Performance of High-rise Buildings during the 2011 Great East Japan Earthquake

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SUMMARY:
Building Research Institute (BRI) has been conducting strong motion observation for buildings since 1957. At the 2011 Great East Japan Earthquake on March 11, 2011, strong motion records were collected at 54 stations in Japan. From the observed records, it was found that the high-rise buildings shook largely because of the effect of long period component of earthquake ground motions. This paper examined the performance of high-rise buildings during the earthquake from several perspectives. Firstly, the time change of vibration characteristics of high-rise buildings during the earthquake was examined using a system identification method. Secondly, the records were compared with the response of nonlinear structural models to verify the accuracy of the model. Thirdly, relationships between intensity of shaking and feeling of people inside the buildings were examined through questionnaire survey. At the end, the suggestions of countermeasures for future earthquakes are summarized.

Keywords: The Great East Japan Earthquake, High-rise buildings, Long period earthquake ground motion

1. INTRODUCTION

Building Research Institute (BRI) has been conducting strong motion observation for buildings since 1957. At the 2011 Great East Japan Earthquake on March 11, 2011, strong motion records were collected at 54 stations located from Hokkaido to Kansai area in Japan (Figure 1). Table 1 shows the list of high-rise buildings under observation and the maximum acceleration values observed in the buildings.

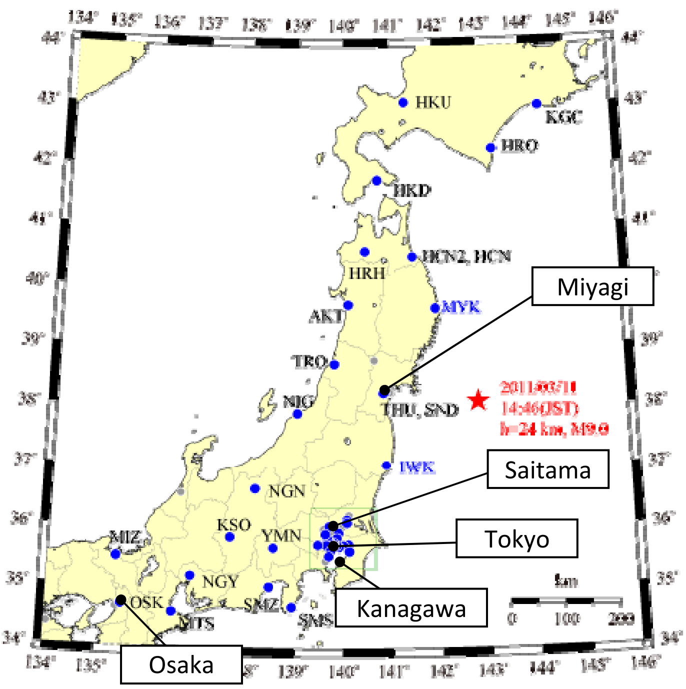


Figure 1. Location of observed buildings

Figure 2 shows the velocity response spectra of the horizontal records at the lowest levels of the high-rise buildings in Miyagi, Tokyo and Osaka. The velocity spectra of Miyagi and Tokyo have strong component in the wide band period from 0.5 seconds to 10 seconds; therefore, it is considered not only high-rise buildings but also low-rise buildings were strongly shaken by the earthquake ground motions. On the other hand, the response spectrum of Osaka has a peak period of 6-7 seconds, and it was a typical long-period ground motion which shakes high-rise buildings.

Table 1. List of high-rise buildings and observed acceleration records

	Location	Structural Type	Structural system	Floor	*Δ* (km)	Location of Sensors	Acc. (cm/s^2)		
							H1	*H2*	*V*
A	Miyagi	S	Normal	B2F 15F	175	B2F	163	259	147
						15F	361	346	543
B	Saitama	S	Control	26F P2F	378	B3F	74	63	42
						10FS	119	138	62
						10FN	118	155	66
						P1FS	248	503	107
						P1FC	265	686	185
C	Tokyo	S	Normal	B4F 20F P1F	386	01F	90	86	45
						20B	208	148	173
						19C	179	133	130
D	Tokyo	S	Control	B4F 21F	386	B4F	75	71	49
						13F	137	113	72
						21F	121	131	104
E	Tokyo	RC	Normal	37F	385	01F	87	98	41
						18F	118	141	64
						37F	162	198	108
F	Kanagawa	S	Normal	B3F 23F P1F	412	B2F	60	-	30
						23F	162	-	72
G	Osaka	S	Normal	B3F 15F	759	B3F	11	9	5
						P3F	65	38	7
H	Osaka	S	Normal	52F P3F	770	01F	35	33	80
						18F	41	38	61
						38F	85	57	18
						52FN	127	88	13
						52FS	129	85	12

Δ: epicentral distance
S: Steel / RC: Reinforced Concrete
Control: building with response control devices

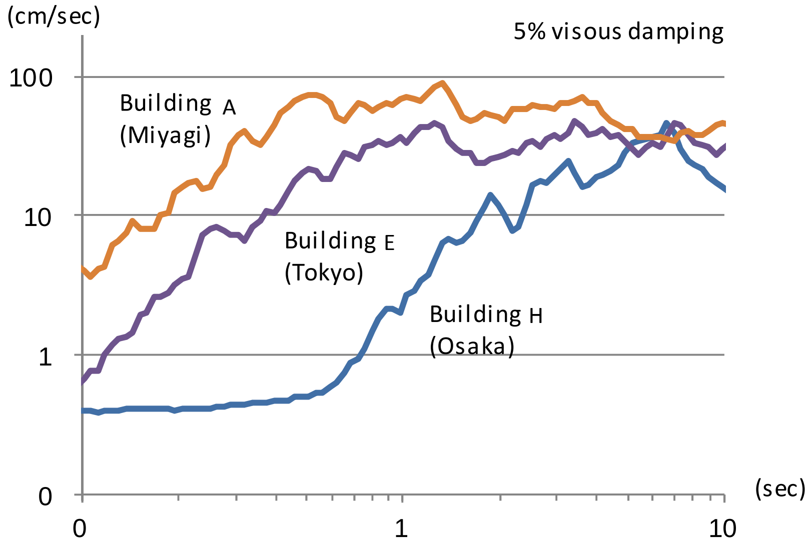


Figure 2. Velocity response spectra in different areas in Japan

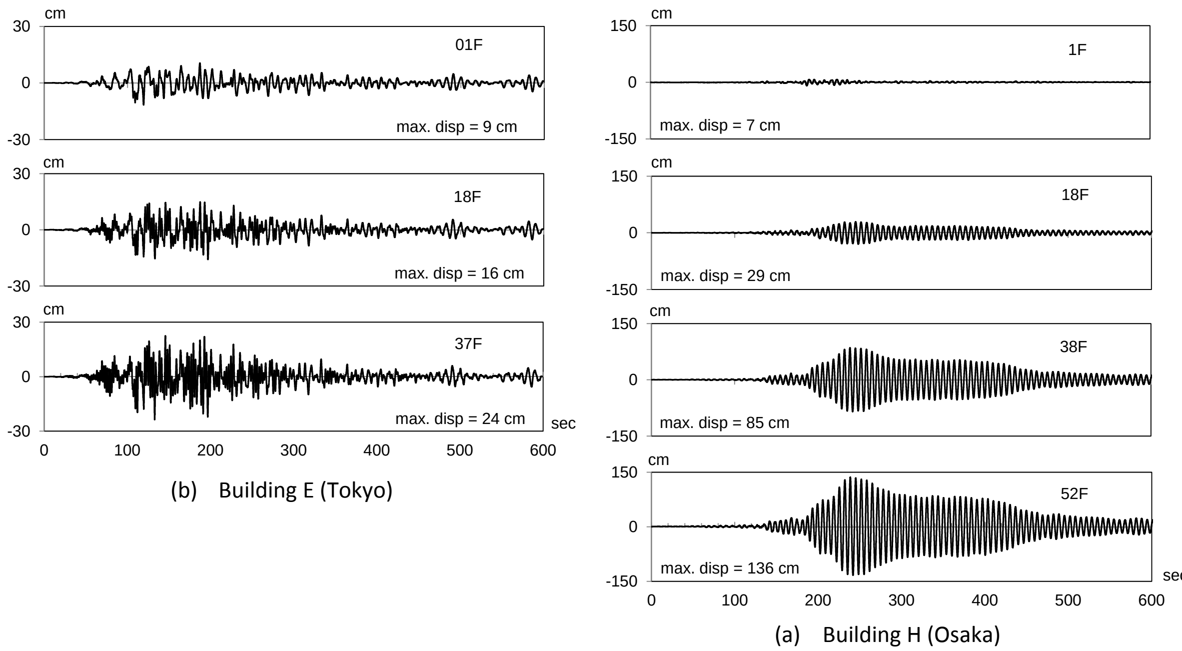


Figure 3. Displacement records of high-rise buildings in Tokyo and Osaka

Figure 3 shows the displacement records observed in different floors of high-rise buildings in Tokyo and Osaka. Whereas the maximum displacement at the top floor of Building E in Tokyo, 385 km away from the epicentre, was 24 cm, the large floor movement of 136 cm amplitude was observed at the 52th floor of Building H in Osaka, 770 km away from the epicentre. By this shaking, in Building E, all 32 lifts stopped and people were trapped in four of them. Damage to non-structural members such as falling of gypsum board and ceiling panels were observed extensively. To avoid such damage and keep safety and function of high-rise buildings at earthquake, this paper examines the observation records at the high-rise buildings from several perspectives.

Firstly, the time change of vibration characteristics of high-rise buildings during the 2011 Great East Japan Earthquake was examined using a system identification method. Secondly, the records were compared with the response of nonlinear structural models to verify the accuracy of the model. Thirdly, relationships between intensity of shaking and feeling of people inside the buildings were examined through questionnaire survey. At the end, the suggestions of countermeasures for future earthquakes are summarized.

2. EVALUATION OF VIBRATION CHARACTERISTICS OF HIGH-RISE BUILDINGS

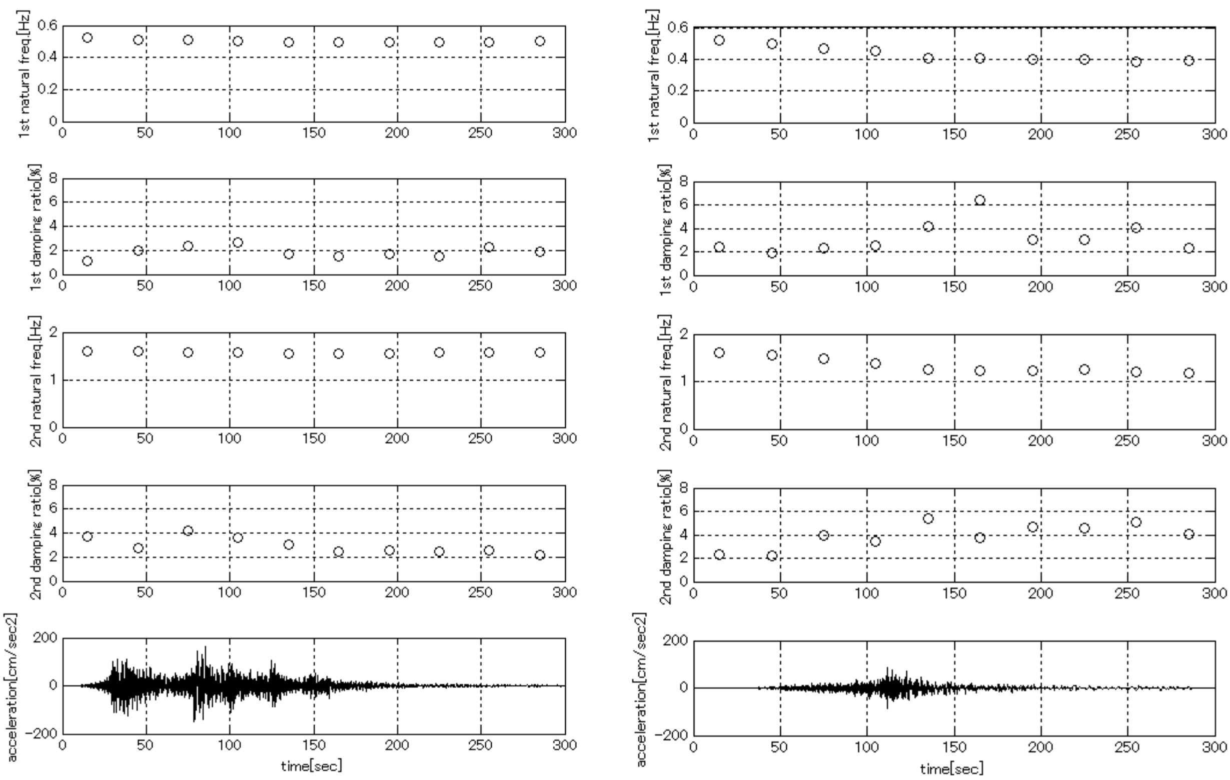
Using strong motion records observed at the main shock of the 2011 Great East Japan Earthquake, the vibration characteristics of high-rise buildings were identified. The N4SID (Numerical algorithm for Subspace based State-Space System Identification) method was used for this analysis.

2.1. Vibration characteristics of steel high-rise building (Building A)

Building A is a 17-story steel building built in Miyagi Prefecture, and seismic dampers are not installed in the building. To split every 30 seconds of the observation record, natural frequency and damping factor were identified for every interval. Figure 4-(a) shows the results of identification. It can be seen that the first and second natural frequencies do not change very much during the earthquake. The first mode damping factor slightly increases up to 3% when ground motion becomes large and then reduces to 2%. A similar trend was also observed in other steel high-rise buildings. Damage of structural members has not been reported in any building.

2.2. Vibration characteristics of reinforced concrete high-rise building (Building E)

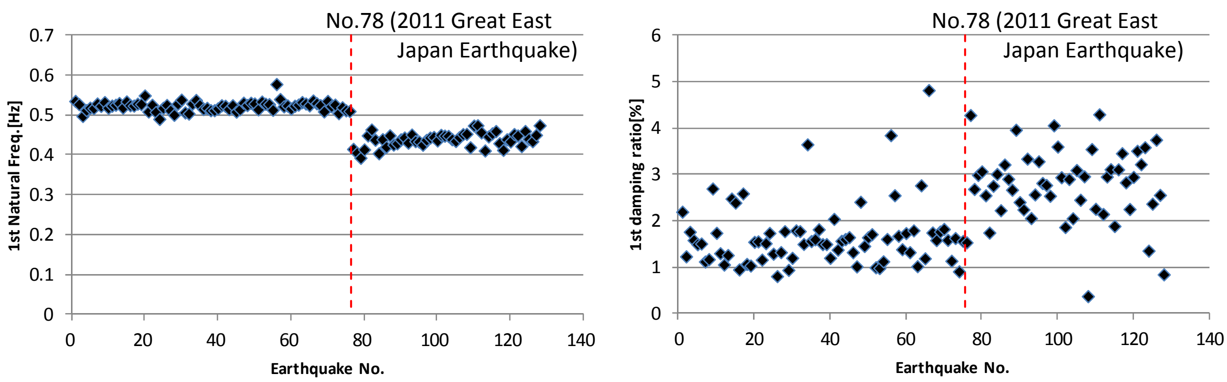
Building E is a 37-story reinforced concrete building built in Tokyo, and seismic dampers are not installed in the building. Figure 4-(b) shows the results of identification. The first natural frequency has declined about 25% compared to the initial value during the earthquake. The first mode damping factor increases up to 6% after ground motion becomes large. We have observed strong motion of this building continuously from May 2007 and records for 130 earthquakes have been obtained including the main shock of the 2011 Great East Japan Earthquake. Using all records, system identification was performed to obtain time series of vibration characteristics of the building as shown in Figure 5. The first natural frequency has declined about 20% and the first mode damping factor has increased 2-4% after the main shock. This change is considered to be due to crack of structural element occurred at the main shock.



(a) Steel (Building A, H1 direction)

(b) Reinforced concrete (Building E, H1 direction)

Figure 4. Change of vibration characteristics of high-rise buildings during the earthquake



(a) The first natural frequency

(b) The first mode damping factor

Figure 5. Vibration characteristics of reinforced concrete building (Building E, H1 direction)

2.3. Summary of vibration characteristics of high-rise buildings

Change of the first natural frequency of all the high-rise buildings listed in Table 1 during the 2011 Great East Japan Earthquake is shown in Figure 6. The maximum change is around 5% for steel buildings. On the other hand, the rate of decrease of natural frequency of reinforced concrete is around 25%. Figure 7 shows the relationship between the first natural period and the first mode damping factor for steel high-rise buildings identified from observation records. The damping factor is distributed in the range of 1-3% and the product of the natural period and damping factor is taking a value between 3 and 6.

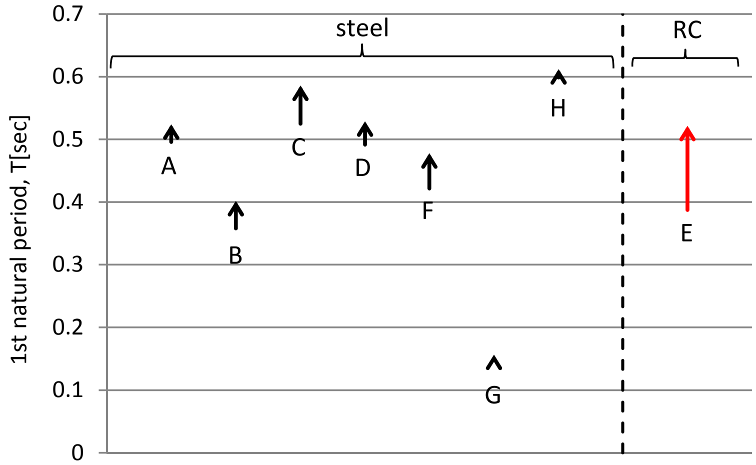


Figure 6. Change of the1st natural frequency of high-rise buildings during the 2011 Great East Japan Earthquake

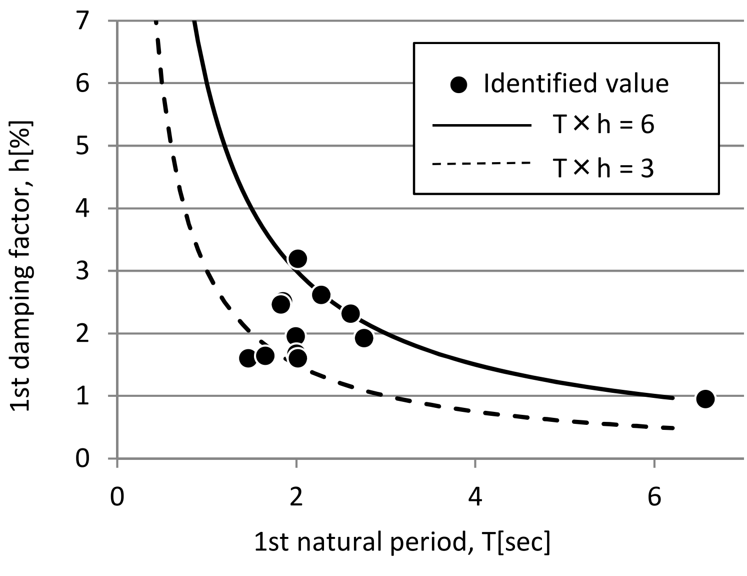


Figure 7. Relationship between natural period and damping factor for steel high-rise buildings

3. EVALUATION OF SEISMIC RESPONSE OF HIGH-RISE BUILDINGS

In the structural design of high-rise buildings in Japan, the time history response analysis by the analytical models is mandatory. To examine the validity of the analytical models, seismic response analysis of the six steel high-buildings listed in Table 1 was carried out and results were compared with observation records at the main shock of the 2011 Great East Japan Earthquake.

3.1. Comparison of natural periods and damping factors

Table 2 shows the comparison of natural periods and damping factors for the six high-rise buildings between the identified values from the observation records and those from the analytical models. A range of the first natural period is 1.47 seconds to 6.57 seconds. The difference between the identified values and those from the analytical model is less than 10% both for the first and second natural periods. With respect to damping factor from identification analysis, the first damping factor is in the range roughly 1.5% to 3% and the second damping factor is in the range about 2% to 4%. On the other hand, stiffness proportional damping with 2% damping factor is assumed for the model.

Table 2. Comparison of natural periods and damping factors

	Location	Structural Type	Structural system		Natural periods				Damping factors		
					Identified[*1]		*Model (Identified/Model)*		*Identified*		*Model*
					T1	*T2*	*T1*	*T2*	*h1*	*h2*	*h1*[*2]
A	Miyagi	S	Normal	H1	2.004	0.638	2.012 (1.00)	0.694 (0.92)	1.67	2.39	2.0
				H2	1.994	0.638	2.012 (0.99)	0.694 (0.92)	1.95	2.88	2.0
B	Saitama	S	Control	H1	2.760	0.978	2.517 (1.10)	0.988 (0.99)	1.92	1.93	2.0
				H2	2.609	0.902	2.394 (1.09)	0.949 (0.95)	2.31	1.87	2.0
C	Tokyo	S	Normal	H1	2.017	0.694	1.966 (1.03)	0.740 (0.94)	1.60	2.70	2.0
				H2	1.853	0.626	1.947 (0.95)	0.743 (0.84)	2.51	3.08	2.0
F	Kanagawa	S	Normal	H1	2.279	0.737	2.192 (1.04)	0.798 (0.92)	2.61	3.36	2.0
G	Osaka	S	Normal	H1	1.465	0.465	1.354 (1.08)	0.494 (0.94)	1.60	2.29	2.0
				H2	1.656	0.517	1.370 (1.21)	0.508 (1.02)	1.64	2.26	2.0
H	Osaka	S	Normal	H2	6.570	2.057	6.504 (1.01)	2.725 (0.75)	0.95	3.01	2.0

*1: identified from observation records, *2: damping matrix is assumed to be proportional to stiffness matrix

3.2. Comparison of maximum story drift between different damping types

Earthquake response analysis of the high-rise buildings was carried out; where input ground motion is the observed acceleration record at the lowest layer of the building at the main shock. Figure 8 shows the results of the maximum story drift of each building comparing two types of damping; one is the stiffness proportional damping with 2% damping factor (dotted line) and another one is the Rayleigh type damping using the identified first and second mode damping factors (solid line). Red dot indicates the drift level of the first plastic hinge of structural elements and white circle of Building B indicates the yielding drift of steel damper devices. Except Building A in Miyagi Prefecture, other responses are within elastic range of structural members. The drift response of Building B exceeds the yielding drift of steel dampers. The response of Rayleigh type damping is slightly larger than that of stiffness proportional damping.

Figure 9 shows the results of the maximum acceleration of each building comparing two types of damping. White circle indicates the acceleration value from the observed record. The acceleration response of Rayleigh type damping is larger than that of stiffness proportional damping and much closer to the observed one.

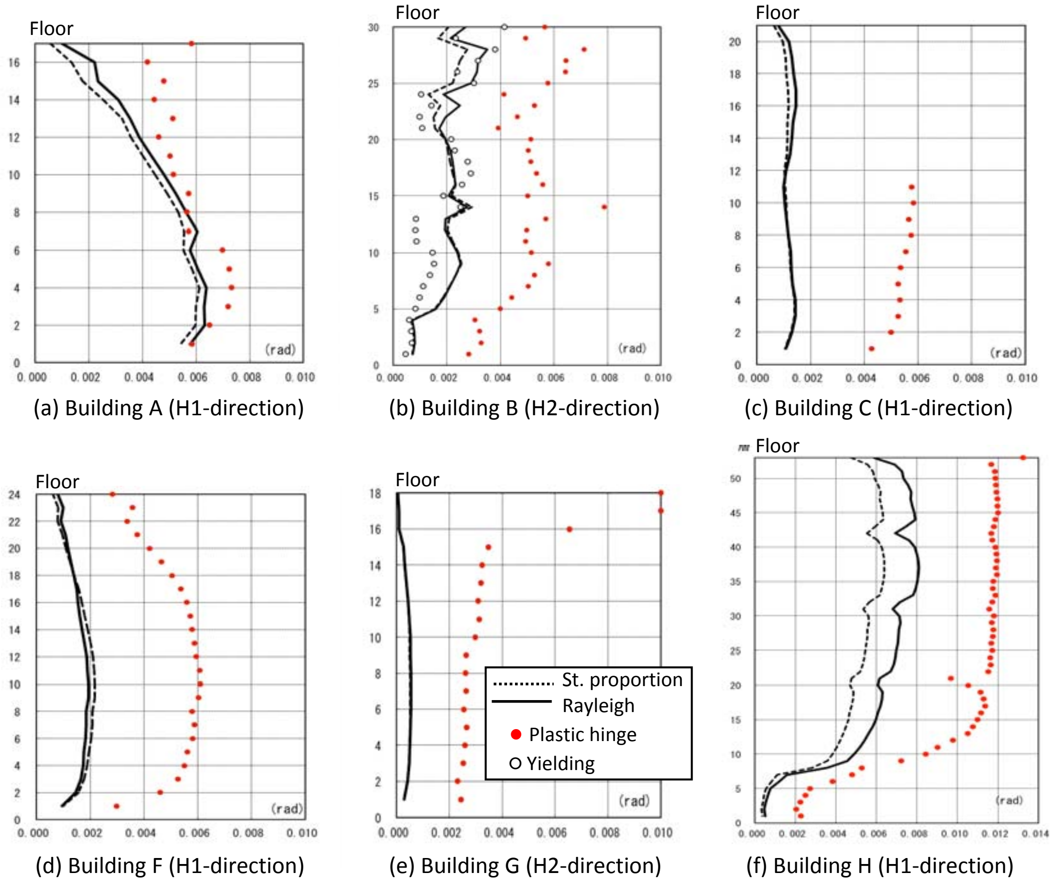


Figure 8. Comparison of the maximum story drift

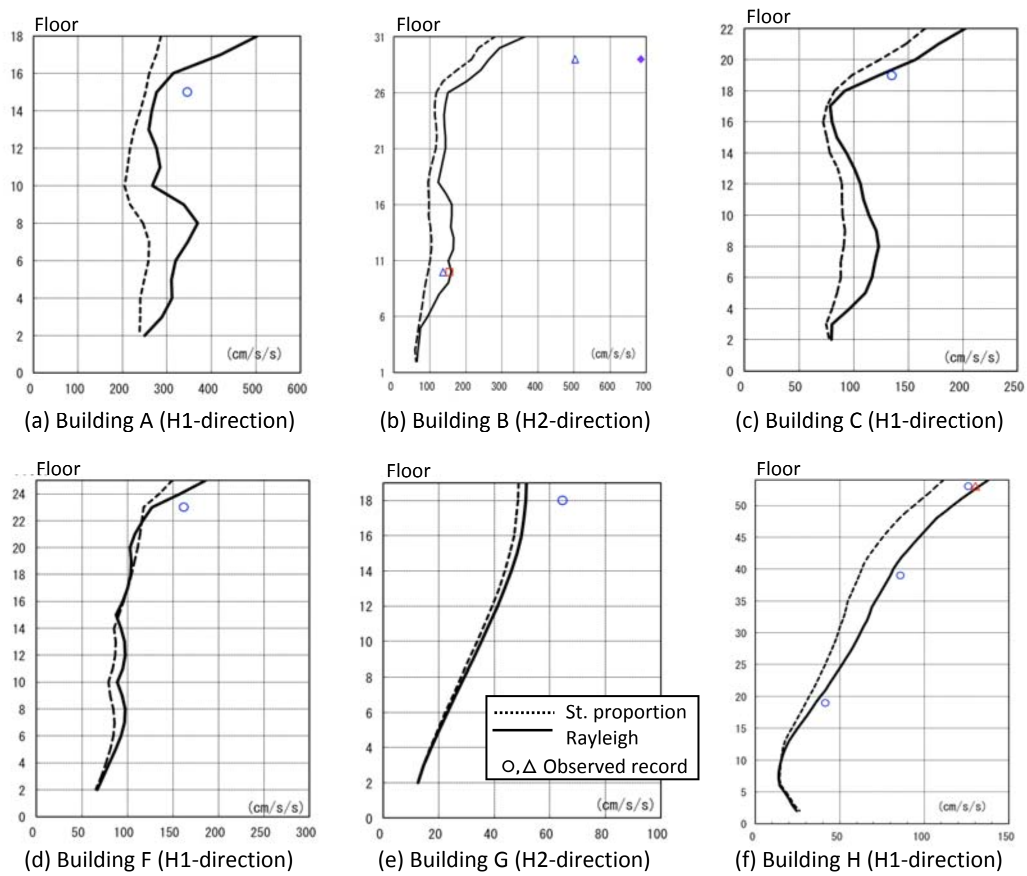


Figure 9. Comparison of the maximum acceleration

4. QUESTIONNAIRE SURVEY FOR RESIDENTS IN HIGH-RISE BUILDINGS

A questionnaire survey was conducted for residents of the high-rise buildings on the behaviour and feeling of fear or anxiety during the 2011 Great East Japan Earthquake and damage to the contents in a room. Respondents have been selected from the upper, middle and lower layers of the building. In the least case, there are six respondents in a building with two of them from each layer. Relationship between the answers from the survey and intensity of shaking such as the maximum floor acceleration and the maximum floor velocity is examined. The intensity of shaking of the floor without sensor was estimated by interpolating the observed values.

4.1 Human behaviour and feeling during earthquake

4.1.1 Actions at the moment of earthquake

From Figure 10, the most common answer is “Stop working and wait and see” and “Hide under the desk” continues. Relation between the floor acceleration and these answers is not seen much. On the other hand, the answer of “Look outside from the window” is concentrated in less than 200 gal (= cm/sec^2) of acceleration.

4.1.2 Difficulty of action during shaking

Figure 11 shows the answers about difficulty of action during the shaking of earthquake. The answer of “No trouble for walking” distributes in less than 100 gal of acceleration and 20 kine (= cm/sec) of velocity. On the other hand, the answer of “Could not do anything” distributes in more than 300 gal and 70 kine.

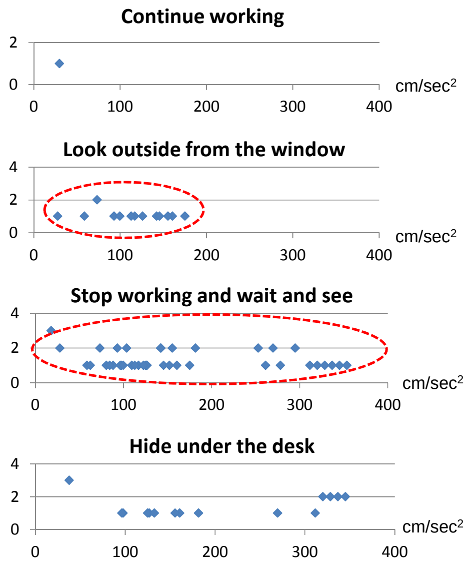


Figure 10. Actions at the moment of earthquake

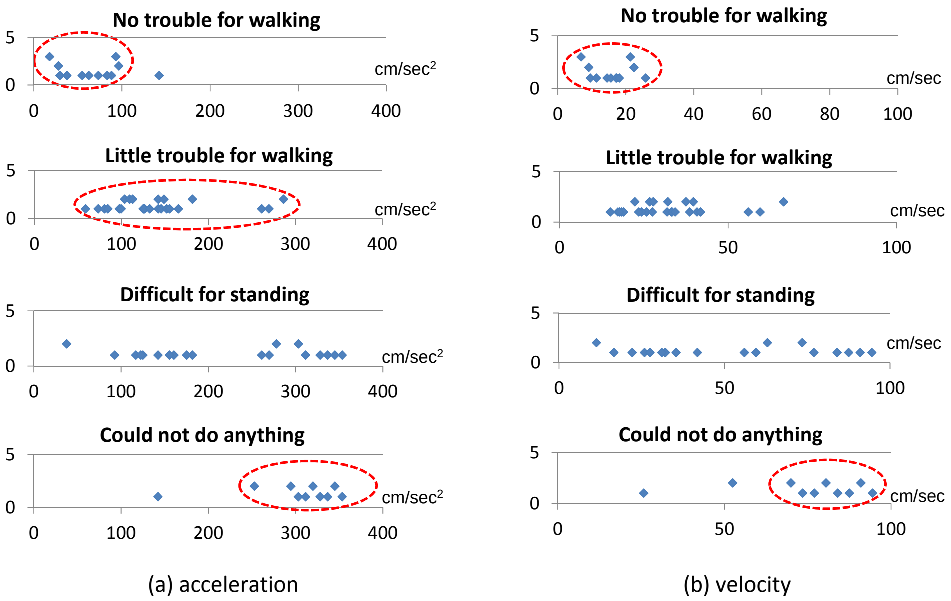
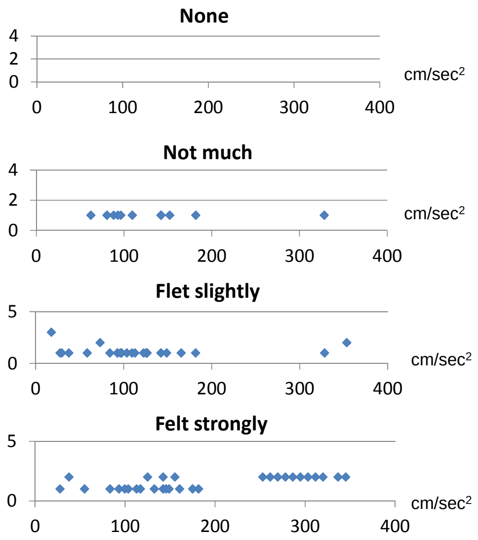


Figure 11. Difficulty of action during shaking

4.1.3 Sense of fear during shaking

Figure 12 indicates the answers about a sense of fear during the shaking of earthquake. There are many answers of “Felt strongly” and “Felt slightly”, but little relationship between floor acceleration. There was an opinion that they felt the fear because of the long time shaking.

4.1.4 Sense of anxiety or sickness during shaking
Figure 13 indicates the answers about a sense of anxiety or sickness during the shaking of earthquake. There was a variety of answers, and the relationship between the floor acceleration is not seen much. Some people answered that they felt like seasickness because of the long time shaking.



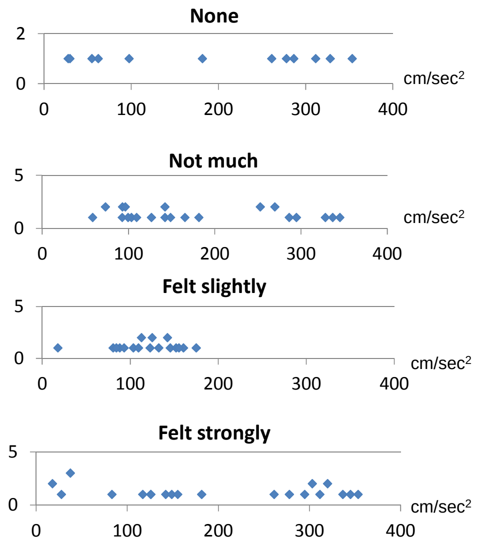
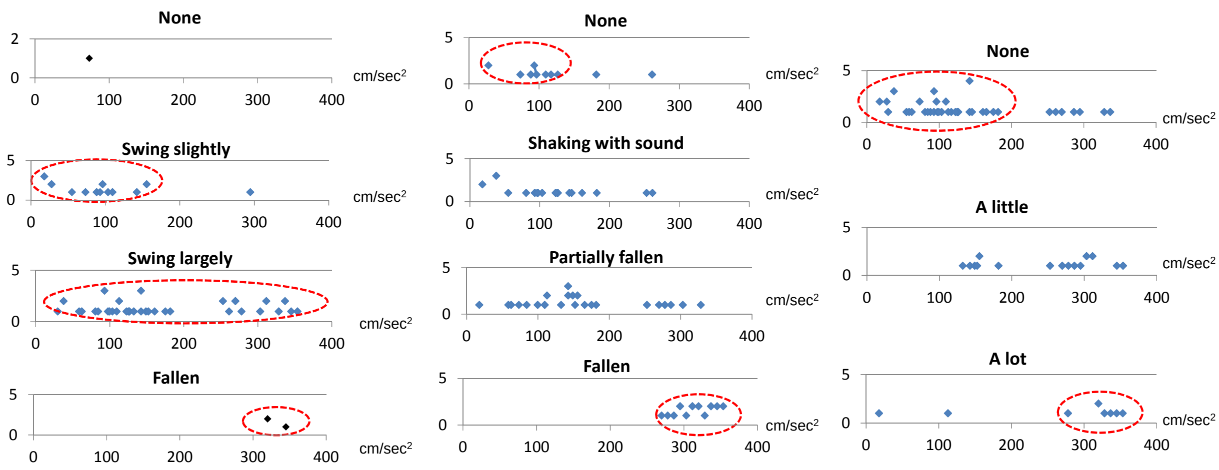


Figure 12. Sense of fear

Figure 13. Sense of anxiety or sickness

4.2 Damage to the contents in a room

The movement of hanging objects in a room is answered in Figure 14-(a). The objects have fallen over 300 gal. The movement of plates in a cabinet has strong correlation with the floor acceleration as shown in Figure 14-(b). Although there was no movement in less than120 gal, the plates have fallen in more than 250 gal. Figure 14-(c) shows the answers related to falling furniture such as a bookcase or chest of drawers. A lot of furniture has fallen in a range greater than 300 gal. According to the formula proposed by Architectural Institute of Japan (AIJ), the limit acceleration of the fall of slender furniture is approximately 250 gal that correspond to the results of the survey as shown in Figure 15.



(a) hanging objects

(b) plates in a cabinet

(c) falling of the furniture

Figure 14. Damage to the contents in a room

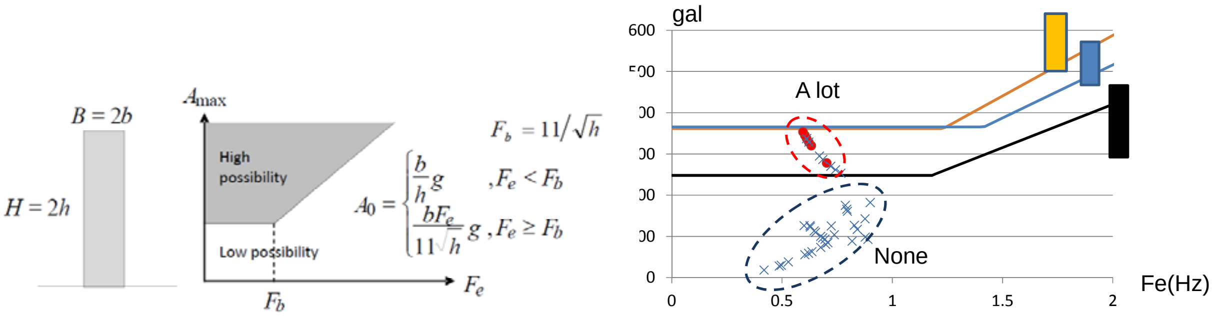


Figure 15. Possibility of falling of the furniture from AIJ formula (F_0: dominant frequency of shaking)

5. CONCLUSIONS

At the 2011 Great East Japan Earthquake, high-rise buildings in a wide area of Japan were shaking largely and damage occurred to non-structural members. Especially, a high-rise building in the city of Osaka, 770 km away from epicentre, experienced large shaking in excess of 1.5 m amplitude at the top floor. This phenomenon is considered due to the impact of long-period earthquake ground motion. This paper examined strong motion records of the high-rise buildings in different area of Japan from several viewpoints.

Firstly, vibration characteristics of the high-rise buildings were examined using a system identification method. It was found out that the natural frequency and the damping factor varied during the earthquake. In case of reinforced concrete high-rise buildings, the first natural frequency declined about 20% and the damping factor increased 2-4% after the earthquake, probably due to the influence of crack of structural members occurred at the earthquake.

Secondly, to verify the accuracy of structural models, the acceleration records observed at the high-rise buildings were compared with the results of analysis. In case of Rayleigh damping using the identified first and second mode damping factors, the analytical results fit well with the observed values.

Thirdly, the results of questionnaire survey for the residents in the high-rise buildings were compared with floor accelerations. It was found that people could move below 100 gal of floor acceleration. On the other hand, people could not do anything above 300 gal. Also the furniture has fallen in a range greater than 300 gal, and this result is compatible with the result of AIJ formula.

To ensure the safety of high-rise buildings against long-period earthquake ground motions, it is important to reduce the damage of non-structural members as well as structural members. It is also important to ensure the safety inside a room to protect residents. Measures to reduce the vibration of high-rise building are urgently needed. Seismic reinforcement using vibration control devise is expected as one of their solutions.

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