THE INTERNATIONAL SYMPOSIUM FOR CISMID 25th ANIVERSARY
TECHNOLOGICAL ADVANCES AND LEARNED LESSONS FROM LAST GREAT EARTHQUAKES AND TSUNAMIS IN THE WORLD

Paper No. M-3

PERFORMANCE OF HIGH-RISE BUILDINGS AND SEISMICALLY ISOLATED BUILDINGS AT THE 2011 GREAT EAST JAPAN EARTHQUAKE

Taiki SAITO[1], Izuru OKAWA[1] and Toshihide KASHIMA[1]

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. Also, from the site investigation, seismically isolated buildings showed excellent performance without any severe damage even to nonstructural elements in superstructure. However, some damage to isolation dampers and expansion joints were observed. This paper summarizes the performance of high-rise buildings and seismically isolated buildings during the earthquake.

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 as shown in Figure 1.

From the records, it was found that the high-rise buildings shook largely because of the effect of long period component of earthquake ground motions. Especially, a high-rise building in the city of Osaka, 770 km away from epicenter, 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.

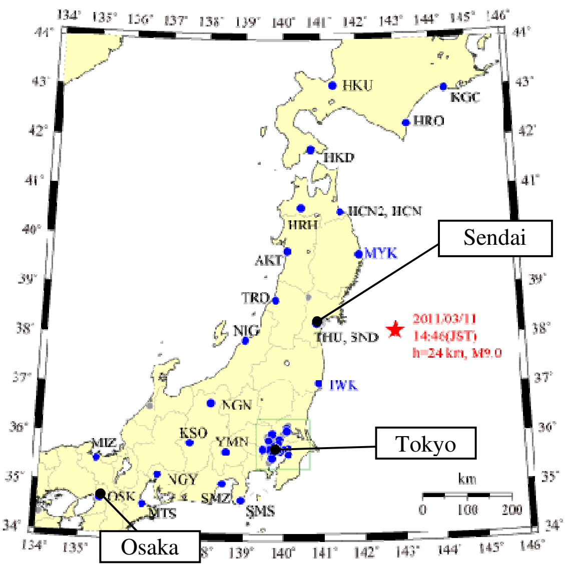


Figure 1. Location of stations

1 Building Research Instititute, Email: tsaito@kenken.go.jp, okawa@kenken.go.jp, kashima@kenken.go.jp

After the 2011 Great East Japan Earthquake, an investigation team consisted by the members from NILIM (National Institute of Land, Infrastructure and Management) and BRI (Building Research Institute) was dispatched to the disaster areas on July 1st and 2nd to examine performance of SI buildings. The seismically isolated buildings showed excellent performance without any severe damage even to nonstructural elements in superstructure. However, some damage to isolation dampers and expansion joints were observed. This paper introduces some cases to explain seismic performance of seismically isolated buildings.

PERFORMANCE OF HIGH-RISE BUILDINGS

Input ground motion and response of high-rise buildings

Table 1 shows the list of high-rise buildings under observation located in Sendai, Tokyo and Osaka and the maximum acceleration values observed in the 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	Sendai	S	Normal	B2F 15F	175	B2F	163	259	147
						15F	361	346	543
B	Tokyo	RC	Normal	37F	385	01F	87	98	41
						18F	118	141	64
						37F	162	198	108
C	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

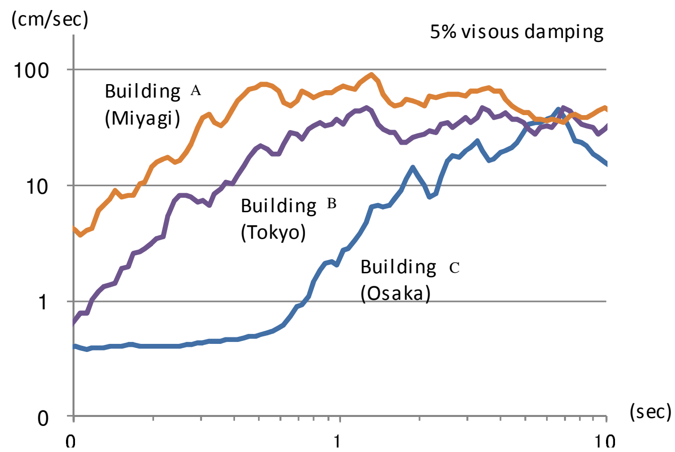
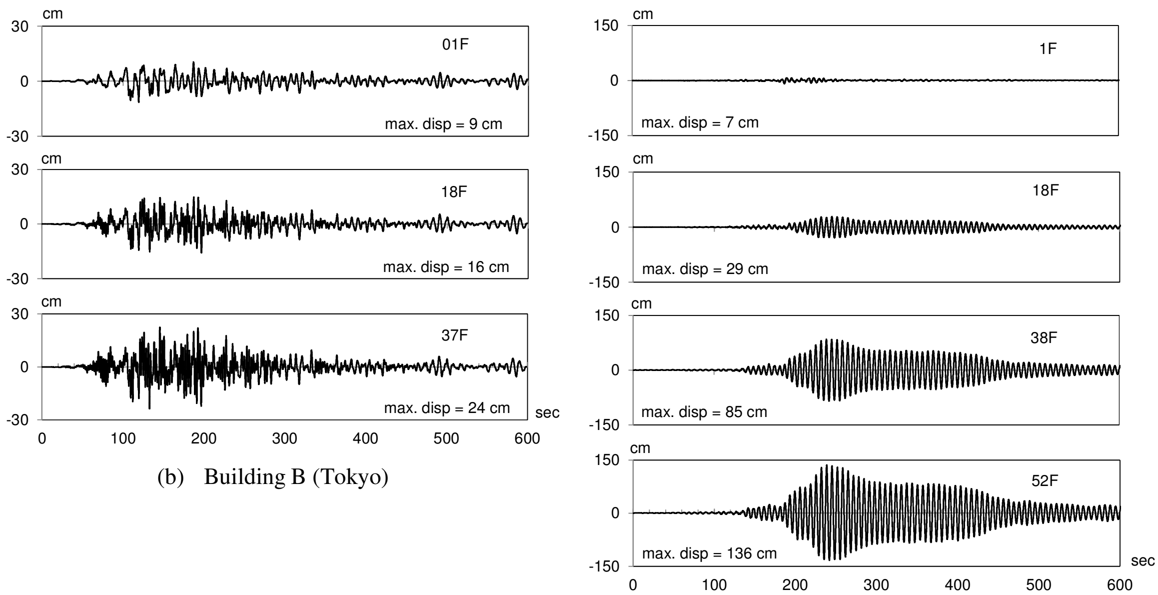


Figure 2. Velocity response spectra

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 B in Tokyo, 385 km away from the epicentre, was 24 cm, the large floor movement of 136 cm amplitude was observed at the 52nd floor of Building C 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.



(b) Building B (Tokyo)

(a) Building C (Osaka)

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

Figure 4 shows the Fourier spectra of acceleration records observed at 1st , 18th and 37th floor of the high-rise building B in Tokyo. The spectra of the records at 18th and 37th floors have two peaks which correspond to the first and second mode vibrations. Minor damage around the entrance of each residential unit was observed as shown in Figure 5. The number of units which suffered damage was counted in each floor and it is seen that the damage distributes in the medium floors. This fact suggests the effect of second mode vibration.

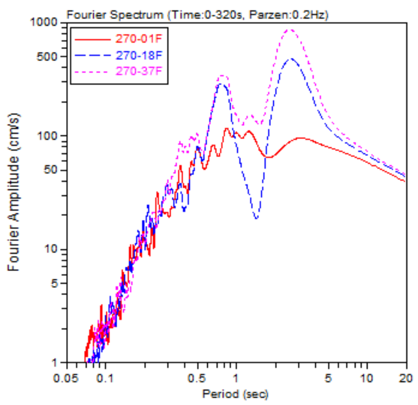


Figure 4. Fourier spectrum (Building B)

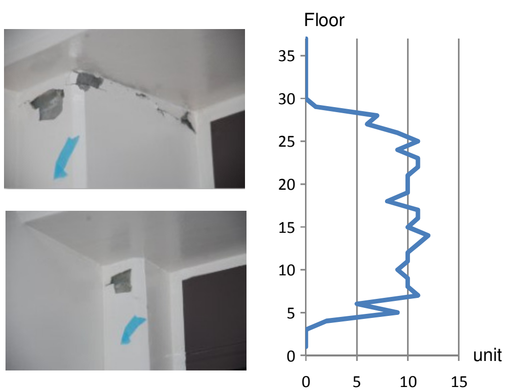


Figure 5. Damage distribution in each floor

Vibration characteristics of high-rise buildings

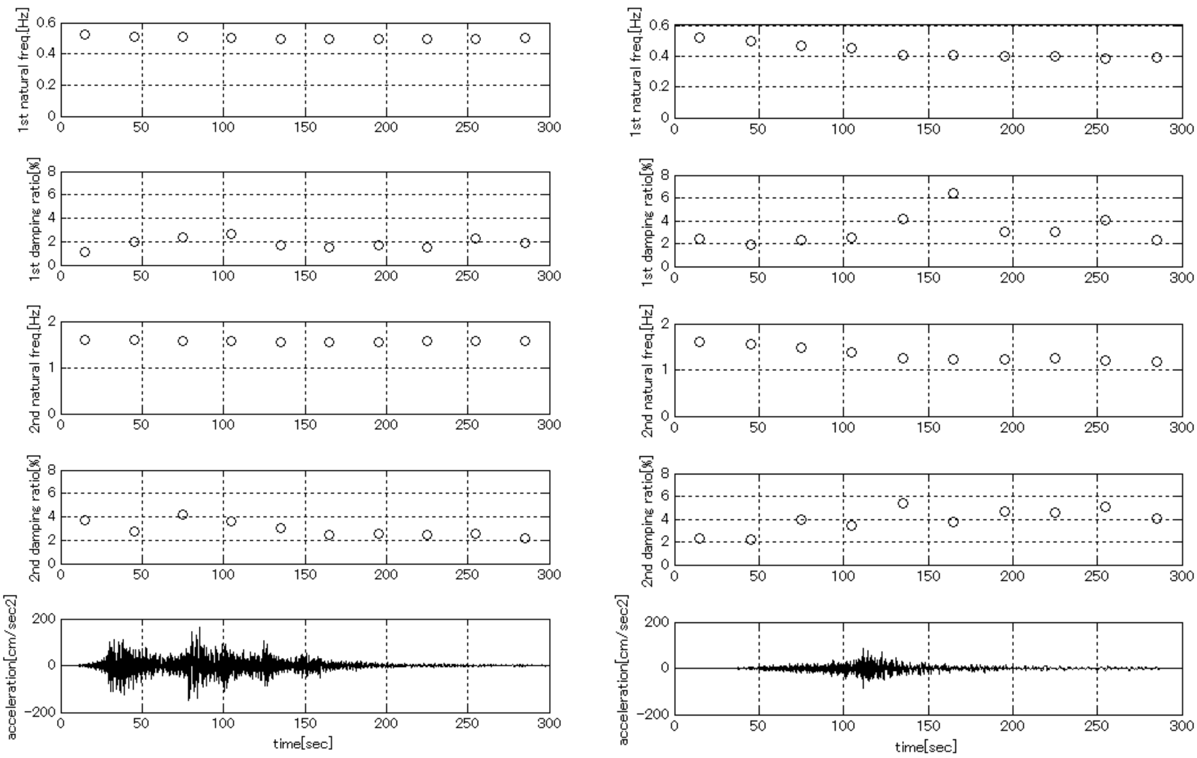
Using strong motion records observed at the main shock of the 2011 Great East Japan Earthquake, the vibration characteristics of high-rise buildings were identified. The N4SID (Numerical algorithm for Subspace based State-Space System Identification) method was used for this analysis.

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 6-(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)Vibration characteristics of reinforced concrete high-rise building (Building B)

Building B is a 37-story reinforced concrete building built in Tokyo, and seismic dampers are not installed in the building. Figure 6-(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. 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 6. Change of vibration characteristics of high-rise buildings during the earthquake

PERFORMANCE OF SEISMICALLY ISOLATED BUILDINGS

Reflecting high consciousness of earthquake risks in Miyagi Prefecture and nearby areas in Tohoku region, Japan, there are many seismically isolated buildings (hereinafter referred to as SI buildings) have been constructed in those areas. Table 2 shows the list of SI buildings investigated by NILIM and BRI. The list contains the JMA (Japan Meteorological Agency) seismic intensity (from 0 to 7) near the building. Most buildings in the list suffered severe ground motion with the intensity more than 6 minus.

Table 2. List of SI buildings investigated on July 2nd and 3rd in 2011

	Usage	Structural type and number of floors	Existence of scratch board	Existence of earthquake record	JMA Seismic Intensity near the building
D	Office	SRC, 9F+B2F	○	○	6 minus
E	Warehouse	S, 1F	○		6 minus
F	Condominium	RC, 14F			6 minus
G	Condominium	RC, 12F			6 minus
H	Condominium	RC, 15F	○		6 minus
I	Condominium	RC, 10F			6 minus
J	Hospital	RC, 6F			6 minus
K	Office	RC, 18F +B2F	○	○	6 minus
L	Hotel	RC,12F			6 plus
M	Firehouse	S, 3F			6 plus
N	Hospital	RC, 5F			6 plus
O	Firehouse	RC, 3F	○		6 minus – 6 plus
P	Hospital	S, 6F	○		5 plus
Q	Firehouse	RC, 3F	○		5 plus - 6 minus
R	Hospital	RC, 4F			6 minus
S	Hospital	RC, 10F		○	4
T	Hospital	SRC, 4F	○		5 plus

(SRC: steel reinforced concrete, RC: reinforced concrete, S: steel)

Summary of investigation

Investigation results of 16 SI buildings in Miyagi-Prefecture and one SI building in Yamagata-Prefecture is summarized as follows:

a) Super-structures of SI buildings suffered almost no damage even under strong shaking with JMA intensity 6 plus. It verifies the excellent performance of SI buildings.
b) In some buildings, damage was observed at the expansion joints. It seems that parts of expansion joints were not well operated due to the large displacement of SI floor during earthquake (Figure 7).
c) Subsidence of ground around the building was observed in some buildings.
d) Many cracks were found in lead dampers. These cracks might be increased by the aftershocks (Figure 8).
e) Peeling off of paint was observed widely for U-shape steel dampers. In some cases, residual deformation of steel was remained (Figure 9).

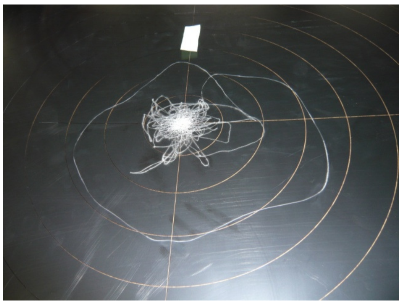
Figure 7. Damage at the expansion joints

Figure 8. Cracks in lead dampers

Figure 9. Peeling off of paint of steel dampers

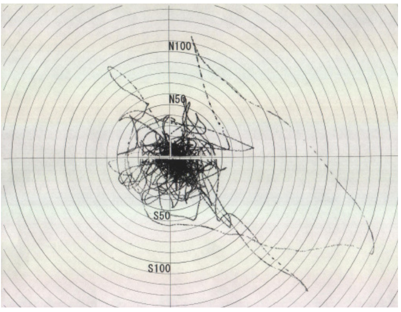
Records of seismically isolated buildings

There are 8 buildings with scratch boards to measure displacement of the SI floor. As shown in Figure 10, in most cases, the maximum displacement has been estimated around 20 cm. There is a one case with the maximum displacement estimated over 40 cm. For two buildings, there are accelerometers in the building and the observed maximum accelerations are listed in Table 3. Around 40-60% reduction was achieved by SI system.

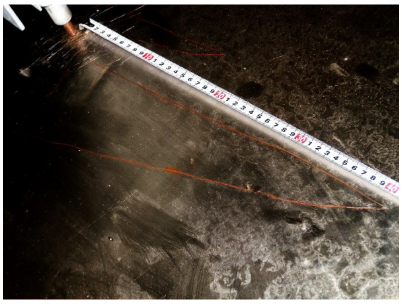


(a) Around 18cm (Building D)

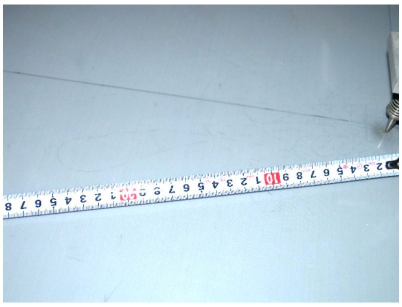
(b) Around 21cm (Building E)



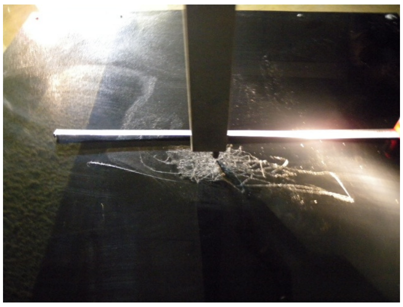
(c) Around 21cm (Building J)



(d) Around 40cm (Building O)



(e) Around 25cm (Building P)



(f) Around 25cm (Building Q)

Figure 10. Maximum displacement from the scratch boards

Table 3. Maximum acceleration observed below and above the isolation floor

	Building B		Building K	
	X direction	Y direction	X direction	Y direction
Below SI floor	250.8 (100.0)	289.0 (100.0)	310.8 (100.0)	225.8 (100.0)
Above SI floor	143.7 (57.3)	120.5 (41.7)	173.0 (55.7)	142.9 (63.3)

Unit: gal (the percentage of reduction by SI is shown in the blancket)

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 epicenter, 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. From the acceleration records observed in a building, it was found out that the natural frequency and the damping factor varied during the earthquake. Especially, 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.

Seismically isolated buildings showed excellent performance without any severe damage even to nonstructural elements in superstructure. However, some damage to isolation dampers and expansion joints were observed.

REFERENCES

1. National Institute for Land and Infrastructure Management (NILIM) and Building Research Institute (BRI) , Summary of the Field Survey and Research on "The 2011 off the Pacific coast of Tohoku Earthquake" (the Great East Japan Earthquake), September, 2011, http://www.kenken.go.jp/english/contents/topics/20110311/0311summaryreport.html

.