Seismic Response and Damage of High-Rise Buildings in Tokyo, Japan, during the 2011 Tohoku Earthquake

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SUMMARY:
We report seismic response and damage of high-rise buildings in the Shinjuku Station area in Tokyo, Japan, for the 2011 Tohoku Earthquake (Mw 9.0). The strong motion data of Kogakuin University, which is the steel frame building of the 29-stories and 143 m height, showed that the maximum amplitudes of accelerations and displacements were amplified from 1 m/s/s and 0.1 m for, at the ground level, to 3 m/s/s and 0.37 m at the top floor, respectively. Not only the 1st mode (about 3 s), but also the 2nd higher mode (about 0.9 s) were well excited. Those results agree with the damage distribution where the falls and movements of ceiling boards and unsettled objects were occurred from middle to the top floors. An elevator stopped for more than 3 weeks, because of tangles of the main cables. The similar damage occurred in the other high-rise buildings in the area.

Keywords: the 2011 Tohoku Earthquake, high-rise building, long-period strong ground Motion

1. INTRODUCTION

The 2011 Tohoku earthquake (the 2011 Great East Japan earthquake, Mw 9.0) paralyzed the function of the city of Tokyo, such as traffic jams and congestions of telephones. Even though the ground motion was not very severe in Tokyo metropolitan area, where JMA Intensity is about 5, many people were difficult to get home and had to stay in the city for all night. Especially, since high-rise buildings shook severely at higher floors by the long-period strong ground motions, many people evacuated from the buildings. This caused extremely crowded areas in the downtown districts in Tokyo, and rescue and fire-fighting activities could be difficult for larger earthquakes.

Figure 1. The Shinjuku station Area (Left) and the campus building of Kogakuin University and STEC office building (Right)

In this paper, we report seismic response, damage and emergency response of high-rise buildings in the Shinjuku Station area during the earthquake. The station is the largest in the world; about 3.5 million passengers use trains every day. Among 30 high-rise buildings (more than 100 m) in the area, digital strong motion data of the Kogakuin University and adjacent the STEC buildings are available for this study (see **Figure 1**). We simulated seismic response of the Kogakuin building using 3D structural model. In addition, we conducted questionnaire and hearing surveys for 22 high-rise buildings in the area, and obtained useful results from 16 building management companies and 23 tenants.

2. SEIMIC RESPONSE OF HIGH-RISE BUILDINS

2.1. Strong Motion Records of High-Rise Building

We explain the structure and strong motion records of the Shinjuku Campus building of Kogakuin University. As shown in **Figures 2 and 3**, it is the steel moment frame building with braces of 29-stories and approximately 140 meter height. The natural periods of the 1th and 2nd modes are about 3 s and 1 s, respectively. **Figure 4** shows the locations of strong motion seismometers, which are located from GL-100m, B6F, and up to the top roof floor (29F).

On the other hand, **Figure 4** also shows the STEC office building, which is the next of the Campus building, and the location of strong motion seismometers. The structure is steel moment frame with braces, which is similar to the Campus building, but it is slightly lower with 28-stories of about 128 m height.

Figure 5 shows the recorded accelerations (left) and displacements (right) of NS components from GL-100 m to the Top Floor in Kogakuin University. And, **Table 1** and **Figure 6** show the maximum amplitudes of the records of the two high-rise buildings during the main shock of the 2011 Tohoku earthquake. The maximum amplitudes of accelerations, velocities, displacements, and seismic intensities of JMA (Japan Metrological Agency) are about 1 m/s/s, 0.2 m/s, 0.1 m, and 4 at the ground level, respectively, whereas those of the top floors are amplified to about 3 m/s/s, 0.7 m/s, 0.37 m, and 6-. The array of the displacements indicates the dominance of the 1st mode at longer periods, whereas that of the accelerations shows the dominance of the 2nd mode at shorter periods, because the amplitudes at the 22th floor are smaller than those of the 16th and 22th floors.

Figure 7 shows the velocity response spectra of the NS and EW components at the 1st and 29th floors of the university building. The spectra of 1st floor show relatively flat amplitudes at broad periods, whereas those of the 29th floor show distinct natural periods around 3 s and 1 s, corresponding to the 1st and 2nd modes, respectively.

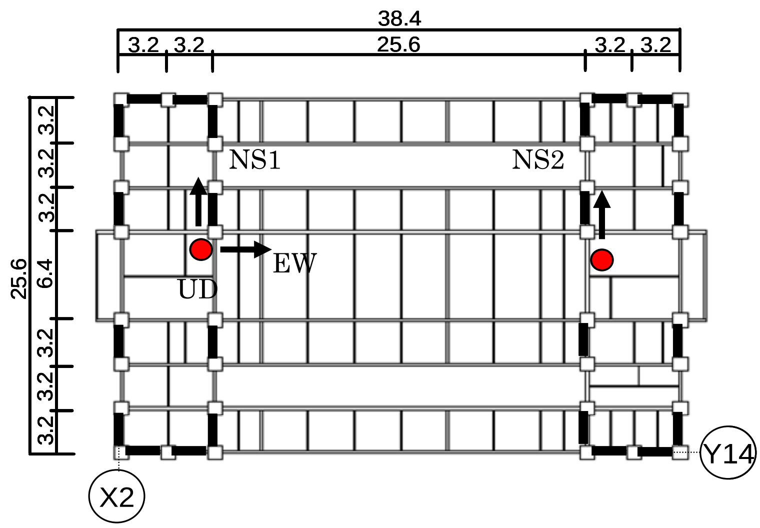
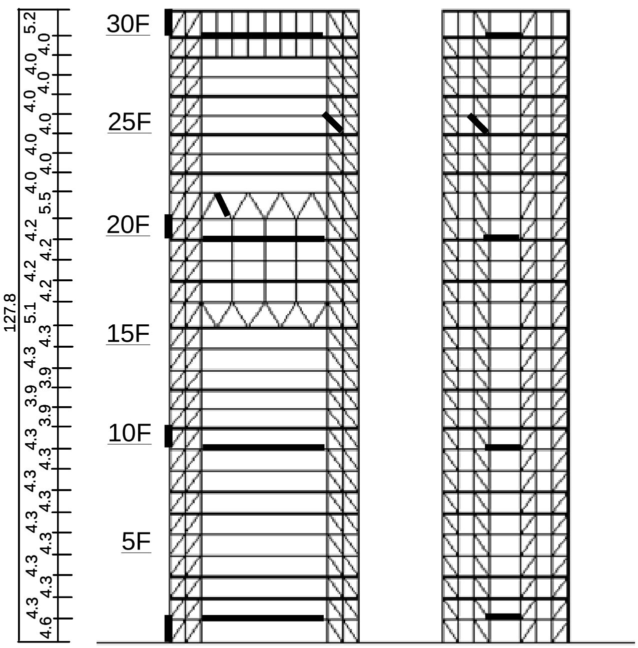


Figure 2. Structural plan and location of strong motion seismometers



(a) EW Direction (b) NS Direction

Figure.3. Structural elevation of Kogakuin University building

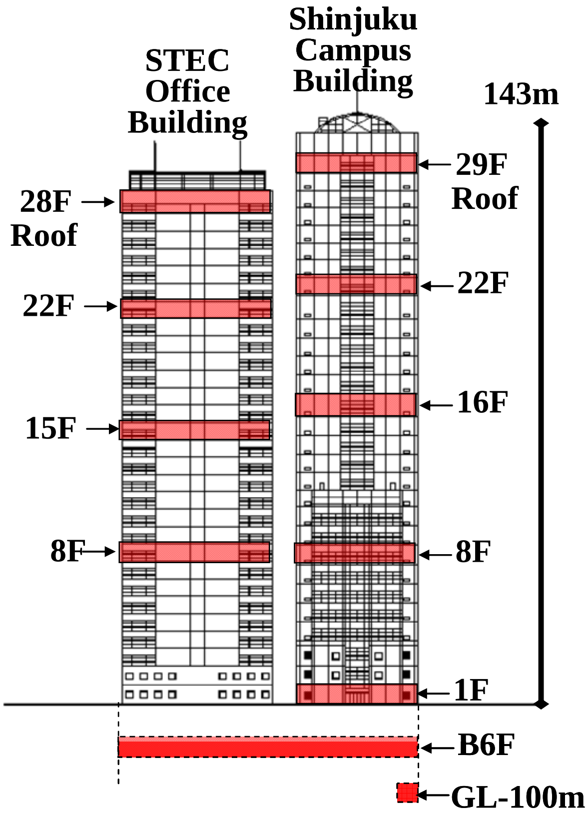


Figure.4. Location of strong motion sensors

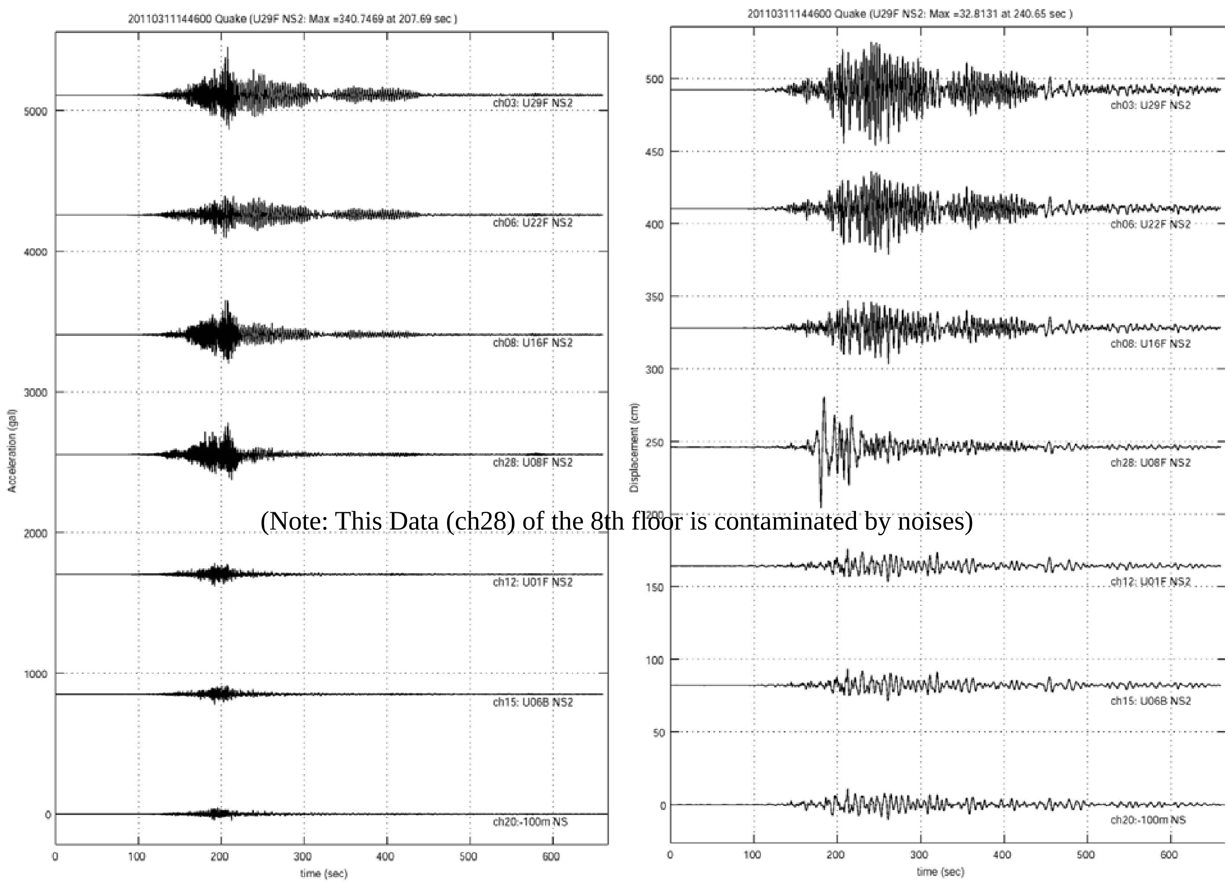


Figure 5. Accelerations (left) and displacements (right) of NS components from GL-100 m to the Top Floor

Table 1. Max. amplitudes of of the Kogakuin and STEC buildings during 2011 East Japan earthquake

(a) Kogakuin University Building

Floor		29	25	22	16	8	1	B6F	−100m
Relative Displacement to1F (cm)	EW	30.5	28.7	24.8	−	−	0.0		
	NS1	33.7	29.0	25.9	16.9	−	0.0		
	NS2	33.5		25.6	16.4	−	0.0		
Absolute Displacement (cm)	EW	30.6	26.1	25.1	−	−	5.7	6.5	5.8
	NS1	34.7	29.9	26.9	17.9	−	6.2	7.1	6.3
	NS2	35.3		27.4	18.2	−	7.2	7.0	
	UD	3.5	3.7					3.4	3.3
Acceleration (cm/s/s)	EW	234.6	134.7	151.7	−	197.1	91.9	63.3	45.9
	NS1	291.6	151.4	153.4	232.4	198.2	97.5	56.8	49.5
	NS2	340.7		159.2	241.9	−	81.6	55.4	
	UD	183.6	−					37.1	29.1
JMA Intensity		5.9	5.2	5.1	−	−	4.5	4.4	4.1

Note: NS1=West Side, NS2=East Side

(b) STEC Office Building

Floor		28	22	15	8	1	B6F
Relative Displacement to 1F (cm)	EW	32.7	27.3	18.8	7.8	0.0	
	NS1	29.7	23.5	15.3	7.0	0.0	
	NS2	34.9	27.4	17.2	8.7	0.0	
Absolute Displacement (cm)	EW	34.4	28.9	20.5	9.9		
	NS1	29.0	23.2	15.8	8.3		
	NS2	35.2	28.0	18.3	8.9		
	UD	3.5					3.5
Acceleration (cm/s/s)	EW	161.0	124.7	152.2	154.7		
	NS1	246.9	125.8	246.0	190.0		
	NS2	302.1	155.8	228.6	159.3		
	UD	134.2					37.9
JMA Intensity		5.6	4.9	5.5	5.3	4.5	

Note: NS1=East Side, NS2=West Side

The JMA intensities of the shaded cells are calculated using the two horizontal components

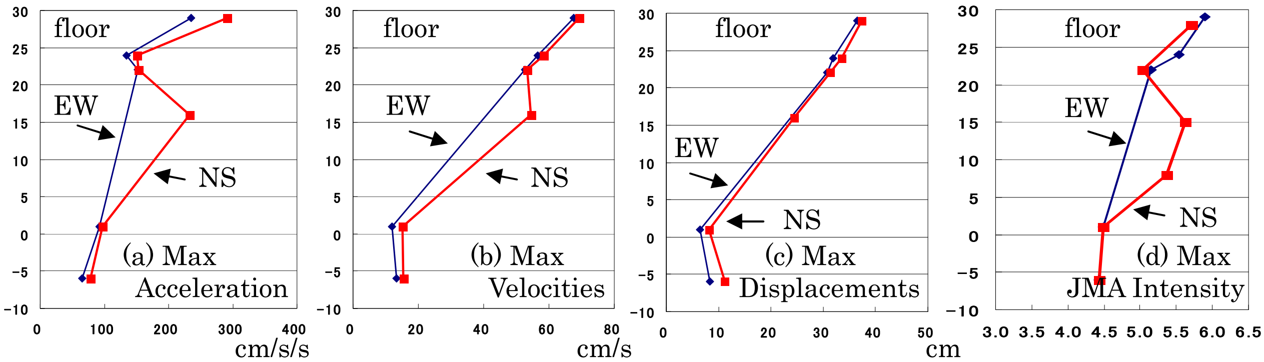


Figure 6. Maximum Accelerations, Velocities, Displacements, and the JMA Intensities of Kogakuin University.

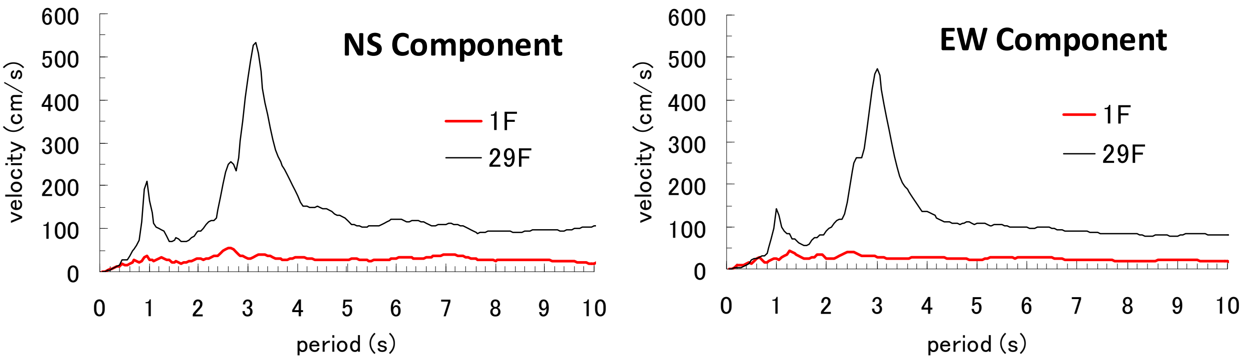


Figure 7. Velocity response spectra (h=5%) of the campus building of Kogakuin University

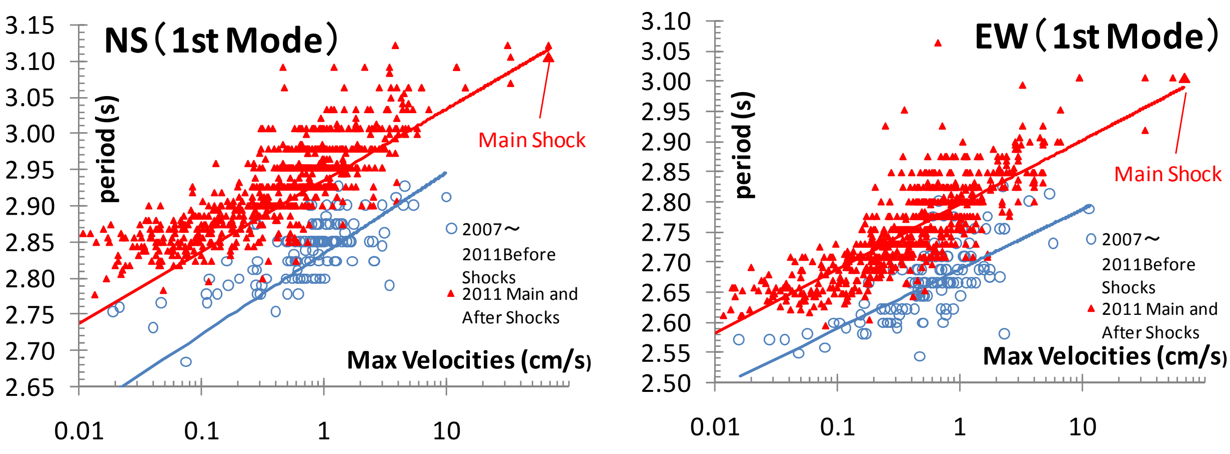


Figure 8. Dependency of natural periods on the maximum velocities of the 29th floor of the university building

We checked the dependency of the natural period on the maximum amplitude of the building response. **Figure 8** shows the natural periods of the 1st modes versus the maximum amplitudes of velocities of the 29th floor. We used the two data sets: one for small earthquakes before the 2012 main shock, and the other for the main-shock and after-shocks. The larger the building response is, the longer the natural period becomes. In particular, the former dataset from small earthquakes shows shorter natural periods than those of the latter including the main shock. This is probably caused by relaxing non-structural elements, such as partitions and curtain walls during the main-shock.

2.2. 3D Seismic Response Simulations

We simulate numerically the seismic response of the Kogakuin building, using a 3D non-linear moment frame model. Since the stiffness of columns is much larger than that of beams and braces, we assumed that plasticity occurred in beams and braces, but not columns. **Figure 9** shows the non-linear hysteretic models for the beams and the braces. In addition, we assumed the rigidness of the floors and the panel zones between column and beam. We also assumed the fixed columns by neglecting the soil-structure interaction. We use the Rayleigh-type damping factors of 1 % for the 1st and 2nd modes, which values were estimated from the forced vibration experiments. The natural periods of the simulation model are about 2.8 s and 0.9 s for the 1st and 2nd modes, respectively, which are slightly shorter than those during the main shock.

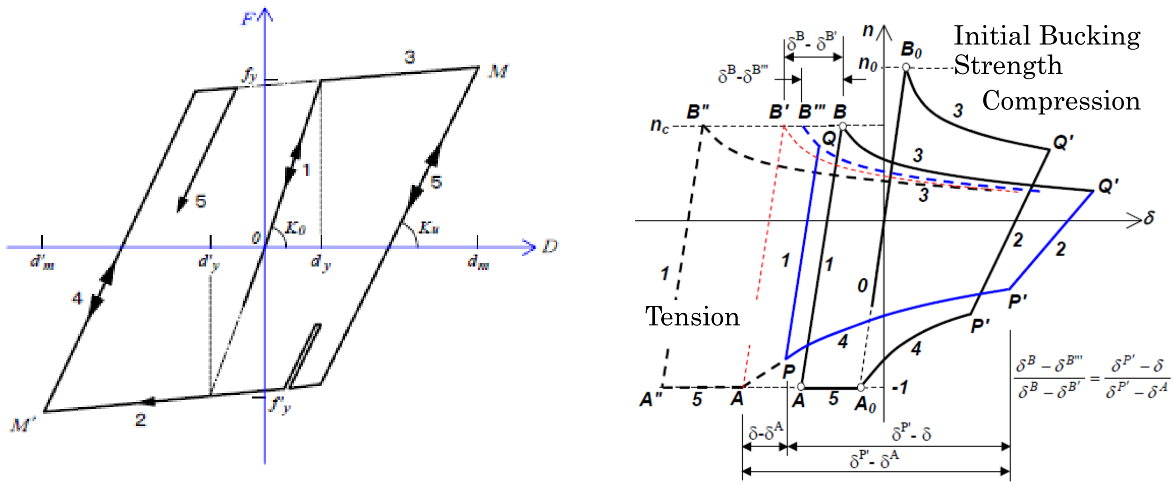


Figure 9. Non-linear hysteretic models for beams and braces of the 3D structural model of Kogakuin University

Figure 10 shows the comparisons between the recorded and simulated waves (accelerations and displacements), for the foreshock (2011/3/9 Sanriku-Oki EQ, M7.3) and the main shock. Since the natural periods of the simulation model are close to those of the building during the foreshock, the results by the foreshock show good agreements with the observations. On the other hand, the simulated results for the main shock show larger accelerations and smaller displacements than those of the observations, because of the discrepancy of the natural periods between the simulation and the observations.

2.3. Strong Motion Data of Other High-Rise Buildings

Table 2 shows the maximum amplitudes of accelerations and displacements of other high-rise buildings in the Shinjuku station area during the 2011 Tohoku earthquake. Note that the displacements for the Shinjuku Center Building (Hosozawa et al., 2011) and Tokyo Metropolitan Government Building (Tokyo Metropolitan Government Financial Bureau, 2011) are relative values to those of the 1F and B3 floor, respectively. On the other hand, those of buildings A and B are absolute values. Since the sizes of buildings A and B are similar to those of the Kogakuin and STEC buildings, the results including the JMA intensities are similar (see **Table 1**). On the other hand, the two taller buildings show the larger response of the displacements, whereas accelerations do not show large differences.

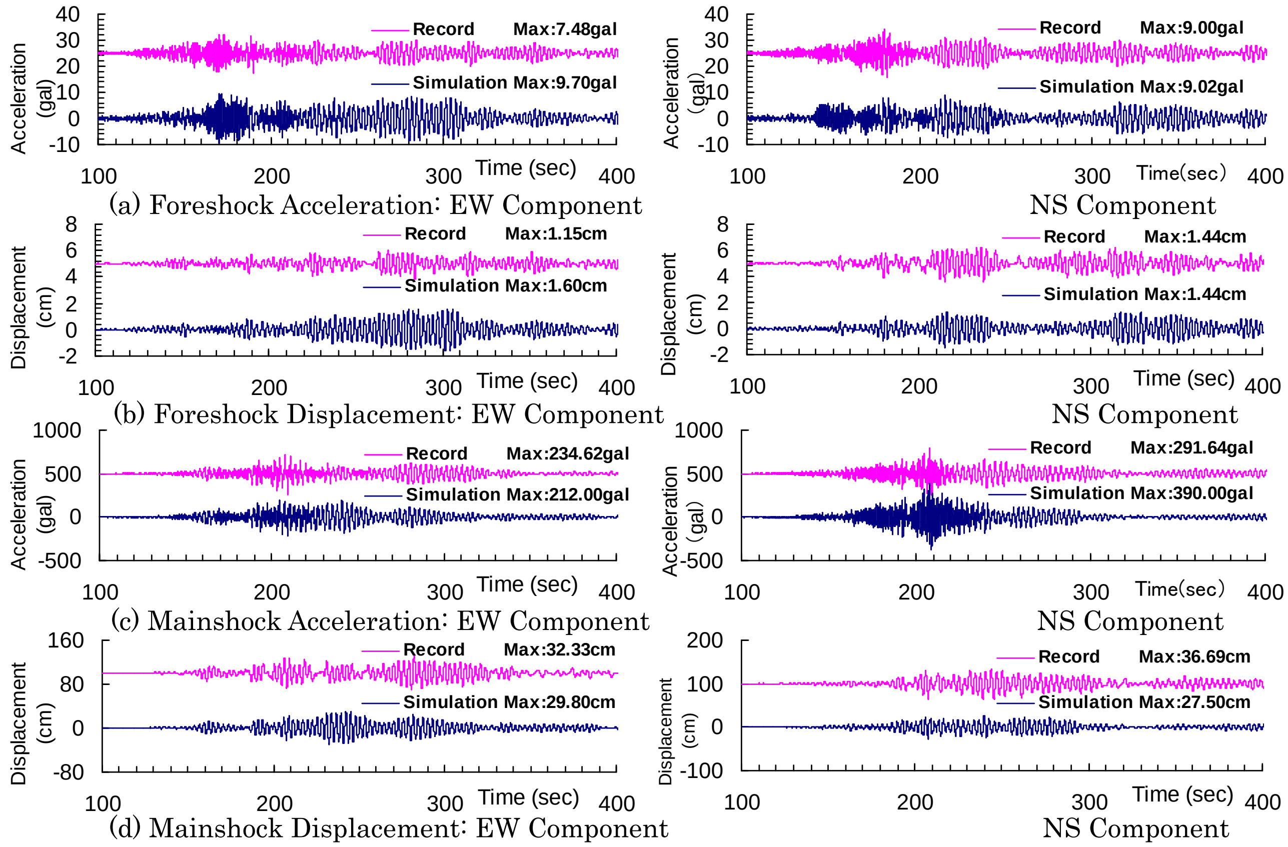


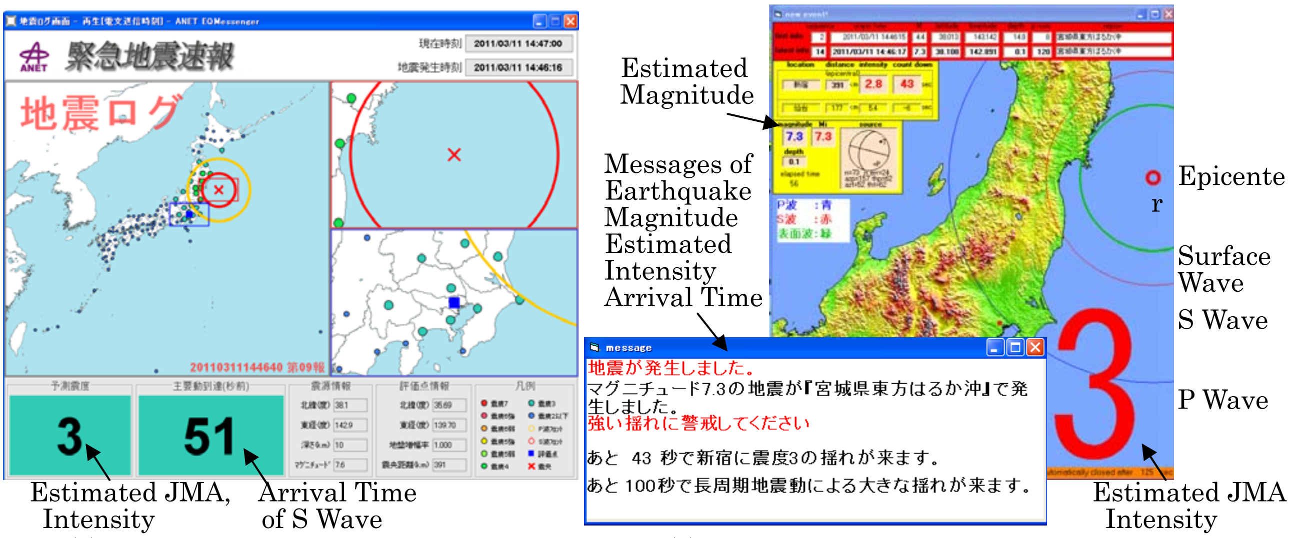
Figure 10. Observed and simulated accelerations and displacements of the 29th floor for the fore- and main-shocks

Table 2. Max. Amplitudes of Strong Motions of High-Rise Buildings in the Shinjuku Station Areas (Note: The displacements of buildings No.1 and 2 are relative values with respect to those of 1F and B3, respectively, whereas those of No.3 and 3 are absolute values.)

No.	Building Name	Floor	Acc. (cm/s/s)			Disp. (cm)			JMA Intensity
			NS	EW	UD	NS	EW	UD	
1	Shinjuku Center Building (54 Stories)	54F	161	236	–	54	49	–	–
		28F	171	113	–	33	26	–	–
		1F	142	94	57	0	0	–	–
2	Tokyo Metropolitan Government Building (48 Stories)	48F	242	288	198	65	66	–	–
		43F	114	136	156	57	54	–	–
		32F	95	117	125	44	39	–	–
		25F	113	141	105	35	31	–	–
		8F	120	89	71	10	9.2	–	–
		1F	91	82	45	0.6	0.7	–	–
		B3	74	73	48	0	0	–	–
3	A Building (31 Stories)	31F	280	239	117	49	35	7.8	5.6
		15F	168	160	83	27	17	7.5	5.2
		1F	155	112	52	14	10	7.7	4.6
		B5	66	62	47	14	10	7.7	4.4
4	B Building (30 Stories)	30F	184	209	291	38	33	7.3	5.5
		20F	158	157	222	30	24	7.2	5.2
		10F	156	138	122	16	12	7.3	5.2
		2F	109	85	62	10	8.5	7.3	4.5
		B3	63	71	52	11	8.4	7.3	4.5

2.4. Systems for Emergency Response

We report emergency response systems, initial response of people, and damage of high-rise buildings in the Shinjuku station area. As the case of Kogakuin University, **Figure 11** shows screenshots of the two EEW (Earthquake Early Warning) systems after the 2011 Tohoku earthquake, whose data are provided by NIED (Nationl Research Institute for Earth Science and Disaster Prevention) and JMA (Japan Metrological Agency through Anet Co.). Since the initially estimated magnitude was small (7.6 and 7.3 by JMA and NIED, respectively), and the epicentral distance was large (about 390 km), the estimated JMA intensity was 3 (the actual intensity was 5). Therefore, the automated warning message was not issued. Even this limitation of accuracy, we believe that the systems are useful for initial response, especially for the long-period ground motion from far and large earthquakes. **Figure 11(b)** shows 100 s of the arrival time for the long-period ground motion (surface waves: Kubo et al., 2011), which is enough time for initial response, such as the emergency stop of elevators and issuing warning announcements



(a) EEW by JMA and Anet Co.　　(b) EEW by NEED and Kogakuin University

Figure 11. EEW (Earthquake Early Warning System) after the 2012 East Japan earthquake at Kogakuin University

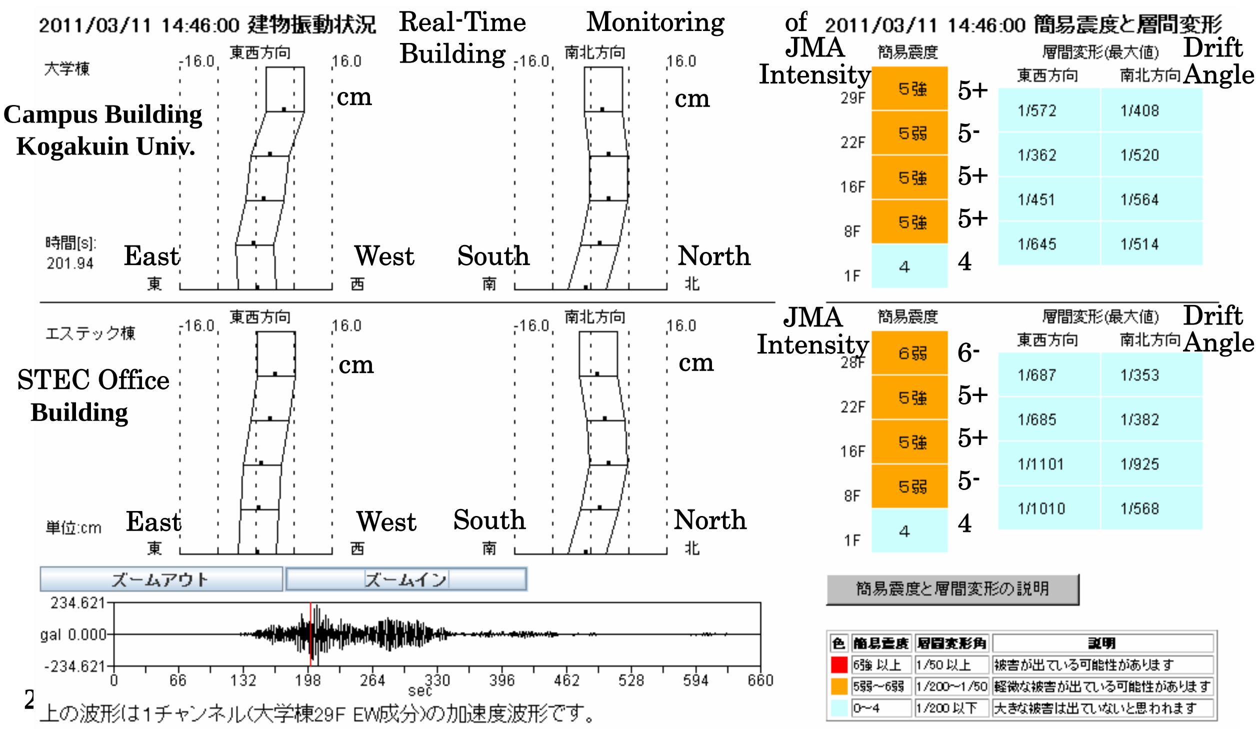


Figure 12. RMS (Real-Time Strong Motion Monitoring System) after the 2012 East Japan earthquake at Kogakuin University

Figure 12 shows the screenshot of the RMS (Real-Time Strong Motion Monitoring System) of Kogakuin University, which shows the real-time information of the building response: the arrays of estimated JMA intensities, and drift angles (Kubo, 2011). Using this system, the emergency control center quickly knew that the building was structurally safe, and made prompt announcements to stay at safe places.

Even though there was no severe damage in the university building, several non-structural elements and equipments suffered damage, as shown in **Figures 13**: fall and deformation of ceiling panels and plaster boards, deforming of partition walls, fall of unsettled objects, and so on. In addition, an emergency elevator stopped the service for about three weeks, because the main cables were twisted, and it was difficult to obtain the replacement parts.

We also conducted questionnaire and hearing surveys about building response, damage, and emergency response at 22 high-rise buildings in the Shinjuku station area, and obtained data from 16 building management companies and 23 tenants. As results, we found that the extent of damage was very similar to that of Kogakuin University: the fall and deformation of non-structural elements and equipments, and tangled elevator cables (see **Figure 13(n)**). In addition, there were a couple of buildings which were suffered water leakage from sprinklers, and a few people were trapped in elevators, because of the activation of emergency sensors.

Generally, communications between building managers and tenants were difficult, because of the telephone lines congestion. Even though there were no severe structural damage of a building, some managers felt difficulty to make an appropriate announcement whether people should stay or evacuate from the building, because they could not obtain the information of damage immediately after the earthquake. This suggests that EEW and RMS are effective for emergency management during a big earthquake.

3. CONCLUSIONS

We reported seismic response, damage and emergency response of high-rise buildings in the Shinjuku Station area in Tokyo, Japan, for the 2011 Tohoku Earthquake, using strong motion data, numerical simulations and questionnaire/hearing surveys. The Shinjuku Campus of Kogakuin University of 29-stories showed that the maximum amplitudes of the strong motions during the mainshock are 1 m/s/s, 0.2 m/s, and 0.1 m for accelerations, velocities, and displacements, respectively, at the ground level. And those of the 29th floors are amplified to 3 m/s/s, 0.7 m/s, and 0.37 m, respectively. The JMA intensity also amplified from 4 at 1st floor to 6- at 29th floor. Even though there was no structural damage, nonstructural elements suffered damage at the middle to higher floor: falls of ceiling boards, and deformation of partition walls. An emergency elevator had been stopped for more than 3 weeks, because of twisted cables and broken parts. The questionnaire/hearing surveys from 16 buildings in the Shinjuku area showed that their seismic response and damage patterns are similar to those of Kogakuin University. Even though there was no severe building damage, emergency managers felt difficulty to make an appropriate announcement whether people should stay or evacuate from the building to obtain the damage information immediately after the earthquake. This suggests the effectiveness of RSM (Real-Time Seismic Monitoring system) after an earthquake.

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(a) 28F (Fall of Ceiling Panels)　　(b) and (c) 25F (Movement of Copy Machine, and Fall of objects)

(d) and (e) 24F(Fall of Bookshelves, and Deformation of Partition Wall)　　(f) 21F (Fall of Ceiling Panels)

(g) 14F (Fall of Ceiling Panels)　　(h) and (k) 12F (Movement of Copy Machine, and Fall of Objects)

(l) 2F (Library: Fall of Books)　　(m) 1F (Hall: Loosen EJ Cover)　　(n) Tangled Elevator Cable (not Kogakuin buildings)

Figures 13. Various Damage observed in the Shinjuku campus building of Kogakuin University