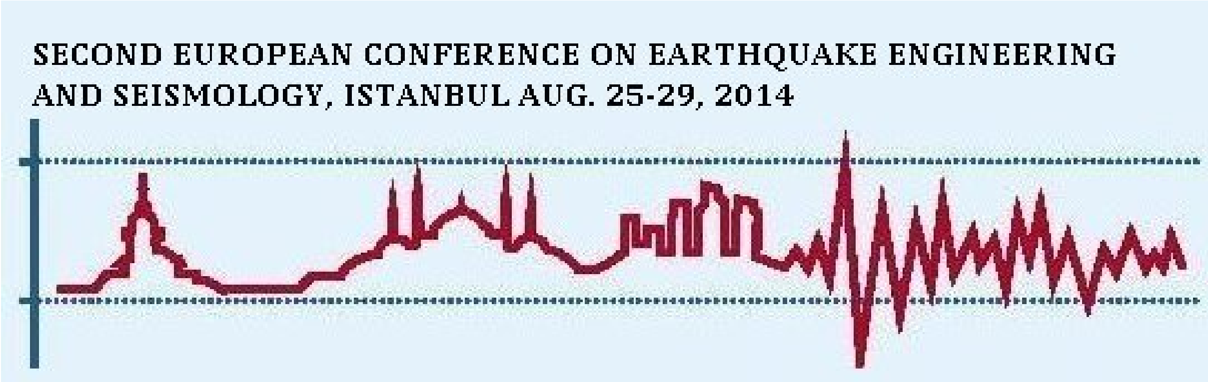

DYNAMIC BEHAVIOUR OF SRC BUILDINGS DAMAGED BY THE 2011 GREAT EAST JAPAN EARTHQUAKE BASED ON STRONG MOTION RECORDS

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ABSTRACT

The Building Research Institute (BRI) of Japan operates a strong motion network of 79 observation stations in major cities across Japan. The Great East Japan Earthquake of March 11, 2011 triggered 61 stations including one covering two densely instrumented BRI buildings and the surrounding ground. The buildings comprised a 7-storey steel-framed reinforced concrete (SRC) building constructed in 1979 and an 8-storey SRC building built in 1998. Both sustained slight damage during the earthquake and recorded valuable strong motion data. The ground motion of the Great East Japan Earthquake having a peak acceleration of 2.8 m/s^2 was quite severe for building structures. Peak acceleration at the basement floors of the two buildings was about 2 m/s^2, and that at the eighth floors was 5.1 to 6.8 m/s^2. Fundamental natural frequencies of the buildings were decreased to about two-thirds by the damage during the quake. The passageway between the two buildings was severely damaged by the quake. Therefore, deformation of the expansion joint between the two buildings was estimated using the strong motion data. The deformation at the eighth floor exceeded the 0.1 m clearance of the joint and caused serious damage around the joint.

INTRODUCTION

The Building Research Institute (BRI) of Japan is a national institute engaged in research and development in the fields of architecture, building engineering and urban planning. As one of its research activities, the BRI operates a strong motion network that covers buildings in major cities across Japan.

On March 11, 2011, an enormous earthquake with a moment magnitude (Mw) of 9.0 occurred off the Pacific coast of northeastern Japan. The earthquake, known as the Great East Japan Earthquake, caused a monstrous tsunami and massive damage to eastern Japan. Seventy-nine stations of the BRI strong motion network were running at the time of the earthquake. Among them, 61 stations were triggered (Kashima et al., 2012 and Okawa et al., 2013).

This paper focuses on two damaged BRI buildings within the strong motion network and discusses their dynamic behaviour.

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OUTLINE OF BUILDINGS

The Building Research Institute (BRI) is located in Tsukuba City, approximately 60 km north-northwest of Tokyo. The BRI has two office buildings consisting of the main building, a 7-storey steel-framed reinforced concrete (SRC) structure completed in 1979, and the annex building, an 8-storey SRC structure built in 1998 that is connected to the main building by a passageway having expansion joints. Both buildings are supported by a spread foundation at a depth of about 8 m. The building features are summarised in Table 1 and the exterior of the buildings is shown in Fig. 1.

Table 1. Outline of BRI buildings

Building	Main building	Annex building
Year of completion	1979	1998
Number of floors	7 with 1 basement	8 with 1 basement
Structure	SRC	SRC
Foundation	Spread	Spread
Building area	3,403 m^2	637 m^2
Total floor area	13,467 m^2	5,050 m^2


Figure 1. BRI main building (right) and annex building (left)

STRONG MOTION INSTRUMENTATION

Strong motion recording in the BRI buildings was started in 1998 (Kashima, 2004 and Kashima et al., 2006b). The strong motion instrumentation comprises four sensors in the main building and eleven sensors in the annex building. The sensor configuration is illustrated in Fig. 2. In addition, seven sensors are installed in the surrounding ground. A sensor labelled GL is set 1 m deep in the ground at a distance of 20 m from the annex building. The installation azimuths of all sensors are N180°E (180° clockwise from the north) and N270°E, being along the building axis. Hereinafter, the N180°E and N270°E directions are referred to as the Y- and X-directions, respectively.

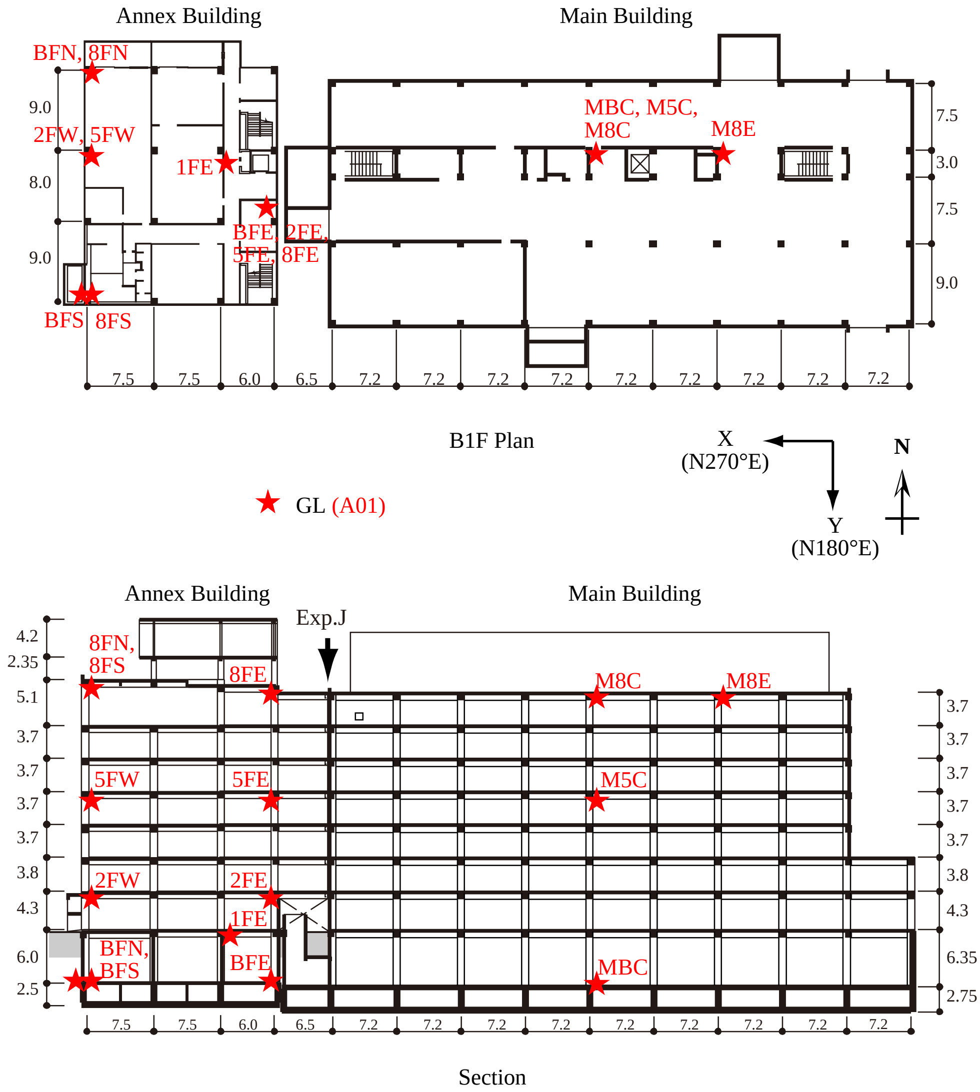


Figure 2. Sensor configuration in the main and annex buildings

STRONG MOTION RECORDS OF THE GREAT EAST JAPAN EARTHQUAKE

On March 11, 2011, the Great East Japan Earthquake with a moment magnitude (Mw) of 9.0 occurred off the Pacific coast of northeastern Japan. The acceleration waveforms recorded on the ground (GL) during the earthquake are shown in Fig. 3. The waveforms in the Y-, X- and Z- (up-down) directions are shown from the top to bottom. Although the BRI was 330 km away from the epicentre, the peak acceleration in the Y-direction reached 2.8 m/s, the most intense earthquake ground motion ever experienced at BRI.

The pseudo-velocity response spectra of the strong motion data at GL are plotted in Fig. 4. The damping ratio of the response spectra is 5%. The response spectra show a wavy shape with peaks at the periods of 0.5, 1.3 and 2.8 s. The pseudo-velocity response spectra in the horizontal directions exceeded 1 m/s at the periods of 1.3 and 2.8 s, which would be very severe ground motion for building structures.

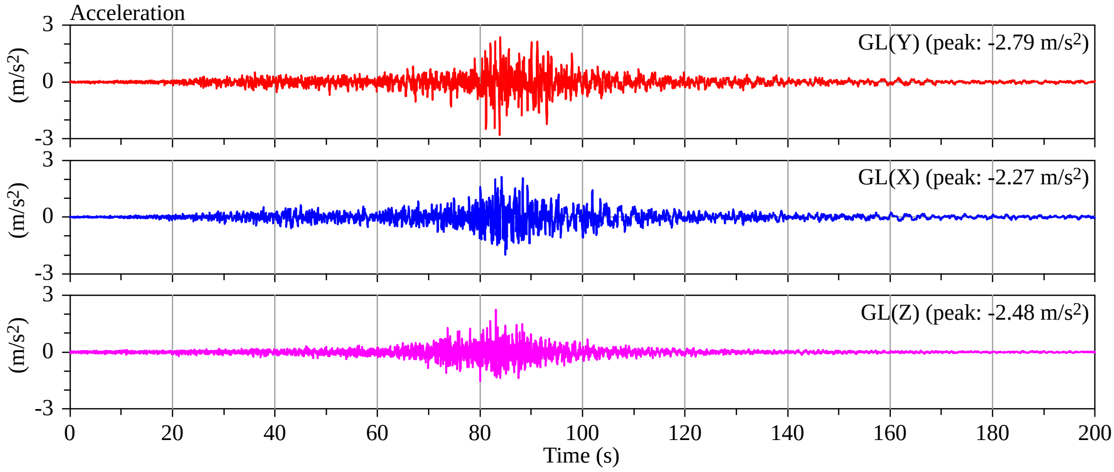


Figure 3. Acceleration waveforms recorded on the ground (GL) during the Great East Japan Earthquake

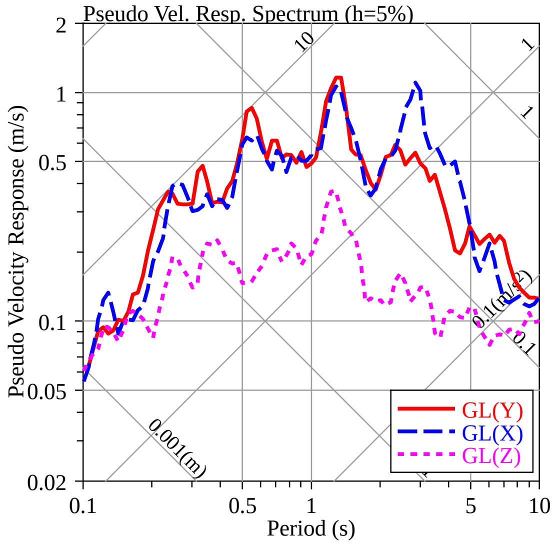


Figure 4. Pseudo-velocity response spectra of acceleration records on the ground (GL) during the Great East Japan Earthquake

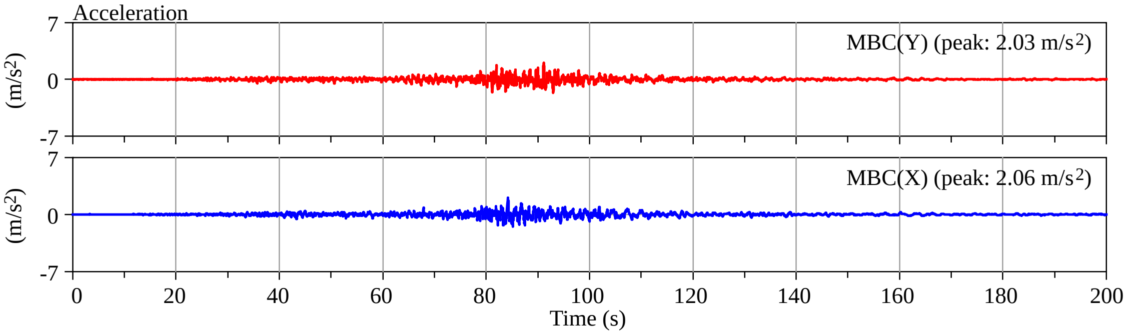
BUILDING RESPONSE TO THE GREAT EAST JAPAN EARTHQUAKE

Peak accelerations recorded in both buildings and on the ground are listed in Table 2. The peak acceleration in the horizontal directions at the basement floors (MBC and BFE) of both buildings was about 2 m/s^2. On the other hand, the acceleration at the eighth floors (8FE and M8C) of the buildings was 2.5 to 3.0 times greater than that at the basement floors, and the acceleration in the Y-direction of the main building reached 6.82 m/s^2.

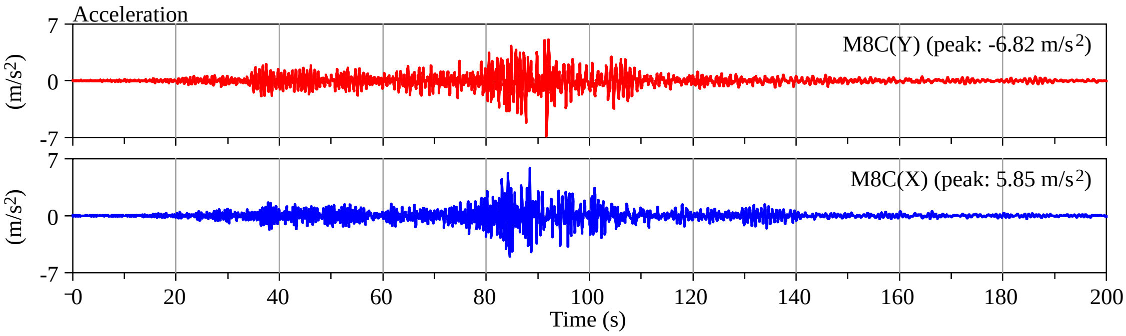
Table 2. Distribution of peak accelerations in the main and annex buildings

Building	Floor (Label)	Peak acceleration (m/s^2)		
		Y-direction	X-direction	Z-direction
Main building	08F (M8C)	6.82	5.85	3.11
	05F (M5C)	3.24	4.40	2.27
	B1F (MBC)	2.03	2.06	1.52
Annex building	08F (8FE)	5.97	5.05	3.44
	05F (5FE)	2.68	3.30	2.47
	02F (2FE)	2.03	2.01	1.58
	01F (1FE)	1.98	1.76	1.54
	B1F (BFE)	1.94	1.91	1.36
Ground	GL (A01)	2.79	2.27	2.48

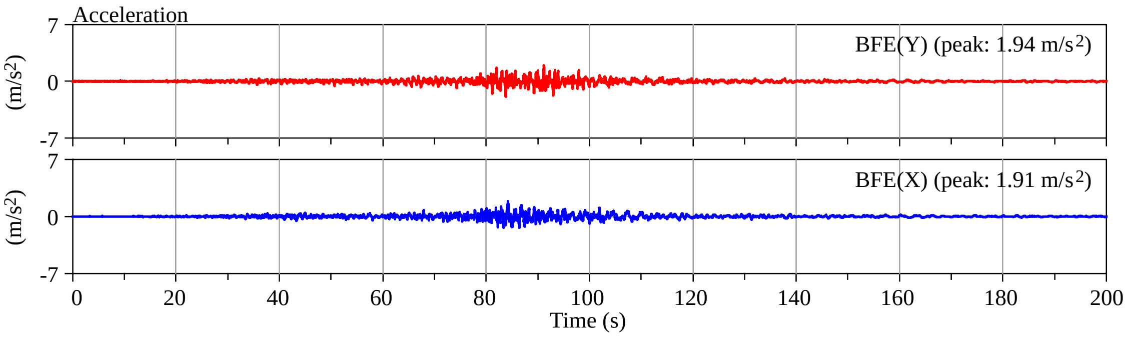
Figure 5 shows the acceleration waveforms in the horizontal directions recorded at the basement and eighth floors in the main and annex buildings. Destructive shaking arrived at the time of 80 s and continued for nearly 30 s. The responses of the buildings were already large at the time of 35 s. The quake lasted for almost 3 min.



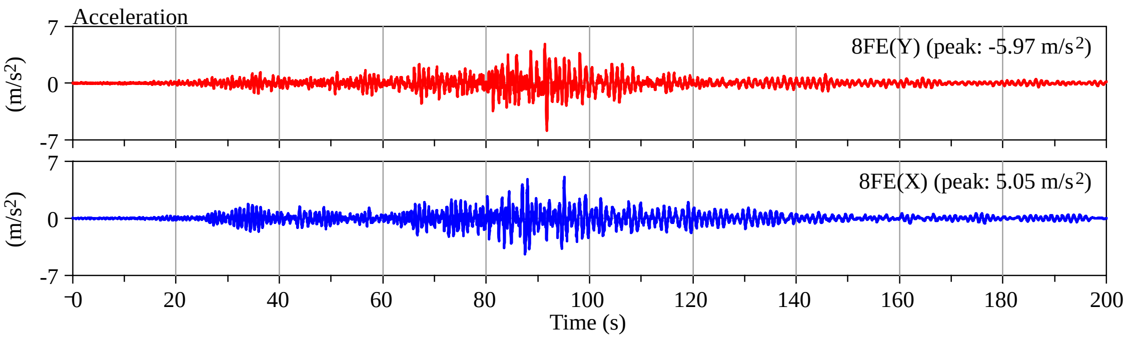
(a) Basement floor of the main building (MBC)



(b) Eighth floor of the main building (M8C)



(c) Basement floor of the annex building (BFE)

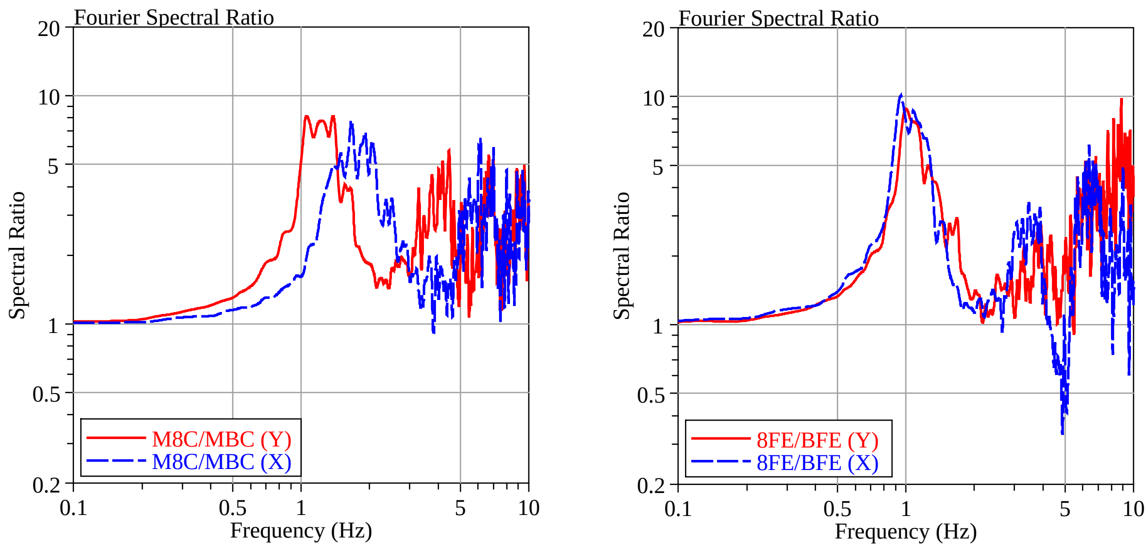


(d) Eighth floor of the annex building (8FE)

Figure 5. Acceleration waveforms recorded in the BRI buildings during the Great East Japan Earthquake

Fourier spectrum ratios of the acceleration data at the eighth floor to the basement floor in the horizontal directions of both buildings are plotted in Fig. 6. The spectra are smoothed using the Parzen window having a width of 0.1 Hz. Looking at Fig. 6(a), peaks corresponding to the fundamental natural frequencies can be found at frequencies of about 1.3 and 1.7 Hz in the Y- and X-directions of the main building, respectively. The natural frequencies of the annex building can be inferred as about 1 Hz in both horizontal directions, as shown in Fig. 6(b). Nevertheless, the spectrum ratios have wide and complicated shapes in the frequency range near the first natural frequencies; therefore, detailed investigation on nonlinear behaviour of the buildings is needed.

In the main and annex buildings, numerous splits in the plasterboard of the partitioning walls and cracks in the concrete walls were found during the post-earthquake investigation. In the passageway between the two buildings, the expansion joints were broken and ceiling material had fallen at the upper floors. Structural damage to the two buildings appeared to be slight, so they could continue to be used.



(a) Main building (M8C/MBC) (b) Annex building (8FE/BFE)

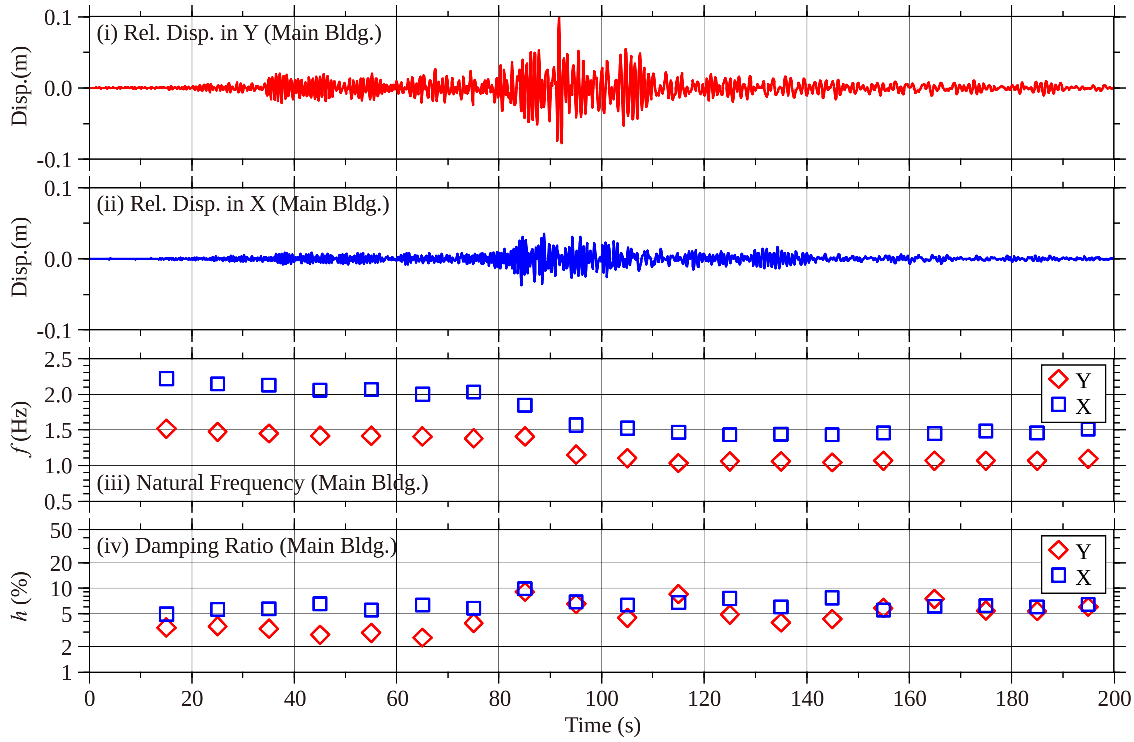
Figure 6. Fourier spectrum ratios of 8F/B1F of the acceleration records in the main and annex buildings during the Great East Japan Earthquake

CHANGE IN DYNAMIC CHARACTERISTICS DURING THE GREAT EAST JAPAN EARTHQUAKE

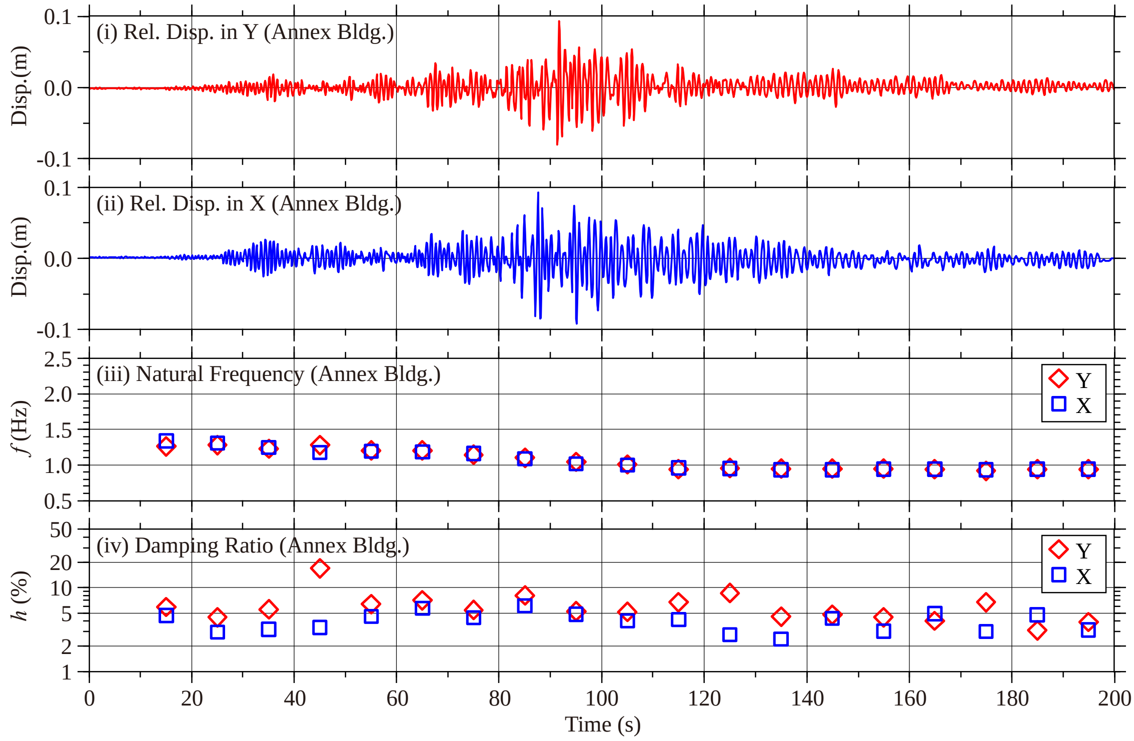
Change in the dynamic characteristics of the buildings during the severe shaking is discussed in this section. Figure 7 indicates the time histories of the building displacement, and the fundamental natural frequencies and damping ratios of the buildings. Building displacement means the relative displacement of the eighth floor to the basement floor. The fundamental natural frequencies and damping ratios were estimated for every 10 s using the acceleration data. As the fundamental frequency and damping ratio, a frequency period and a damping ratio of a single-degree-of-freedom system that can simulate an actual response having the best fitness were determined using the grid search method (Kashima et al., 2006a). The relative displacement of the eighth to the basement floor was selected as the response to be fitted. Red diamonds (◇) and blue squares (□) represent the values in the Y- and X-directions, respectively.

Looking at Fig. 7(a), the maximum building displacement in the Y-direction of the main building reached nearly 0.1 m. The natural frequency in the Y-direction was initially about 1.5 Hz, and started to drop from the time of 80 s. Finally, the natural frequency fell to 1.1 Hz. The maximum displacement in the X-direction was less than 0.04 m, but the natural frequency decreased from 2.2 to 1.5 Hz as well. The damping ratio of the main building was 2% to 5% in the initial part, and seemed to increase during the intense shaking.

Looking at Fig. 7(b), the natural frequencies of the annex building fell from about 1.3 to 0.9 Hz in both horizontal directions during the earthquake. The damping ratios of the annex building were around 5% on average in both directions.



(a) Main building



(b) Annex building

Figure 7. Building displacement, transition of natural frequencies and damping ratios of the BRI buildings during the Great East Japan Earthquake

BEHAVIOUR OF EXPANSION JOINT

The damage to the expansion joint of the passageway between the two buildings was significant, as shown in Fig. 8; therefore, the dynamic behaviour of the expansion joint is investigated in this chapter.

Figure 8. Damage to the expansion joint and passageway at the eighth floor

Since multiple sensors are installed on the eighth floor of both buildings, it is possible to calculate the displacement at the expansion joint considering torsional movement, as shown in Fig. 9. Displacement at the expansion joint, x_2 and y_2, is given by Eqs. (1) and (2) from the displacement at both sides of the floor. In Fig. 9, (x_1, y_1) can be calculated from the acceleration records at 8FN and 8FS, and (x_2, y_2) can be represented by the movement at 8FE.

$$x_2 = x_0 + L_2 \cos\theta = x_0 + \frac{L_2}{L_1}(x_1 - x_0) \tag{1}$$

$$y_2 = y_0 + L_2 \sin\theta = y_0 + \frac{L_2}{L_1}(y_1 - y_0) \tag{2}$$

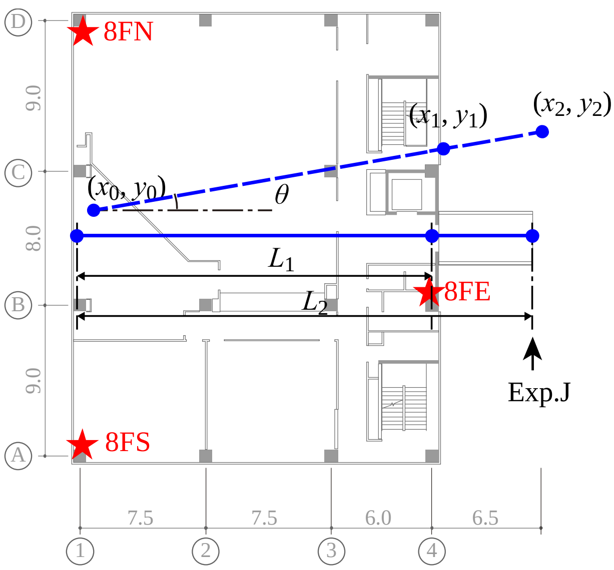


Figure 9. Concept for calculating displacement at the position of the expansion joint

The building displacement at the position of the expansion joint at the eighth floor of both buildings is shown in Fig. 10 (a) and (b). Although the maximum building displacement in the X-direction of the main building was less than 0.04 m, that in the Y-direction of the main building and both directions of the annex building was about 0.1 m.

Figures 10 (c) and (d) indicate the deformation of the expansion joint at the eighth floor in the Y- and X-directions, respectively. The deformation of the expansion joint represents the difference between the building displacement at the position of the expansion joint of the main and annex buildings. The maximum deformation in the X-direction exceeded the 0.1 m clearance of the expansion joint. The analytical results of the strong motion data suggest that the lack of clearance of the expansion joint caused its damage.

Although the maximum displacement in the X-direction of the main building was less than that in the other directions, the deformation of the expansion joint in the X-direction was larger than that in the Y-direction. It is considered that this was caused by the difference in the natural frequencies of the two buildings. Since the natural frequencies of the two buildings in the Y-direction were close, they were vibrating with almost the same phase. Consequently, the deformation of the expansion joint did not become large. On the other hand, the natural frequencies in the X-direction were quite different between the two buildings. The vibrations of the two buildings with different phases resulted in the large deformation of the expansion joint.

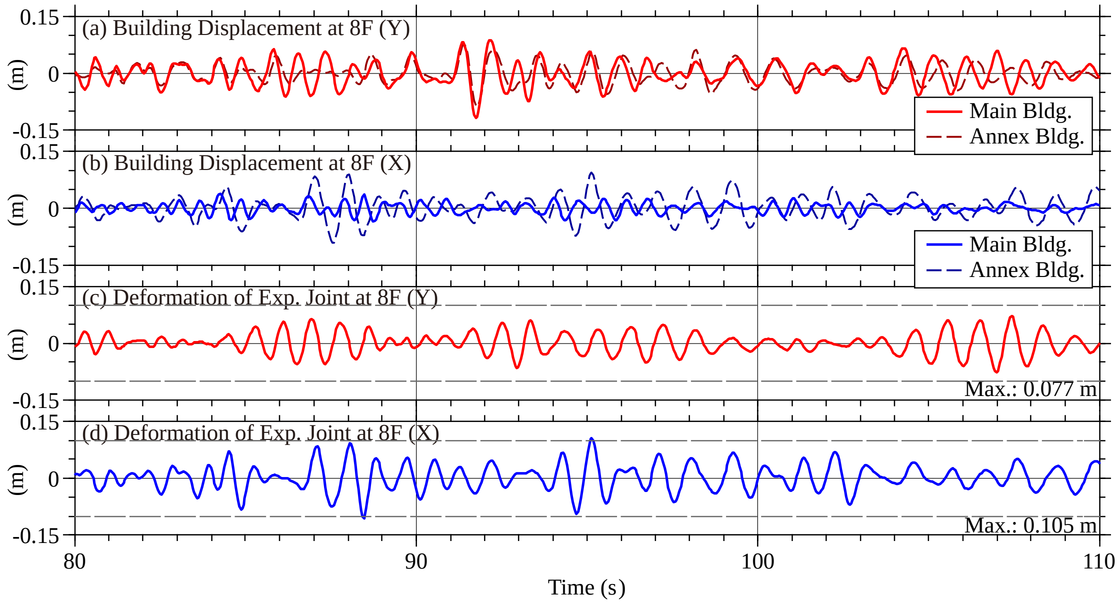


Figure 10. Building displacement and deformation of the expansion joint between the main and annex buildings

RESULTS OF LONG-TERM MONITORING

Long-term observation of strong motion detected an interesting phenomenon. Figure 11 illustrates the change in natural frequencies in the horizontal directions of both buildings for 16 years from the start of observation (Kashima and Kitagawa, 2006a). The upper (a) and lower (b) plots represent the main building and annex building, respectively. Solid red circles (●) and hollow blue triangles (△) indicate the natural frequencies in the Y- and X-directions, respectively.

In the case of the main building, the natural frequencies in both horizontal directions were generally stable until the time of the Great East Japan Earthquake. The damage by the quake reduced the natural frequencies to two-thirds. In the case of the annex building, the natural frequencies gradually decreased during the first seven years. The cause of the decrease is not clear but the natural frequencies seemed to be stable for the next six years. The natural frequencies dropped to about 1 Hz due to the damage by the Great East Japan Earthquake, and have not yet been recovered.

Restoration work on the buildings was carried out in 2012. Cracks on the concrete walls were filled with epoxy resin and splits on the partitioned walls were repaired. However, the work did not recover the stiffness of the buildings.

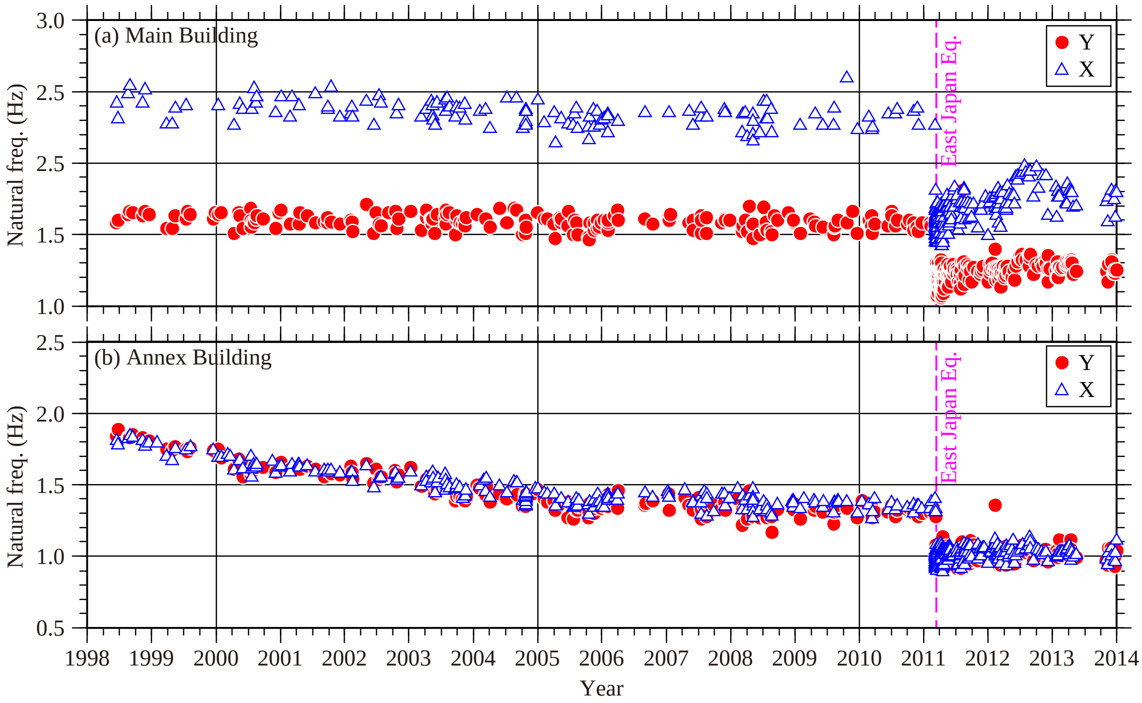


Figure 11. Change in fundamental natural frequencies of the main and annex building with time

CONCLUSIONS

The dynamic behaviour of the main building and annex of the Building Research Institute was investigated in detail based on strong motion data analysis. The earthquake motion of the 2011 Great East Japan Earthquake was remarkably severe and the buildings showed a nonlinear response. The natural fundamental frequencies of the buildings were reduced to about two-thirds during the quake.

Deformation of the expansion joint between the two buildings during the Great East Japan Earthquake was estimated using strong motion data. The deformation of the expansion joint at the eighth floor exceeded 0.1 m. It can be inferred that a lack of clearance of the joint caused the damage to the passageway and expansion joint.

Long-term observation of strong motion detected an interesting phenomenon. Natural fundamental frequencies of the annex building gradually decreased for seven years from the time of completion and then seemed to be stable until the Great East Japan Earthquake. In contrast, there was no significant change in fundamental natural frequencies of the main building from 1998 to the time of the earthquake. When the strong motion instruments were installed in 1998, nearly 20 years had already passed since the completion of the main building.

The strong motion observation has provided useful information on the dynamic behaviour of the buildings, including the nonlinear seismic response. Further detailed study continues today.

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