with a magnitude of 9.0) ever to have hit Japan, serious structural damage caused by ground shaking, including collapse, seems to have been smaller than expected.

During this earthquake, seismic waves generated by the rupture of the huge seismic fault spread and traveled into the Kanto and Osaka Plains, where thick sedimentary layers exist on the seismic bedrock. They were reflected and amplified within the sedimentary basins and observed the so-called "long-period ground motions," with long predominant periods and durations. More than 800 super high-rise residential buildings have been constructed in the highly urbanized area, where the long-period ground motions must have influenced the shaking of those buildings.

The influence of these motions on long-period structures has been the subject of many engineers' interest in Japan since the 2000 off Tokachi earthquake (Mw8.3), Hokkaido. The long-period ground motions observed in the sedimentary Yofutu Plain, far from the epicenter, are considered as one of the plausible reasons for the damage to several oil tanks located in Tomakomai, central part of the Yofutu Plain. The occurrence of the Tokai, Tonankai, and Nankai earthquakes, along the western part of the Japanese archipelago, must have had a serious effect on the dynamic behavior of the long-period structures densely constructed in the Kanto, Nohbi, and Osaka Plains because of the resonant phenomenon with long durations. Despite these urgent situations, it has been difficult to paint a precise picture of what will happen to the dynamic behavior of super high-rise buildings during intense shaking because of a lack of recorded motions. In addition, the behavior and psychology of the residents living in such buildings, as well as the moving and overturning of household appliances and furniture, have remained unresolved.

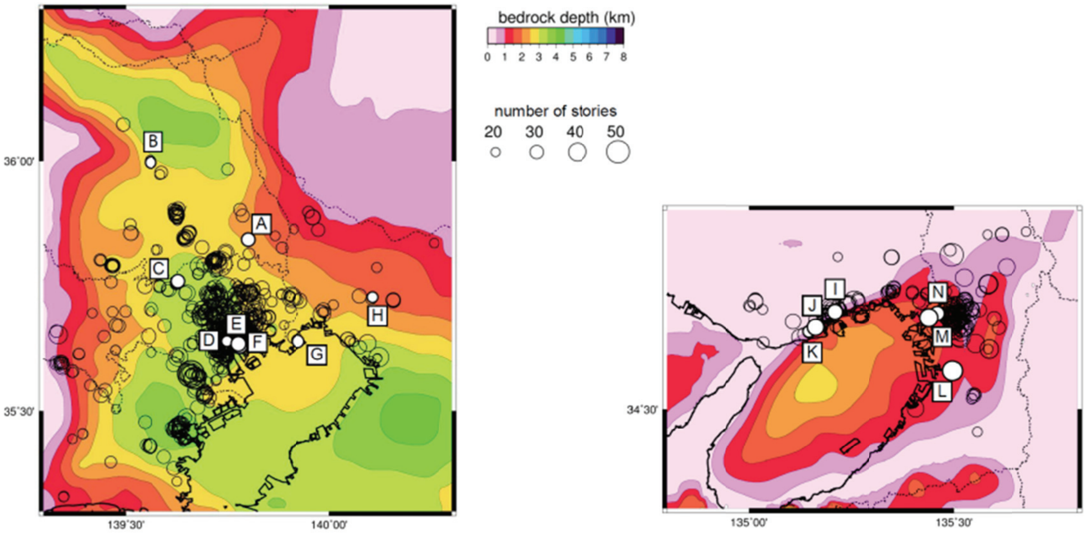
During the 2011 Great East Japan Earthquake, strong motion records were simultaneously obtained at the top and bottom floors in 14 super high-rise residential buildings constructed in the Kanto and Kansai areas. All buildings were located within the Kanto and Osaka Plains, where thick sedimentary layers overlie the seismic bedrock, and observed long-period ground motions. This study investigates the dynamic response characteristics of super high-rise reinforced concrete buildings on the basis of the recorded motions, focusing on the maximum structural responses as well as temporal variations in predominant frequencies. We also investigate the psychological condition of residents and the actual damage caused to household property during the main shock via a questionnaire survey.

PROFILES OF BUILDINGS

The buildings targeted for the investigation were 14 super high-rise residential buildings constructed in the Kanto and Kansai areas. Fig.1 illustrates the location of these buildings plotted against the contours of the seismic bedrock depth. There were eight and six buildings in the Kanto and Kansai areas, respectively. All buildings were located within the Kanto and Osaka Plains, where thick sedimentary layers exist on the seismic bedrock. Long-period ground motions during the Great East Japan Earthquake must have influenced the dynamic behavior of these super high-rise buildings.

The profiles, names, number of stories, structural types, and strong-motion observation floors of the buildings are listed in Table 1. These buildings were equipped with strong-motion observation systems, and seismic accelerometer records were simultaneously obtained at more than two floor levels, the top and first or basement floors and, if any, the middle floors.

Most of these buildings are reinforced concrete (RC) structures with over 24 stories, except for Building K, which is a steel RC (SRC) structure and Building M, which is a concrete-filled tube (CFT) structure equipped with visco-elastic dampers. Each building incorporated moment-resistant frames with high strength materials. Most of them were designed and constructed before the year 2000.



(a) Kanto area (b) Kansai area

Fig.1 Construction site maps of target buildings scoped in this paper

Table 1 Profiles of buildings

Area	Building name	Stories	strong-motion observation floors	Area	Building name	Stories	strong-motion observation floors
Kanto	**A**	30	B1F,15F,30F	Kansai	**I**	33	B1F,16F,33F
Kanto	**B**	25	1F,25F	Kansai	**J**	37	1F,14F,36F
Kanto	**C**	30	1F,30F	Kansai	**K**	25	B1F,5F,24F
Kanto	**D**	24	B1F,12F,24F	Kansai	**L**	43	B2,15,30,43
Kanto	**E**	33	1F,14F,24F,32F	Kansai	**M**	40	B1F,12F,26F,40F
Kanto	**F**	33	B1F,17F,33F	Kansai	**N**	31	1F,16F,31F
Kanto	**G**	28	1F,10F,28F				
Kanto	**H**	24	1F,24F				

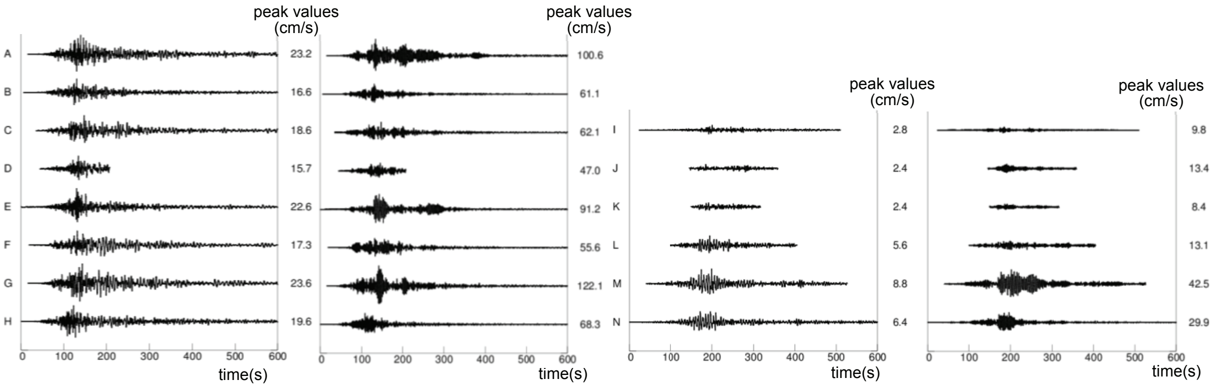
STRONG MOTION RECORDS FROM BUILDINGS

Velocity waveforms and response spectra

Fig.2 shows the velocity waveforms obtained at the top and basement (or ground) floors during the main shock of the Great East Japan Earthquake. They are traced in the principal axis of maximum velocities. In most buildings in the Kanto area, strong motions were recorded with long durations of about 10 min. Peak velocities in Building G were the largest in the Kanto area. Building G is located in Urayasu area, where traditional Japanese wooden houses were seriously damaged by heavy soil liquefaction. Local site amplification of the ground motions must have influenced structural responses of Building G.

In the Kansai area, the amplitudes and durations of the shock waves on Buildings M and N were larger than those of other buildings. Both buildings are located in the Osaka Bay area, which must have been affected by local site amplification of ground motions.

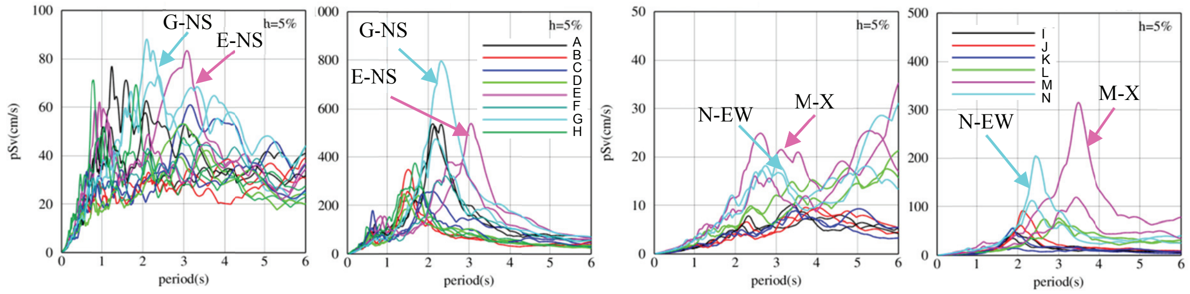
Fig.3 shows pseudo velocity response spectra for a damping factor h = 5%. The results for each building are plotted in two horizontal directions. In the Kanto area, spectral amplitudes at the bottom floors were 30–80 cm/s for the period range of 2 to 4 s, corresponding to the predominant period for these buildings. Buildings G and E showed large peaks at 2 and 3 s on both bottom and top floors. Building E is located in the Tokyo Bay area. In the Kansai area, the spectral levels of Buildings N and M were larger than those of the other four buildings. In both cases, the structural response was closely related to the building location.



Basement or 1st floor Top floor Basement or 1st floor Top floor

(a) Kanto area (b) Kansai area

Fig.2 Velocity waveforms of recorded motions in super high-rise residential buildings



Basement or 1st floor Top floor Basement or 1st floor Top floor

(a) Kanto area (b) Kansai area

Fig.3 Pseudo velocity response spectra of recorded motions in super high-rise residential buildings

Peak floor responses

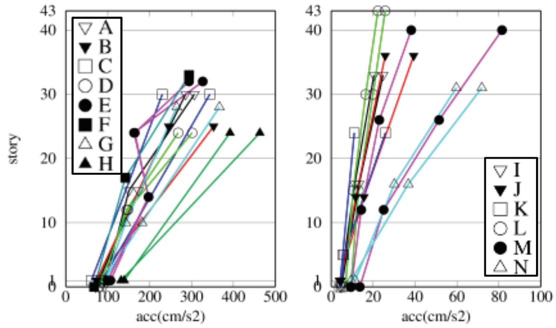
Fig.4 shows the peak acceleration for each floor. The results for each building are plotted in two horizontal directions. In the Kanto area, the peak accelerations at the 1st floors or basements were around 100 cm/s^2. They were amplified by two to four times at the top floors. Building H showed the largest acceleration because it is located relatively close to the epicenter, where the peak ground acceleration was high.

The level of accelerations in the Kansai area was much smaller than that in the Kanto area because of the high attenuation caused by the long distance. Structural responses in buildings constructed in the bayside area were greater than those in other areas because ground motions were amplified in the soft surface soil of that area.

The JMA (Japan Meteorological Agency) instrumental seismic intensity (I_{JMA}) was evaluated using the recorded data. The seismic intensity at each floor is plotted in Fig.5. In the Kanto area, I_{JMA} at the 1st floors or basements varied from 4-lower to 5-lower. At the top floors, it was amplified to 6-lower or 6-upper. In the Kansai area, I_{JMA} values were generally lower than those in the Kanto area.

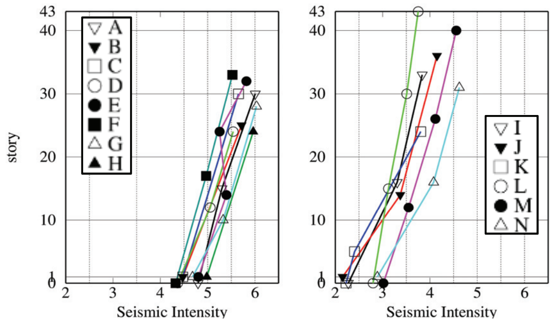
The increment of I_{JMA} from the base to the top of the buildings was about 1 to 1.5 in both areas.

The absolute peak displacement and the average deformation angles were evaluated from the motions recorded at two floors and plotted in Figs.6 and 7, respectively. The maximum deformation angles varied around 1/500 rad in the Tokyo area. Building G, located in the bayside area, experienced the largest deformation angle of 1/170 rad. In the Kansai area, most buildings experienced a maximum angle of less than 1/1000 rad. On the other hand, Building M, located in the bayside area, experienced the largest deformation angle of 1/500 rad.



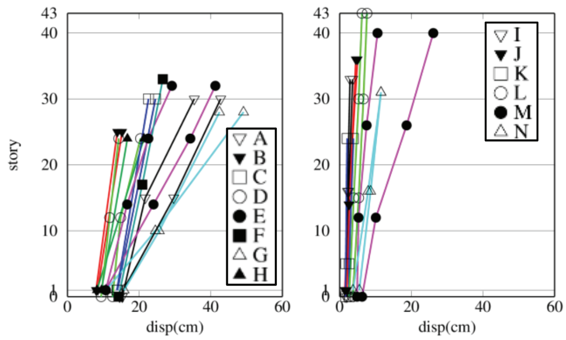
(a) Kanto area (b) Kansai area

Fig.4 Peak acceleration floor responses



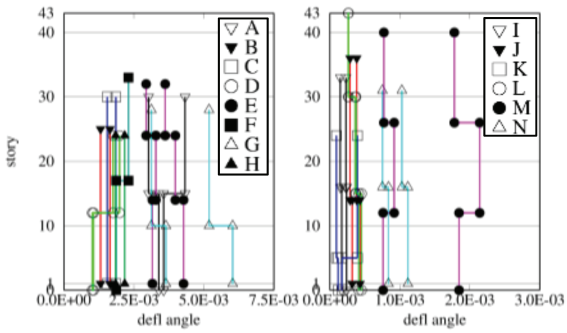
(a) Kanto area (b) Kansai area

Fig.5 JMA instrumental seismic intensity



(a) Kanto area (b) Kansai area

Fig.6 Peak displacement floor responses



(a) Kanto area (b) Kansai area

Fig.7 Deformation angles

VARIATION IN DYNAMIC CHARACTERISTICS DURING THE MAIN SHOCK

The dynamic characteristics of a reinforced building are known to vary according to the level of input earthquake excitation (Kawashima et al., 2011). Variation in the predominant frequencies of the RC buildings in this study was investigated using motions recorded at more than two floor levels. The subspace method (Katayama, 2004) was applied to identify the varying dynamic characteristics of the buildings during the main shock. Motions recorded at the bottom and other floors including the top floor were used as the input and output data, respectively. Signals with a 20 s duration were used for system identification of multiple 10 s intervals. System identification was performed for the two directions separately. The identified systems included rocking motion at the basement because only the horizontal components of the recorded motions were used.

As an example of the results, Fig.8 illustrates the temporal variation in the fundamental predominant frequencies in Building C over the recorded time. The frequencies were normalized by the initial frequency obtained during the first part of the recorded motions. The time history of the relative displacement of the superstructure was also traced. The predominant frequencies gradually diminished as the structural response increased from its initial level. This was caused by nonlinear behavior, e.g., the cracking and yielding of structural members in moment-resistant frames The predominant frequency was reduced by about 30% by the time the relative displacement reached its peak. Structural shaking continued for over 10 min and the reduced frequencies never recovered to their initial level.

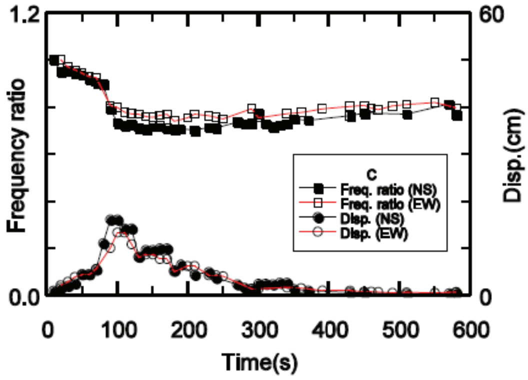
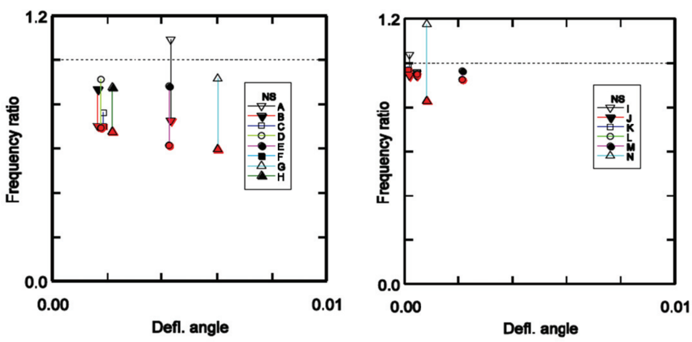


Fig.8 Temporal variation in the fundamental predominant frequencies in Building C during the 3.11 main shock

Fig.9 shows the variation in the predominant frequencies of all the buildings. All frequencies have been normalized to the initial frequency mentioned above. The symbols in the lower part of the figure are the minimum predominant frequencies during the main shock. The symbols in the upper part are the frequencies evaluated during the structural design, which were lower than the initial frequencies in most cases. Frequency ratios during the main shock were reduced by 20% to 40% of the original condition and it tends to decrease as the relative displacement increases. The reduction in the predominant frequencies of the buildings in the Kansai area was much smaller than that in the Kanto area.



(a) Kanto area (b) Kansai area

Fig.9 Minimum frequency ratios of all buildings during the 3.11 main shock (NS direction)

SHAKING AND DAMAGE QUESTIONNAIRE

Outline of questionnaire

More than 800 super high-rise residential buildings have been constructed in highly urbanized areas throughout Japan. However, the behavior and psychology of residents living in such buildings—as well as the moving and overturning of household appliances, gadgets, and furniture—have remained unresolved. Kaneko (2002) reported an evaluation method for the overturning ratio of furniture during earthquakes, and Okada (1993) investigated the seismic casualty risk potential based on the overturning of furniture.

During the Great East Japan Earthquake, long-period ground motions influenced the dynamic behavior of super high-rise residential buildings in the Kanto and Kansai areas, as described in the previous sections. Midorikawa et al. (2011) reported, on the basis of a questionnaire survey, that the residents in a high-rise building were frightened during the earthquake. In general, this type of survey is very rare.

In this study, a questionnaire survey was conducted for residents of 15 super high-rise apartments in the Kanto and Kansai areas (the 14 buildings in Table 1 plus another 40 story building in the Kanto area) in late July 2011, about 4 months after the main shock. The questionnaire was put in mail boxes of five consecutive stories around the strong-motion observation floors indicated in Table 1. A total of 516 responses were returned. The floors were divided into three levels, i.e., “Upper floors,” “Middle floors,” and “Lower floors.” Fig.10 shows the quantity of the respondents and whether they were in their dwellings during the main shock (about a half of them were). The questions mainly concerned the shaking during the main shock, though there were several comments on shaking and damage during the aftershocks.

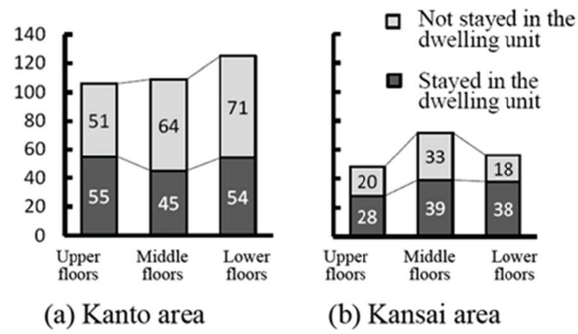


Fig.10 Quantity of respondents

Psychological condition during the main shock

First, questions about the residents’ psychological condition during the shaking were asked to those who were staying in their dwellings during the main shock. Fig.11 shows the response to the question regarding seismic intensity. The responses in the Kanto area were greater than those in the Kansai area. In both areas, the responses tended to increase with the floor level. Although an explanation about seismic intensities was not provided to the respondents, they were consistent with I_{JMA} shown in Fig.5.

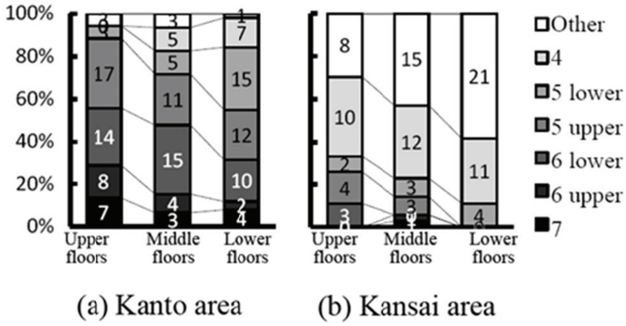
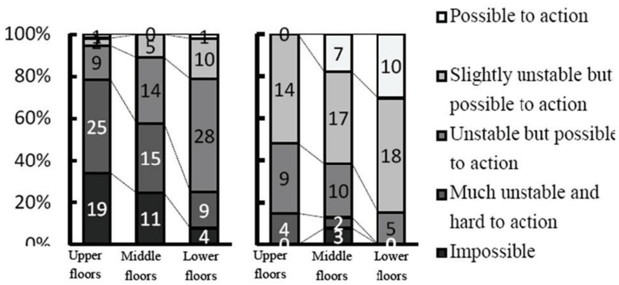


Fig.11 Responses to question regarding seismic intensity

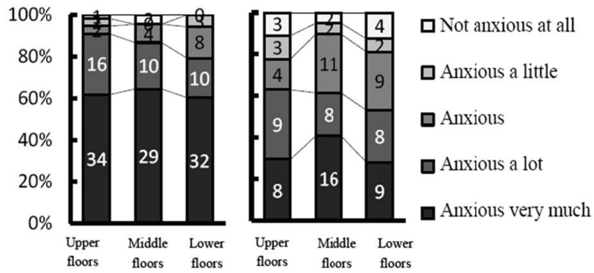
Fig.12 shows the difficulty faced by the residents in movement (Takahashi et al., 2010) during the main shock. More than half of the residents in the upper floors in the Kanto area felt unstable during the main shock. The difficulty encountered in movement in the Kanto area was greater than that in the Kansai area. Furthermore, the higher the floor level was, the higher was the movement difficulty. This result suggests that the movement difficulty tends to increase with seismic intensity.

Fig.13 illustrates the anxiety (Takahashi et al., 2010) felt during the main shock. The anxiety felt in the Kanto area tended to be greater than that in the Kansai area. In both areas, most respondents felt anxious regardless of the floor height. The conclusion is that anxiety is not necessarily affected by seismic intensity.



(a) Kanto area (b) Kansai area

Fig.12 Difficulty faced by the residents in movement

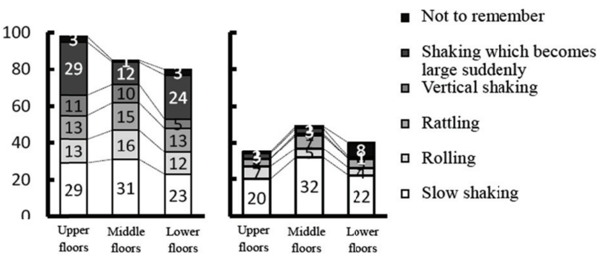


(a) Kanto area (b) Kansai area

Fig.13 Anxiety felt during the main shock

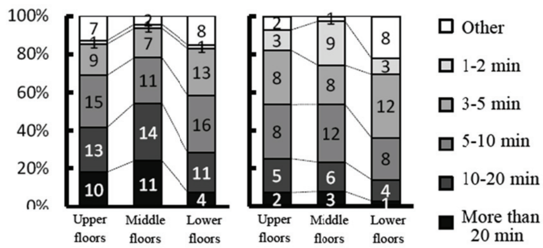
Fig.14 shows the types of shaking that the residents felt during the main shock. In both areas, many respondents felt slow shaking, regardless of the floor height. In the Kansai area, the majority of responses were about slow shaking, because the short-period component of shaking had been attenuated because of the long distance from the epicenter. In the Kanto area, a relatively large number of people felt the shaking to increase suddenly.

Fig.15 illustrates the perceived duration. The duration in the Kanto area was longer than that in Kansai. In the Kanto area, the percentages of respondents who felt shaking for more than 10 min on the upper and middle floors were about 40% and 50%, respectively.



(a) Kanto area (b) Kansai area

Fig.14 Types of shaking that residents felt
(Multiple choice answers)



(a) Kanto area (b) Kansai area

Fig.15 Perceived duration

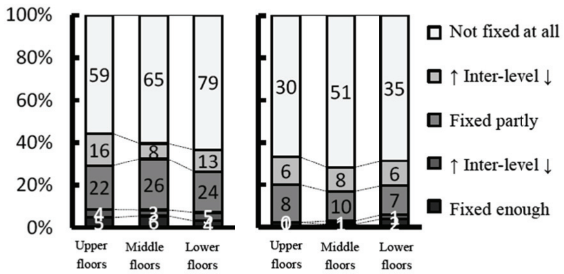
Indoor damage

Next, questions about fixing condition of furniture, household appliances, and small gadgets on tables or in cupboards in rooms after the main shock were asked to all respondents.

The fixing condition of drawers, refrigerators, and cupboards are presented in Fig.16. The percentages of respondents who had fixed the furniture in the Kanto area were slightly larger than those in the Kansai area. In both areas, the percentages of respondents who had fixed their furniture sufficiently were very few. More than half of all respondents had not fixed the furniture at all.

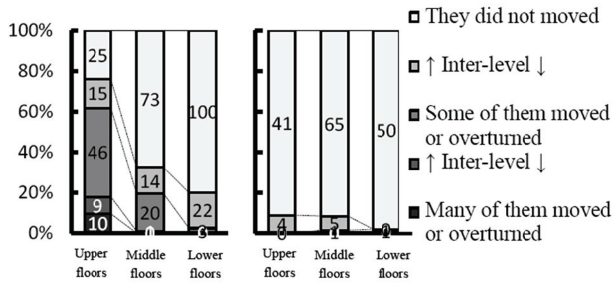
Fig.17 shows the situations of drawers, refrigerators, and cupboards after the main shock. The situations of tables, beds, and chairs are compared in Fig.18. Almost none of the furniture and household appliances moved and overturned in the Kansai area and the lower floors of buildings in the Kanto area. On the other hand, more than 70% of respondents answered that furniture moved and overturned to a varying extent at the higher floors of buildings in the Kanto area.

Fig.19 indicates the situations of dishes, books, and small gadgets on tables after the main shock. Many small gadgets moved and fell from tables in the Kanto area. In both areas, the percentage of small gadgets that moved or fell from tables in the upper floors was larger than that in the lower floors. This result indicates that the greater the shaking intensity, more the furniture and small gadgets move, overturn or scatter.



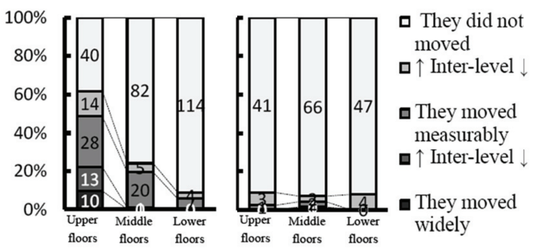
(a) Kanto area (b) Kansai area

Fig.16 Fixing condition of drawers, refrigerators or cupboards



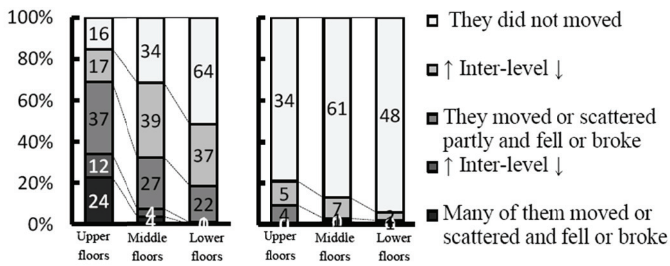
(a) Kanto area (b) Kansai area

Fig.17 Situations of drawers, refrigerators or cupboards after the main shock



(a) Kanto area (b) Kansai area

Fig.18 Situations of tables, beds or chairs after the main shock



(a) Kanto area (b) Kansai area

Fig.19 Situations of dishes, books or small gadgets on the table after the main shock

Fig.20 shows the cracks in interior materials including wall paper after the main shock. Fig.21 shows the cracks in concrete columns, walls, and beams. The cracks in interior materials and concrete were very few in the upper floors of the Kansai area. In contrast, many interior materials and a large amount of concrete cracked in the lower floors, especially in the Kanto area. The relationship between the shaking intensity and the damage caused to interior materials or concrete showed an inverse correlation. This visible damage is closely related to the maximum story drift rather than the amplitudes of the floor responses.

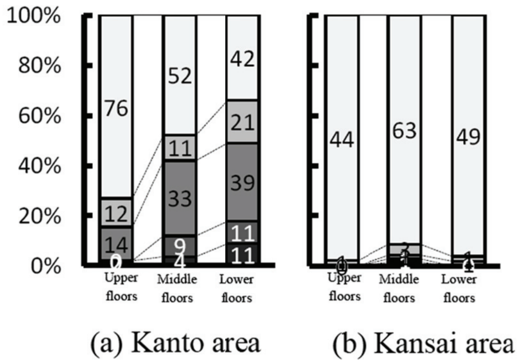


Fig.20 Cracks in interior materials

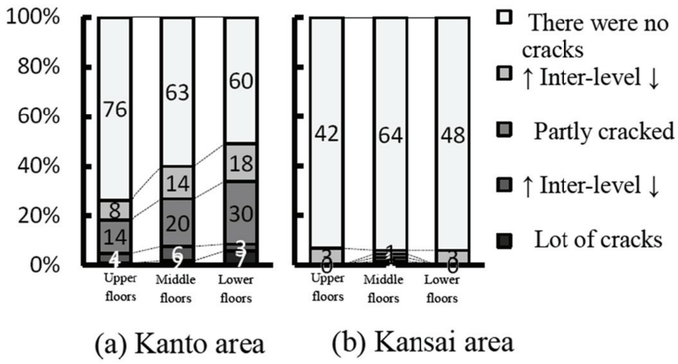


Fig.21 Cracks in concrete
(Columns, walls, and beams)

Free comments

Many useful free comments were given in open-ended questions in addition to the closed-form questions. Some keywords were set in relation to shaking and damage by selecting specific comments from the total pool of comments. Fig.22 shows the retrieved number of free comments by keywords. Many respondents made comments about slow shaking in the middle and upper floors. In the Kanto area, the comments regarding damage to an elevator and a lifeline or means of escape from upper and middle floors were more as compared to the lower floors. In both areas, the comments regarding damage to their own buildings and anxiety about the seismic resistance of their buildings were numerous at the lower floors. There were some comments saying that several residents from the upper floors had moved. In both areas, many respondents commented on the rasping sound of the building at the lower floors. This suggests that the rasping sound was related to the cracks in the interior materials or the concrete (Figs.20, 21). Moreover, several comments about anxiety being heightened by the sound during the main shock or during aftershocks were provided. Fortunately, the number of injuries was very less despite the intense shaking.

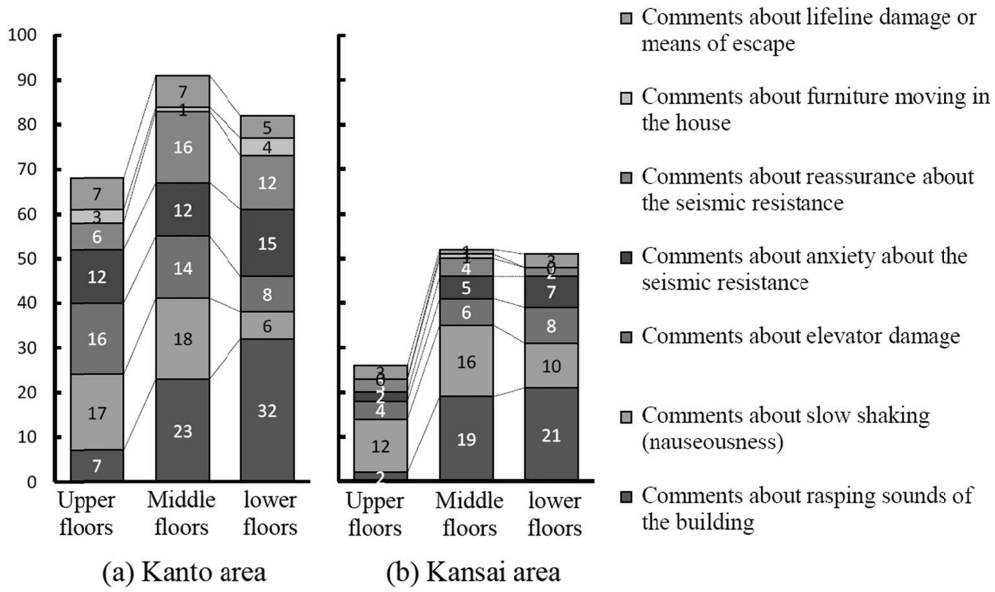


Fig.22 Retrieved number of free comments by keywords

CONCLUSIONS

The dynamic response characteristics of 14 super high-rise residential buildings in the Kanto and Kansai areas were investigated on the basis of the motions recorded during the main shock of the Great East Japan Earthquake.

The Structural response of buildings located near the bayside area was larger than the other buildings at both the base and top floors. Local site amplification of the ground motions must have influenced the structural response of the bayside buildings.

Maximum deformation angles varied around 1/500 rad in the Tokyo area. Building G, located at the bayside area, experienced the largest deformation angle of 1/170 rad. In the Kansai area, most buildings experienced a maximum angle of less than 1/1000 rad. On the other hand, Building M, also located at the bayside area, experienced the largest deformation angle of 1/500 rad.

The predominant frequencies gradually diminished as the structural response increased from their initial level. This was caused by nonlinear behavior, e.g., the cracking and yielding of structural members in moment-resistant frames. Structural shaking continued for over 10 min and the reduced frequencies never recovered to their initial level. The minimum frequency ratios during the main shock were reduced by 20% to 40% of the original situation and decreased as the relative displacement increased.

A questionnaire was also conducted to examine the psychological condition of residents and the actual damage to household items during the main shock. The higher the floor level was, the higher the movement difficulty experienced during the main shock. This result suggests that difficulty in movement tends to increase with seismic intensity. On the other hand, many respondents felt anxious regardless of the floor height. This indicates that anxiety is not necessarily affected by seismic intensity.

Many small gadgets and furniture moved, overturned, and scattered in the higher floors of buildings in the Kanto area. This result indicates that the greater the shaking intensity, more furniture and small gadgets move, overturn, and scatter.

Many interior materials and a large amount of concrete cracked in the lower floors of the Kanto area. Moreover, many respondents described a rasping sound produced by the building at the lower floor. This suggests that the rasping sound was related to the cracking of the interior materials or the concrete. Moreover, comments about anxiety being heightened by the sound during the main shock or during aftershocks were provided.

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