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STRONG MOTION DATA RECORDED IN BUILDINGS DAMAGED BY THE 2011 GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT: Building Research Institute (BRI) has initiated construction and operation of the strong motion network aimed at building structures in 1957, as one of its research activities. Fifty-nine stations in the BRI strong motion network were triggered by the 2011 Great East Japan Earthquake. The paper reported notable cases recorded during the East Japan Earthquake and its aftershocks in the BRI strong motion network.

Key Words: Great East Japan earthquake, strong motion data, building damage

INTRODUCTION

The Building Research Institute (BRI) of Japan is a national institute engaging the research and development in the field of architecture, building engineering and urban planning. BRI has initiated construction and operation of the strong motion network aimed at building structures in 1957, as one of its research activities (Kashima, 2006a).

On March 11, 2011, a massive earthquake occurred off the Pacific coast of northeastern Japan. The earthquake (hereinafter referred to as the East Japan earthquake) caused devastating tsunami and severe shaking in extensive area.

Fifty-nine stations in the BRI strong motion network were triggered by the East Japan earthquake. Most of the stations experienced the strongest shaking ever. Among buildings in the BRI network, at least four buildings suffered some damage due to the severe earthquake motions. Through the analyses of strong motion data recorded in those buildings, obvious change of the natural periods during intense shaking could be identified.

The paper reported notable cases recorded during the East Japan Earthquake and its aftershocks in the BRI strong motion network.

OUTLINE OF STRONG MOTION DATA

The East Japan earthquake has triggered 59 stations of the BRI strong motion network as shown in Fig. 1. The stations were widely distributed over the eastern Japan, and nearly 30 stations were located in the Tokyo metropolitan area and its outskirts. Almost buildings in the network have experienced the most severe earthquake motion in the past. Among buildings in the BRI network, at least four buildings in the three stations suffered some damage due to the intensive earthquake motions. The maximum accelerations recorded in the three stations are listed in Table 1.

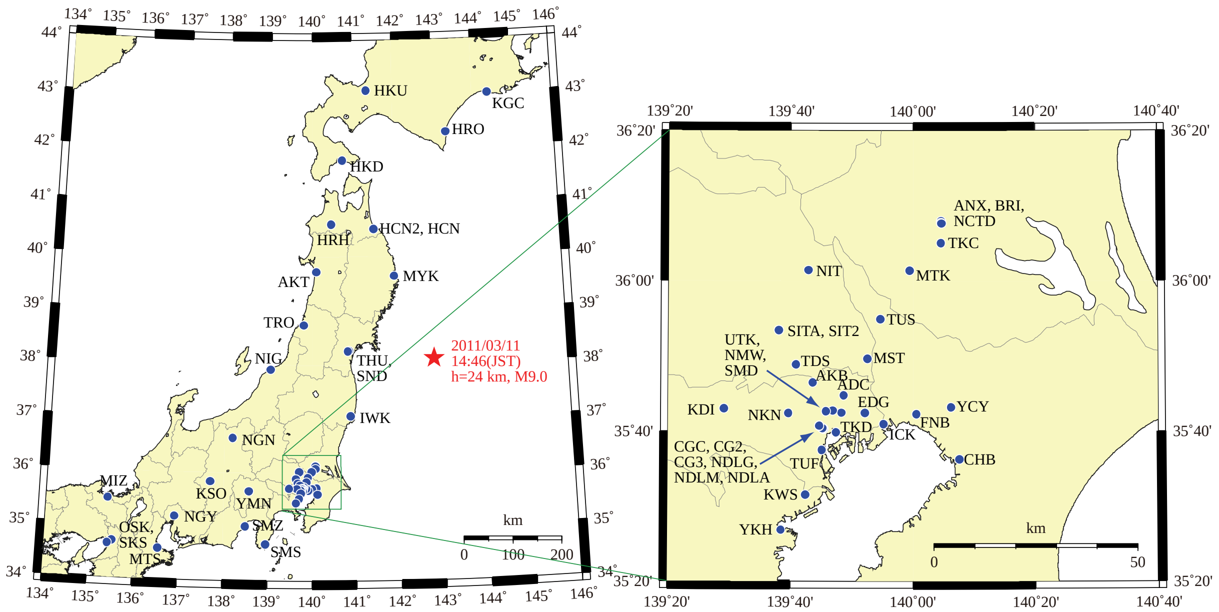


Fig. 1 Triggered stations in the BRI strong motion network

Table 1 Maximum accelerations in three stations of damaged buildings

Code	Station name	Δ (km)	I_{JMA}	Az.	Loc.	Max. Acc. (cm/s^2)			Note
						H1	H2	V	
THU	Tohoku University	177	5.6	192°	01F*	333	330	257	
					09F	908	728	640	
IWK	Iwaki City Hall	210	5.3	180°	B1F*	175	176	147	
					09F	579	449	260	
ANX	Annex and Main Buildings, Building Research Institute	330	5.3	180°	A01*	279	227	248	GL
					A89	142	153	102	GL-89 m
					BFE	194	191	136	Annex
					8FE	597	506	344	Annex
					MBC	203	206	152	Main bldg.
					M8C	682	585	311	Main bldg.

Note) Δ: Epicentral distance, I_{JMA}: JMA instrumental seismic intensity (using an asterisked sensor), Loc.: Sensor location, Az.: Sensor direction (clockwise from North), H1, H2, V : Maximum accelerations in horizontal #1 (Az.), horizontal #2 (Az.+90°) and vertical directions

THU BUILDING

At the station THU, a nine-story steel-framed reinforced concrete building in the Aobayama Campus of Tohoku University, Sendai city, is the target of instrumentation. This building has a long history of strong motion observation. Among them, strong motion records on the ninth floor of the building that were obtained in the 1978 Miyagi-ken-oki (Off Miyagi prefecture) earthquake are well known to have represented a maximum acceleration of more than 1,000 cm/s^2. The instrument has two acceleration sensors on the first floor (01F) and the ninth floor (09F).

During the East Japan earthquake, multi-story shear walls suffered serious bending failure. Figure 2 shows acceleration waveforms recorded during the main shock of the East Japan earthquake. Upper two waveforms are accelerations on the first floor (01F) in the transverse (N192°E) and longitudinal (N282°E) directions, and lower two are on the ninth floor (09F). Maximum accelerations on the first floor (01F) exceeded 330 cm/s^2 in both of the directions. Maximum accelerations on the ninth floor (09F) were twice to three times larger than that on the first floor, and exceeded 900 cm/s^2 in the transverse direction.

Pseudo velocity response spectra with a 5% damping ratio of the acceleration records on the first floor (01F) are plotted in Fig. 3. The highest peak around the period of 1 second in the N192°E direction is striking. At that period, the velocity response reaches 179 cm/s.

Figure 4 (a) and (b) represent building displacements (relative displacement of the ninth floor to first floor) in the both directions, and Fig. 4 (c) shows fundamental natural periods of the building that were estimated in every 10 seconds (Kashima, 2006b). The fundamental natural periods in Fig. 4 (c) represented about 0.7 seconds at the initial time of the earthquake motion in both of the directions, but increased to about 1 second in the first wave group at the time of 40 to 50 seconds, and increased from 1.2 seconds to about 1.5 seconds in the second wave group at the time of 80 to 100 seconds. Due to the seismic damage, the fundamental natural periods finally became twice longer than the natural periods at the initial stage. It can be estimated that the stiffness of the building was reduced to 1/4.

Photo 1 THU building

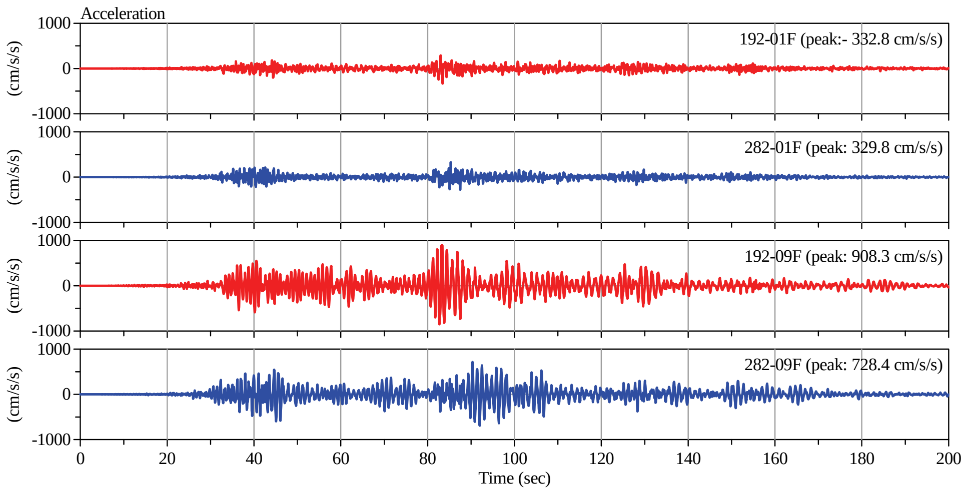


Fig. 2 Acceleration waveforms recorded in THU building

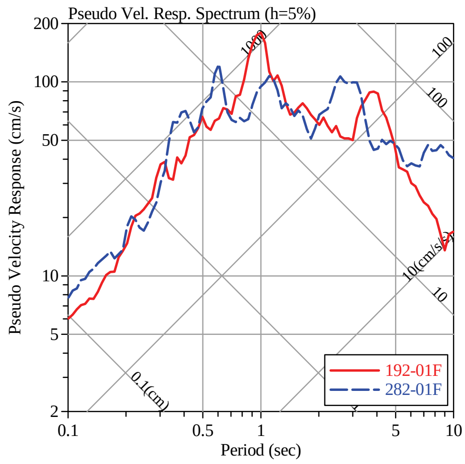


Fig. 3 Pseudo velocity response spectra of the strong motion record on 01F at THU (h=5%)

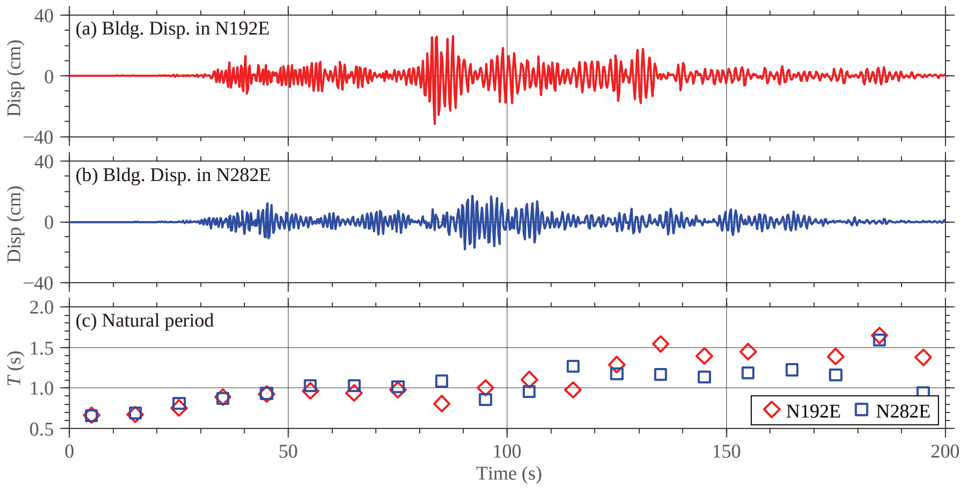


Fig. 4 Building displacements and fundamental natural periods of THU building

IWK BUILDING

The Iwaki City Hall that is an eight-story steel-framed reinforced concrete building is instrumented in the station IWK. Two acceleration sensors are placed on the first basement floor (B1F) and the penthouse floor (09F). The appearance of the building is shown in Photo 2. The epicentral distance of the IWK station was 210 km.

Severe earthquake motion of the East Japan earthquake caused cracks on some concrete walls and damages to finishing materials in the building. Acceleration records of the East Japan earthquake are shown in Fig. 5. The first wave group composed mainly of S-waves appeared at the time of around 30 seconds. Earthquake shaking continued for long time and the maximum amplitudes were recorded around the time of 80 to 90 seconds. The maximum accelerations on the basement floor (B1F) were 175 cm/s^2 and 176 cm/s^2 in the transverse (N180°E) and longitudinal (N270°E) directions, respectively. On the building top (09F), those were amplified to 579 cm/s^2 and 449 cm/s^2 (3.3 and 2.5 times) in the N180°E and N270°E directions, respectively.

Figure 6 represents pseudo velocity response spectra with 5% damping ratio of the records on the basement floor (B1F). The response spectra shows a form like a loose hill and the maximum velocity response exceeded 100 cm/s at the periods of around 2 seconds in the N180°E direction.

Figure 7 (a) and (b) indicate building displacements in the N180°E and N270°E directions. The maximum building displacement reached 11 cm in the N180°E direction. Natural fundamental periods identified from the strong motion in every 10 seconds are plotted in Fig. 7 (c). The natural period in the N180°E direction was 0.6 seconds in the initial time. The intensive shaking lengthened the natural period to 0.8 seconds at the time of around 40 seconds, and then to 1 second at the time of 100 seconds. The similar phenomenon can be observed in the transition of the natural periods in the N270°E direction.

Photo 1 IWK building

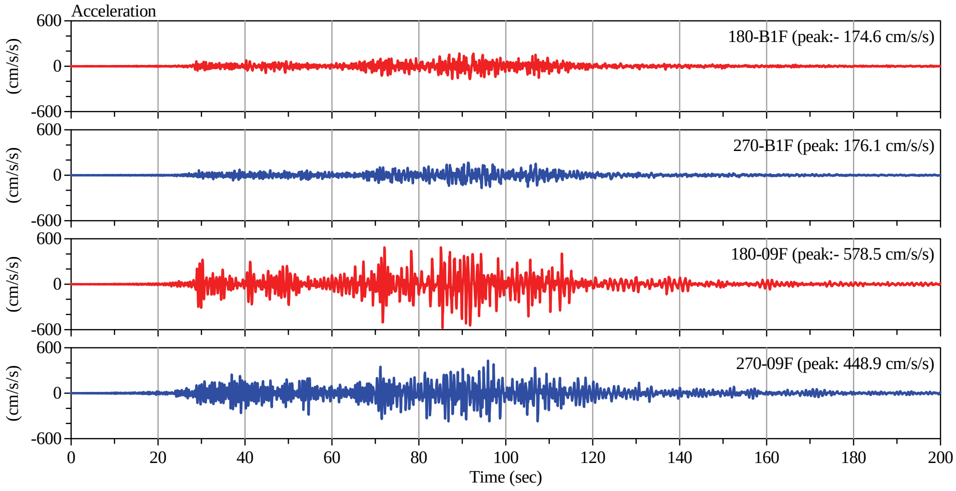


Fig. 5 Acceleration waveforms recorded in IWK building

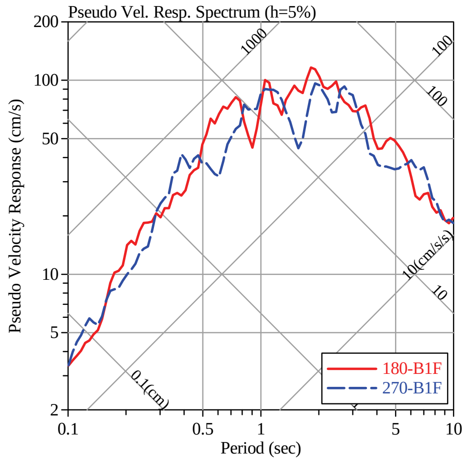


Fig. 6 Pseudo velocity response spectra of the strong motion record on B1F at IWK (*h*=5%)

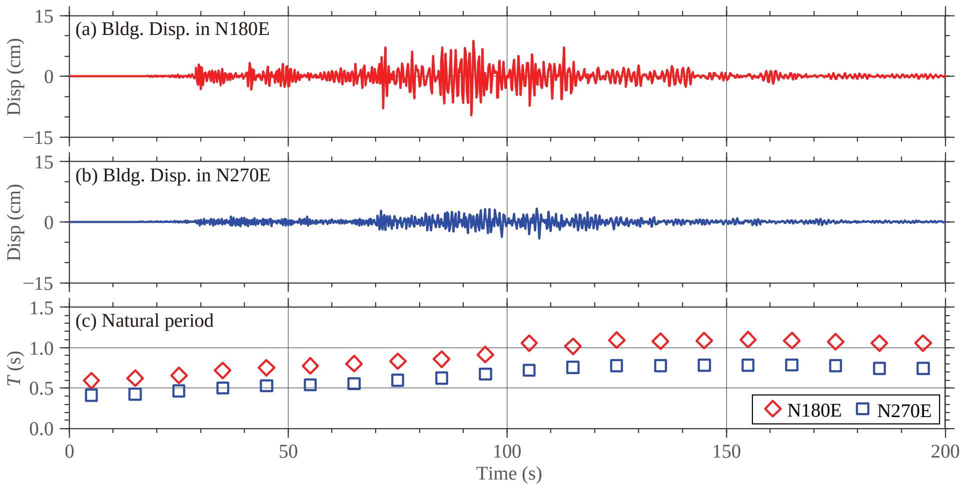


Fig. 7 Building displacements and fundamental natural periods of IWK building

ANX BUILDINGS

The station ANX has a densely instrumented system targeted on two buildings and the surrounding ground in the Building Research Institute (BRI) in Tsukuba City, Ibaraki Prefecture. The target is equipped with eleven acceleration sensors in the annex building, seven sensors in the surrounding ground, and four sensors in the main building. The annex building is an eight-story steel-framed reinforced concrete building with one basement floor, and the main building is a seven-story steel-framed reinforced concrete building with one basement floor. Two buildings are connected by the passage way with the expansion joint. Photo 3 shows the annex building and main building of BRI and Fig. 8 indicates the sensor configuration.

The East Japan earthquake violently shook and damaged both of the buildings. Especially in the passage way between the two buildings, the expansion joints were broken and ceiling boards fell off. Figures 9 and 10 indicate acceleration waveforms recorded in the annex and main building, respectively. Maximum accelerations on the basement floors (BFE and MBC) are about 200 cm/s^2 in the both of the buildings. Accelerations on the eighth floors (8FE and M8C) are 2.5 to 3.0 times larger than that on the basement floors.

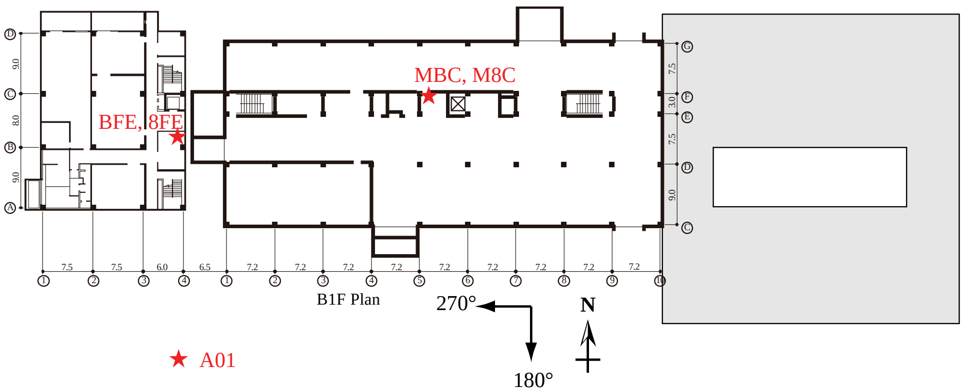
Pseudo velocity response spectra of the strong motion data recorded on the basement floors of the both buildings are plotted in Fig. 11. Several peaks appear on the spectra in the both horizontal directions, and the pseudo velocity response at the period of 1.3 seconds exceeds 100 cm/s.

Building displacements and transition of the fundamental natural periods of the annex building and the main building are shown in Figs. 12 and 13, respectively. Although the natural periods in both of the horizontal directions of the annex building were initially less than 0.8 seconds, those were gradually getting longer during the main part of the shaking. Finally the natural periods reached more than 1.0 second in the both directions. In case of the main building, the natural periods were 0.7 seconds and 0.45 seconds in the transverse (N180°E) and longitudinal (N270°E) directions, respectively. At the end of strong shaking, the natural periods were lengthened to about 1 second in the N180°E direction and 0.7 seconds in the N270°E direction.

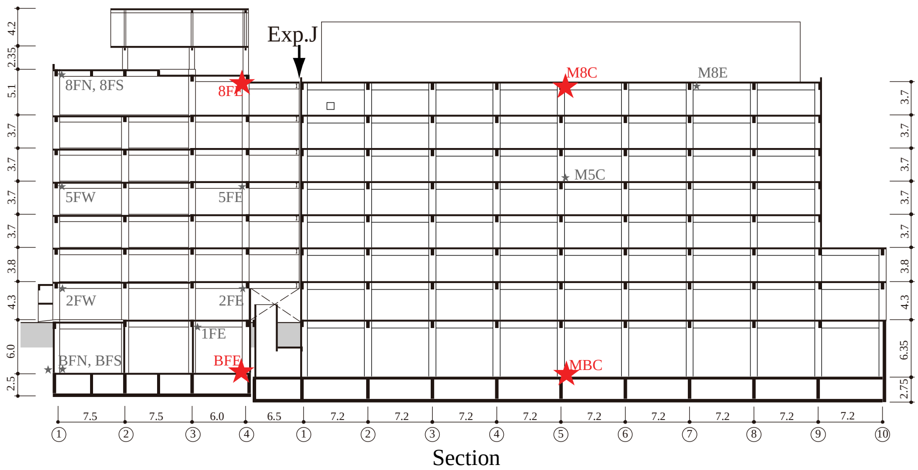
In order to discuss damage to the expansion joint, displacements of the expansion joint are calculated. Figure 14 shows relative displacements of the annex building and the main building to the respective foundation, and relative displacement of the annex building side of the expansion joint to the main building side. Figure 14 (a) and (b) represent building displacements in the N180°E and N270°E directions, respectively. In Fig. 14 (a) and (b), solid lines indicate displacements of the annex and dashed lines represent those of the main buildings. The both buildings show similar movement in the N180°E direction because of close fundamental natural period. In contrast, movement of the two buildings in the N270°E direction is quite different with each other.

Figure 14 (c) and (d) show expansion joint displacements in the N180°E and N270°E directions, respectively. Maximum displacement of the expansion joint direction reaches 12 cm in the N270°E and exceeded the clearance of the expansion joint.

Photo 3 Instrumented buildings of ANX station



(a) B1F Plan



(b) Elevation

Fig. 8 Sensor configuration at ANX station

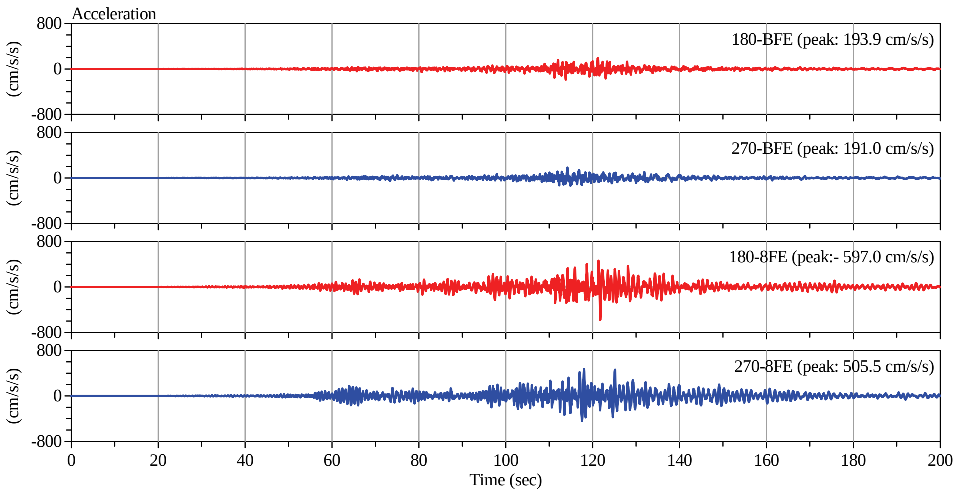


Fig. 9 Acceleration waveforms recorded in annex building at ANX

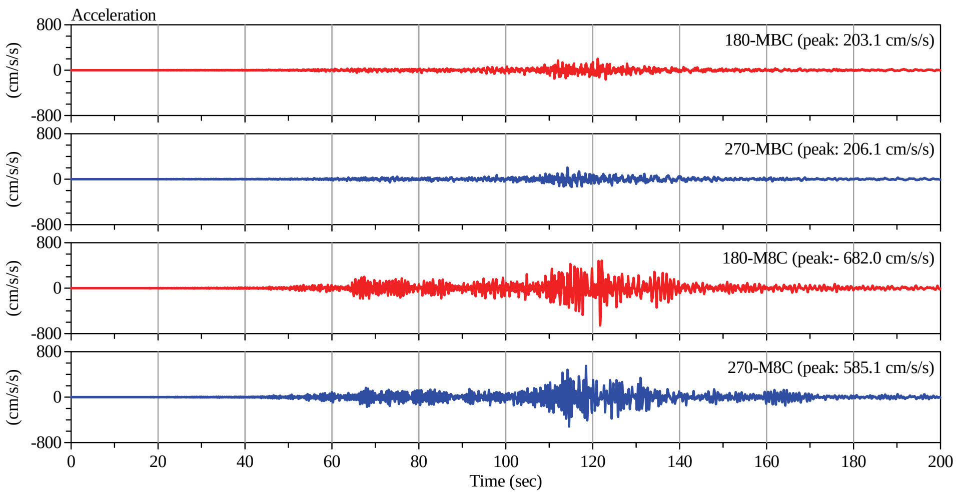


Fig. 10 Acceleration waveforms recorded in main building at ANX

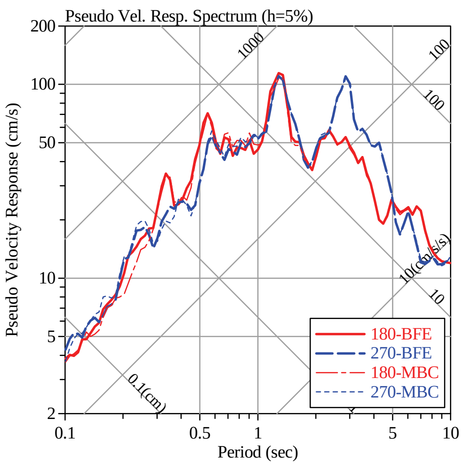


Fig. 11 Pseudo velocity response spectra of the strong motion records at BFF and MBC (h=5%)

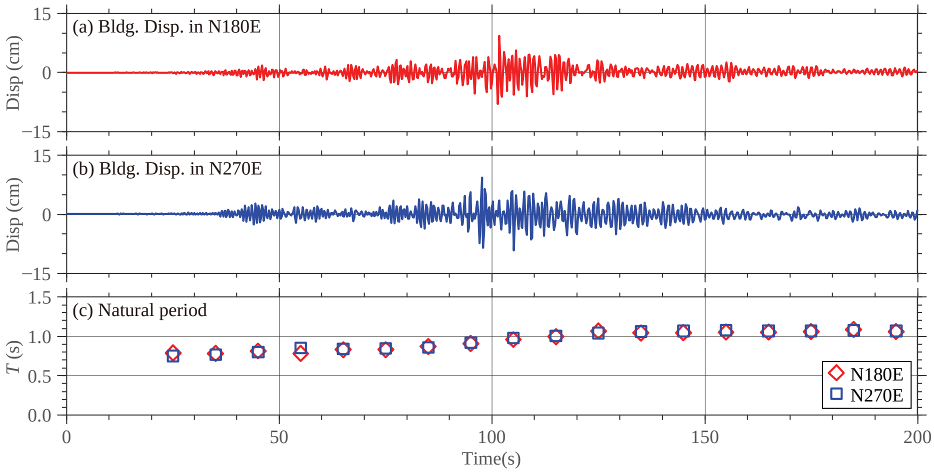


Fig. 12 Building displacements and fundamental natural periods of annex building at ANX

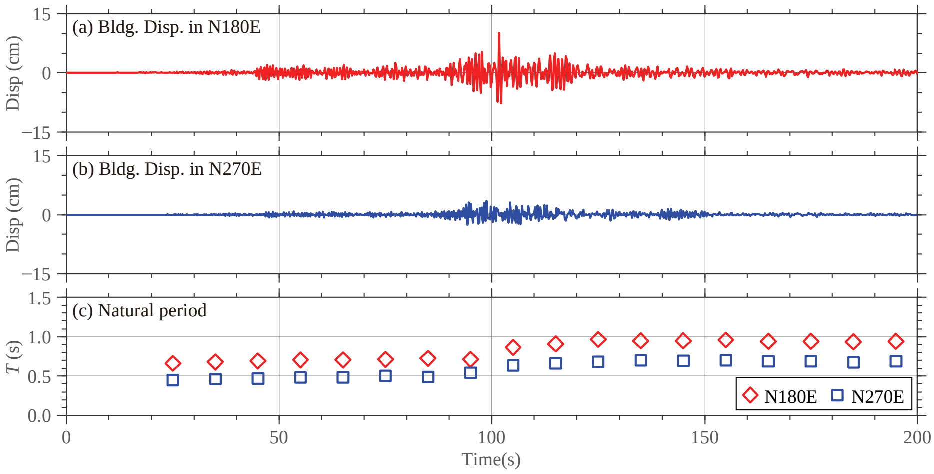


Fig. 13 Building displacements and fundamental natural periods of main building at ANX

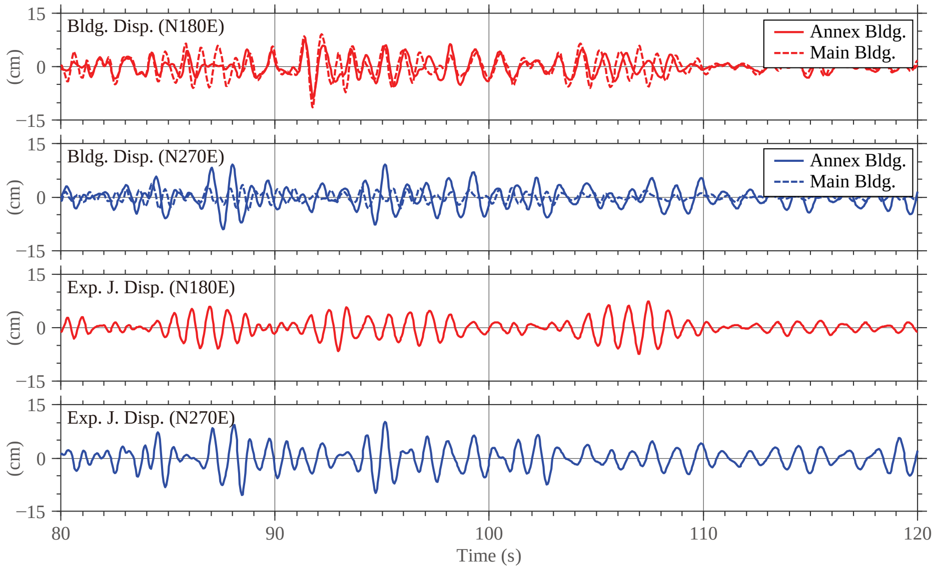


Fig. 14 Building displacements and expansion joint displacements at ANX

CONCLUSIONS

The BRI strong motion network has obtained a large number of strong motion data from the 2011 East Japan earthquake and its aftershocks and induced earthquakes. In some buildings, strong motion data clearly identified damage process by the intensive earthquake motions. The analysis of the data recorded in two buildings at the station ANX suggests lack of the clearance of the expansion joint.

In the BRI network, we have various types of buildings, including nine super-high-rise buildings and six base isolated building. We intend to contribute to the improvement of the seismic safety of building structures through the analyses of the extensive strong motion data.

ACKNOWLEDGMENTS

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REFERENCES

Kashima, T. and Y. Kitagawa (2006a). "Dynamic Characteristics of Buildings Estimated from Strong Motion Records," *Proceedings of the 8th U.S. National Conference on Earthquake Engineering*, Paper No. 1136

Kashima, T. and Y. Kitagawa (2006b). "Dynamic Characteristics of An 8-storey Building Estimated from Strong Motion Records," *Proceedings of the First European Conference on Earthquake Engineering and Seismology*, Paper No. 1005