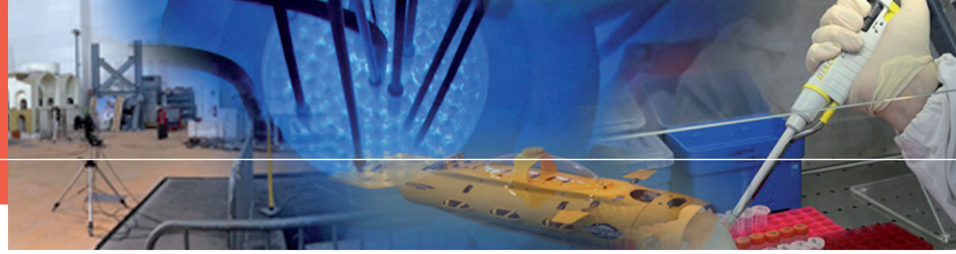

Behavior of response controlled and seismically isolated buildings during severe earthquakes in Japan

Passive control techniques have been widely used in Japan since the 1995 Kobe earthquake. Until the end of 2011, nearly 3000 buildings and 4000 private houses are seismically isolated. The 2011 Great East Japan Earthquake, which caused casualties more than 18300 people and collapse of 127830 building, allowed testing the effective seismic performance of several base isolated buildings. This is quite important for further dissemination of response control and seismic isolation technologies and to prove their effectiveness

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Introduction

The Great East Japan Earthquake

The 2011 Great East Japan Earthquake with a magnitude 9.0 (Mw) occurred at 14:46 for the local time on Friday, 11 March 2011 in Japan. This earthquake triggered destructive tsunami waves which caused extensive damage to the coastal areas in Tohoku region. The National Police Agency has confirmed 15891 deaths, 6152 injured and 2584 people missing as of April 10, 2015. More than 92 percentages of casualties are caused by Tsunami. The number of casualties caused by building collapse, landslides, drop of ceiling panels, etc. from earthquake shaking effect is reported more than 90. Building damage is reported as 127830 total collapses and 275791 partial collapses.

Figure 1 shows the distribution of peak ground acceleration (PGA) recorded during the earthquake, summarized by Earthquake Research Institute (ERI), the University of Tokyo. The K-NET Tsukidate station near the epicentre recorded the PGA of 2699 cm/s^2 in the N-S direction. Strong motions with PGA larger than 200 cm/s^2 were observed over a very wide area in Tohoku. Tokyo is located 300 km away from the epicentre and its stations recorded the PGA of 50 to 150 cm/s^2.

Response of high-rise buildings under long period ground motion

The Building Research Institute (BRI) has been conducting strong motion observation for buildings since 1957. At the 2011 Great East Japan Earthquake, strong motion records were collected at 54 stations. Table 1 shows the list of high-rise buildings under observation in Sendai, Tokyo and Osaka and the maximum acceleration values observed in these buildings (Saito, 2012). Figure 2 shows the velocity response spectra of horizontal records at the lowest floor of the buildings. The velocity spectra of Miyagi and Tokyo have strong component in the wide band period from 0.5 to 10 second. On the other hand, the response spectrum of Osaka has a dominant period around 6 second which corresponding to the predominant period of the long period ground motions occurred in the deep sedimentary plain in Osaka.

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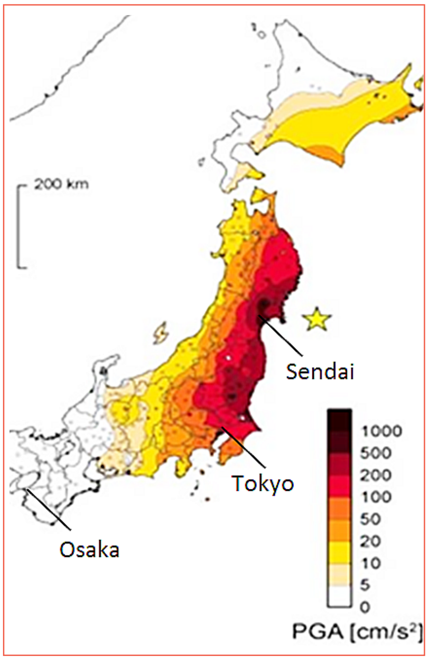

FIGURE 1 Peak ground acceleration recorded at the 2011 Great East Japan Earthquake
Source: ERI, University of Tokyo

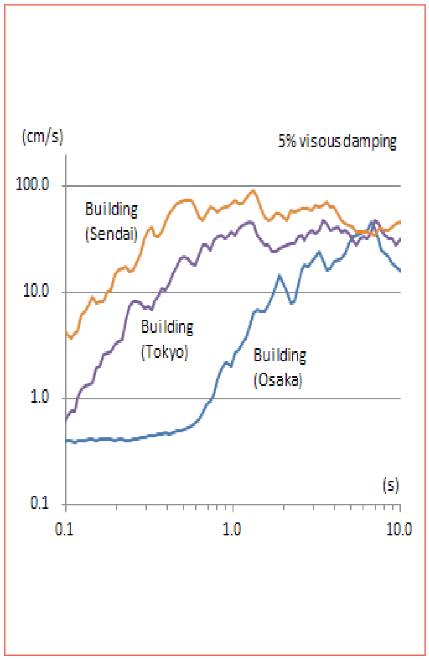

FIGURE 2 Velocity response spectra of the records observed at the lowest floor of high-rise buildings in Japan

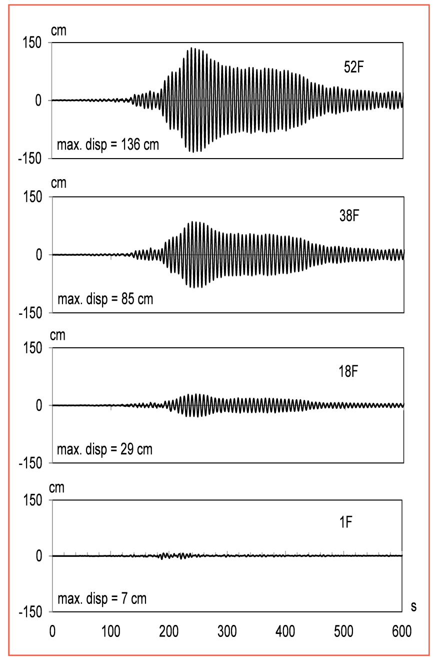

FIGURE 3 Displacement records of the high-rise building in Osaka

LOCATION	STRUCTURAL TYPE	FLOOR	Δ (KM)	LOCATION OF SENSORS	ACC. (CM/S²)		
					H1	H2	V
Sendai	S	B2F 15F	175	B2F	163	259	147
				15F	361	346	543
Tokyo	RC	37F	385	01F	87	98	41
				18F	118	141	64
				37F	162	198	108
Osaka	S	52F P3F	770	01F	35	33	80
				18F	41	38	61
				38F	85	57	18
				52FN	127	88	13
				52FS	129	85	12

TABLE 1 Observed acceleration records at high-rise buildings (From BRI). S: steel, RC: reinforce concrete; Δ: epicentral distance, H1, H2: horizontal components, V: Vertical component

Figure 3 shows the displacement records of the high-rise building in Osaka. Even Osaka is located 770 km away from the epicentre, the large floor movement of 136 cm amplitude was observed at the 52th floor. By this shaking, extensive damage to non-structural elements such as falling of gypsum boards and ceiling panels were observed. The building has no passive damper inside.

Performance of seismically isolated buildings

Profile of Seismically Isolated Buildings in Japan

The number of seismically isolated buildings increased after the 1995 Kobe Earthquake. Half of the buildings are condominiums and 15% of the buildings are hospitals. Figure 4 shows the latest statistics of seismically isolated buildings from the database of JSSI (Japan Society of Seismic Isolation). The construction of seismically isolated detached houses was increased tremendously after year 2000 when the new regulation was issued to approve not the individual design of houses but the manufacture of the specific type of construction to streamline the inspection process.

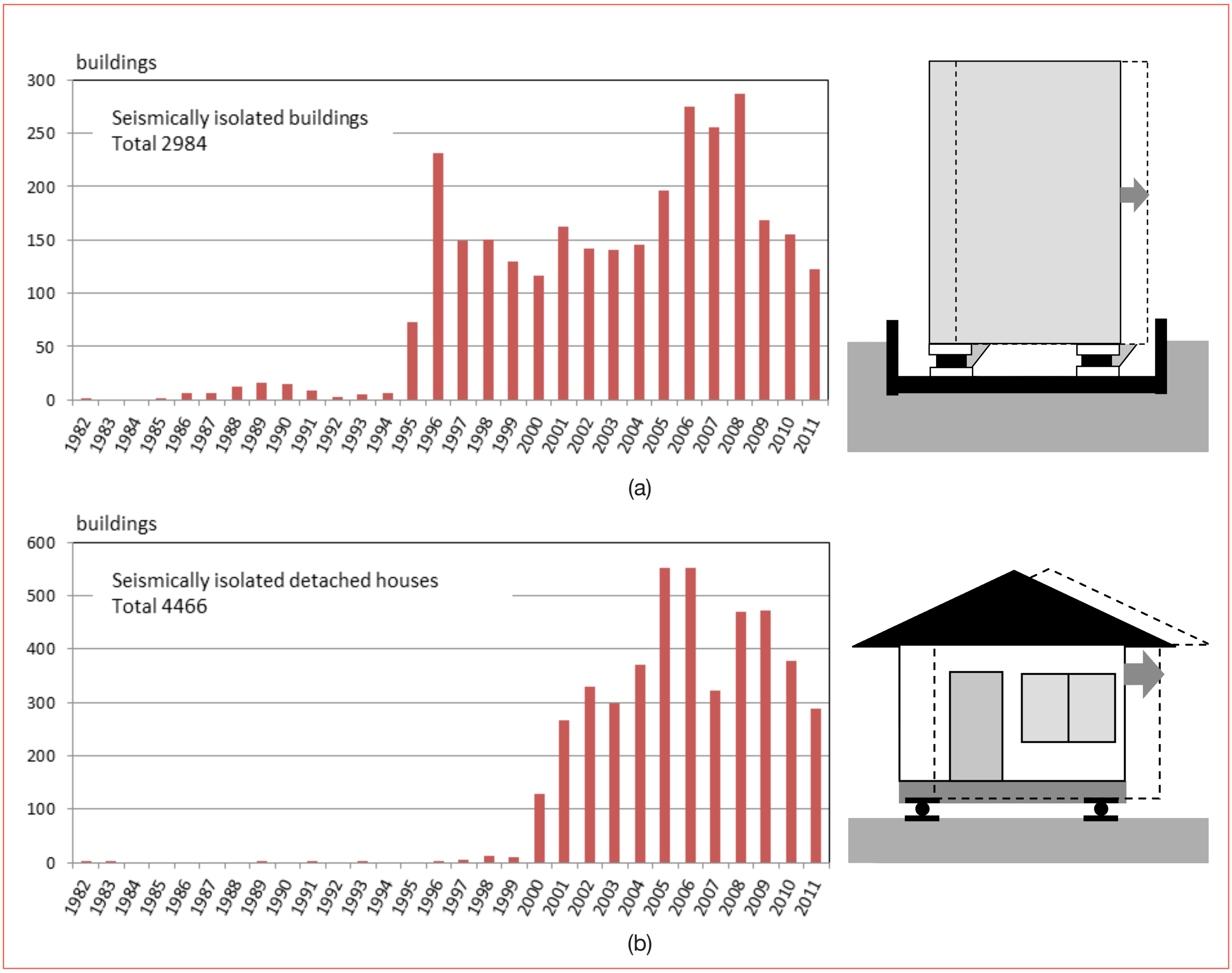

FIGURE 4 Statistics of seismically isolated buildings in Japan (from JSSI). (a) Buildings; (b) Private houses

Performance of Seismically Isolated Buildings during the 2011 Great East Japan Earthquake

Table 2 summarizes the list of seismically isolated (SI) buildings with instrumentation of sensors (Iiba 2013). The maximum acceleration values at different floor levels (under SI, above SI and top floor) and the maximum displacement of SI floor are listed in the table. Those buildings are located in the range of epicentre distance from 172 km to 457 km. The ratios of the maximum acceleration between the foundation (under SI) and superstructure (above SI and top floor) are plotted in Figure 5. For horizontal acceleration in Figure 5-(a), the ratio decreases as the maximum acceleration at the foundation increases. It certifies excellent performance of seismically isolation system to reduce the horizontal acceleration of superstructure. On the other hand, as shown in Figure 5-(b), the vertical acceleration is amplified in superstructure and the ratio is over 1.0. Figure 6 shows the trajectory of displacement of SI floor on the plane.

	Site	Usage	Structure Type	Floor	Δ (km)	Main isolator and damper	Location of Sensors	ACC. (CM/S²)			Disp. of SI (cm)
								X	Y	Z	
KA	Sendai	Office	SRC	B2F 9F	172	HRB	*under SI* *above SI* *top floor*	289 121 142	251 144 170	235 374 524	15.7
KB	Fukushima	Office	RC	2F	178	NRB, LRB, OD	*under SI* *above SI* *top floor*	582 176 155	756 213 185	446 516 621	24.6
KC	Fukushima	Office	RC	3F	184	unknown	*under SI* *above SI* *top floor*	411 184 154	334 226 157	324 463 581	5.8
KD	Tsukuba	Office	PcaPC	7F	334	NPB, LRB, SD	*under SI* *above SI* *top floor*	327 92 126	233 76 91	122 198 243	6.8
KE	Tokyo	Musium	RC	B1F 3F	382	HRB	*under SI* *above SI* *top floor*	100 76 100	79 89 77	84 87 90	4.2
KF	Tokyo	Office	RC	B2F 12F	386	NRB, LRB	*under SI* *above SI* *top floor*	104 55 94	91 41 82	58 62 104	5.1
KG	Kawasaki	Residence	PcaPC	6F	401	NRB, LRB	*under SI* *above SI* *top floor*	86 58 63	104 65 68	34 49 55	5.22
KH	Odawara	Office	RC	6F	457	NRB, LRB	*under SI* *above SI* *top floor*	136 58 63	120 134 67	47 47 48	25.2

TABLE 2 Observed records of seismically isolated buildings (Iiba 2013). SI: seismic isolation floor, PcaPC: precast prestreesed concrete; NRB: natural rubber bearing, HRB: high damping rubber bearing, OD: oil damper, SD: stee; damper

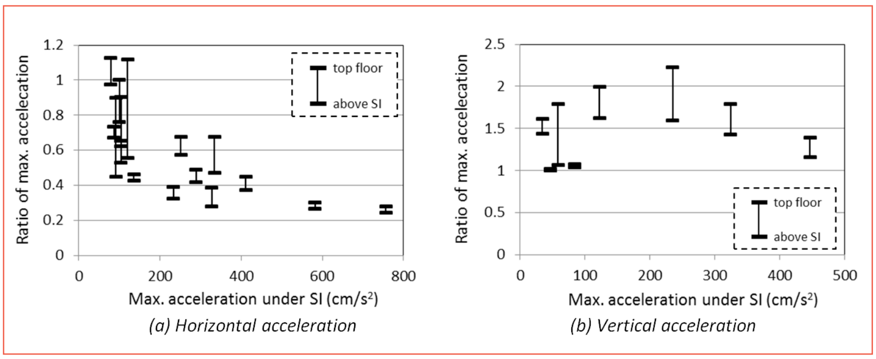

FIGURE 5 Maximum acceleration ratio of superstructure to foundation

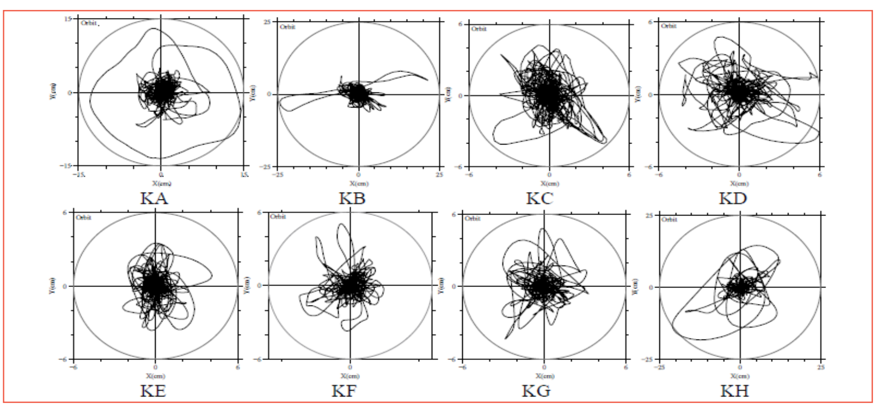

FIGURE 6 Trajectory of displacement at SI floor on the plane (Iiba 2013)

After the 2011 Great East Japan Earthquake, the Japan Society of Seismic Isolation (JSSI) conducted a questionnaire survey for 327 seismically isolated buildings including 19 detached houses. It is reported that superstructures of all seismically isolated buildings suffered almost no damage even under strong shaking with JMA intensity 6 plus. It proved the excellent performance of seismically isolated buildings. On the other hand, various damages were observed in seismic isolation devices (Saito 2013). For example, many cracks were found in lead dampers (Photo 1) which might be increased by the aftershocks. Loose of the bolts, peeling off the paint and residual deformation were observed for steel dampers (Photo 2). Minor damage to expansion joints between SI floor and superstructure was found extensively (Photo 3).

Performance of Response controlled high-rise buildings

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

Passive energy dissipation dampers including viscous dampers, oil dampers, viscoelastic dampers, steel dampers and friction dampers have been widely adopted for buildings in Japan in recent years. Especially, after the 1995 Kobe earthquake, it has become standard to install passive dampers in steel high-rise buildings to reduce and attenuate

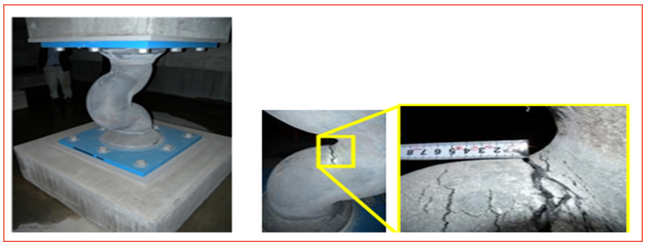

PHOTO 1 Crack on the surface of a lead damper

PHOTO 2 Deformation of U-shaped steel damper

PHOTO 3 Damage to cover panel

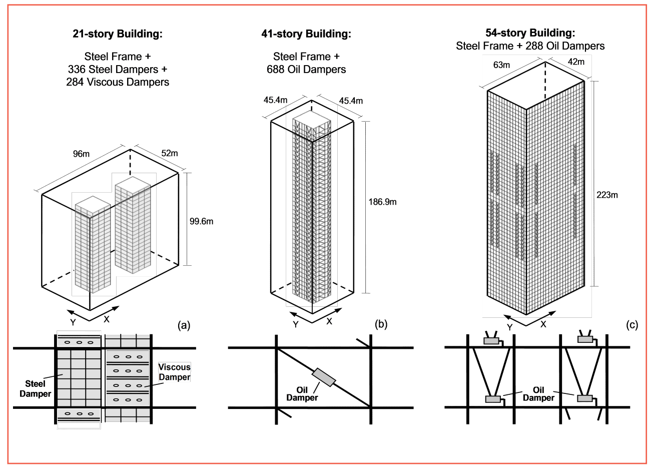

FIGURE 7 Three response controlled buildings with velocity-dependent dampers (Kasai 2012)

shaking of the buildings during earthquakes. However, real performance of buildings with passive dampers has not been proven due to the lack of observation date. At the 2011 Great East Japan Earthquake, valuable observation data were obtained in several buildings with passive dampers which could be one of the best resources to study the effect of dampers.

Kasai et al. (2012, 2013a, 2013b) studied responses of tall buildings in Tokyo during the 2011 Great East Japan Earthquake. Figure 7 shows three high-rise buildings selected in the study. A 21-story building consists of a steel frame and 336 low yield point steel wall dampers and 284 viscous wall dampers. The first natural period of the building is 1.83 second in X-direction and 1.97 second in Y-direction. A 41-story office building consists of a frame using concrete-filled tube columns and steel beams, and 688 oil dampers. The first natural period of the building is 3.97 second in X-direction and 4.10 second in Y-direction. A 54-story office steel building constructed in 1979. It was retrofitted in 2009 by attaching 288 oil dampers. The first natural period of the building is 5.37 second in X-direction and 6.43 second in Y-direction. It is reported that modal superposition up to the 3rd mode is valid to simulate the time histories of acceleration and displacement from the comparison of observed data (Kasai 2012). Responses at the top floor calculated by modal superposition methods are shown

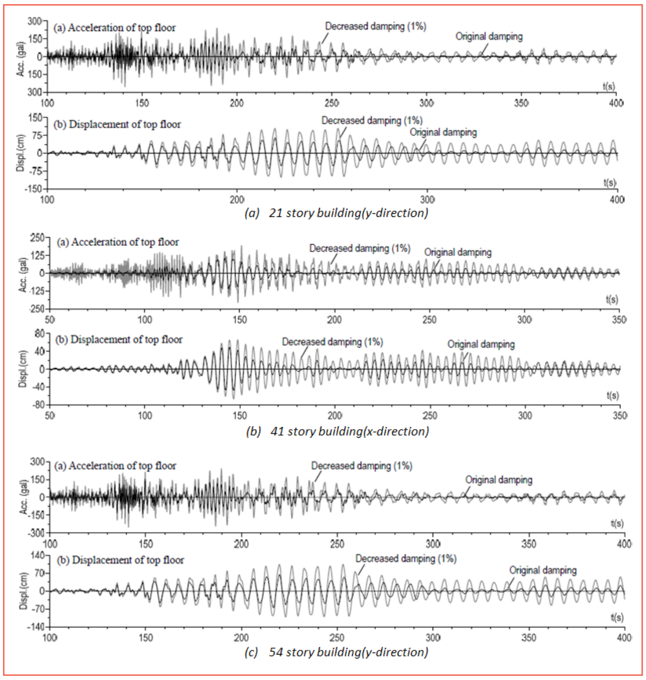

FIGURE 8 Building responses with original and decreased damping ratios (Kasai 2012)

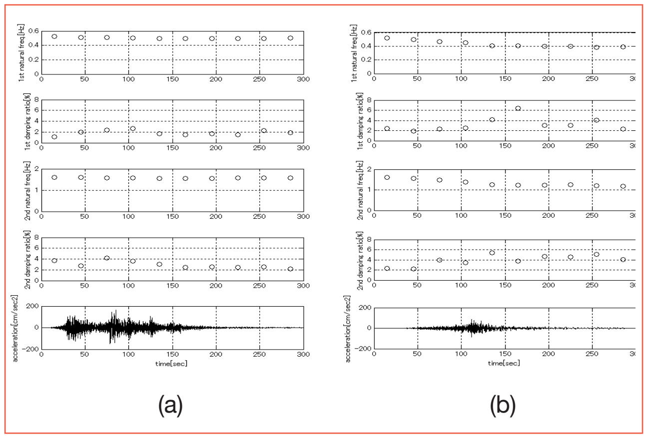

FIGURE 9 Change of vibration characteristics of high-rise buildings during the earthquake (Saito 2012).
(a) Steel building in Sendai (H1 direction); (b) Reinforced concrete building in Tokyo (H1 direction)

by black lines in Figure 8. The responses are compared with those of decreased damping ratio shown by grey lines which represent a hypothetical case of not using the dampers (by Kasai). In all three buildings, the responses with damper (black lines) are considerable smaller than those without dampers.

It is worth to mention about the vibration characteristics of high-rise buildings without dampers. For the high-rise buildings listed in Table 1, the first and second natural frequencies and damping factors are identified for every 30 sec in the observation records at the top of the building by the N4SID (Numerical algorithm for Subspace based State-Space System Identification) method (Saito 2012). Figure 9-(a) shows the results of identification of a 15 story steel building in Sendai. 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%. Damage of structural members has not been reported. Figure 9-(b) shows the results of identification of a 37 story reinforced concrete building in Tokyo. 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. Minor damage of slight concrete crack was reported on the non-structural walls.

Response control using passive dampers is suitable for steel buildings because of large deformation capability and small viscous damping. However, it is not suitable for reinforced concrete buildings because of small deformation capability. In other words, for reinforced concrete buildings, small damage such as concrete cracks works to increase damping effect instead of dampers.

Conclusions

Responses of the response controlled and seismically isolated buildings during the 2011 Great East Japan Earthquake are discussed based on the strong motion observation records.

It was proved that superior performance of seismically isolated buildings made it possible not only to reduce the damage of structures but also to protect occupants and contents. Even in the affected areas, hospitals with seismic isolation system succeeded to continue medical operation after the earthquake.

Also the effectiveness of response control techniques using passive dampers in steel high-rise buildings were verified by analysing observation records using the modal superposition method (Kasai 2012, 2013b).

A massive earthquake with a magnitude 9.0 is believed to occur in the near future in southwest of Japan. In order to protect cities and buildings against this earthquake, there is a need for further dissemination of response control and seismic isolation technology.

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