OBSERVED RESPONSE OF SEISMICALLY ISOLATED BUILDINGS DURING THE 2016 KUMAMOTO EARTHQUAKE

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Abstract

In Japan, there are more than 4000 seismically isolated buildings; the number does not include detached houses. The seismic isolation technology applies to office buildings, condominiums, hospitals and detached houses. To obtain the optimum isolation effect, various devices (rubber bearings, sliding bearings, roller bearings, hysteresis dampers, oil dampers, etc.) are used in combination. The 2016 Kumamoto earthquake is an extremely rare case, because Magnitude 6.5 and 7.3 earthquakes hit Kumamoto and Oita Prefecture within 28hours. There are 24 seismically isolated buildings in Kumamoto Prefecture at that time. The seismically isolated buildings indicated excellent performances during the earthquakes. They protected people, buildings and other important facilities from damages caused by the earthquake. We introduce the behavior of seismically isolated buildings during the earthquakes.

Introduction

Earthquakes have lately been active along the Japanese archipelago. After the1995 Hyogo-ken Nanbu Earthquake (magnitude M of 7.3), the 2000 Western Tottori Earthquake (M 7.3), 2004 Niigaka-ken Chuetsu Earthquake (M 6.8), 2011 Great East Japan Earthquake (M 9.0) followed in succession until the Kumamoto Earthquakes in 2016.

After the Kumamoto Earthquakes, the Architectural Institute of Japan (AIJ) Kyushu Chapter established the Disaster Survey Committee (chaired by M. Takayama, Prof. of Fukuoka University). The Disaster Survey Committee was composed of members of the Structural Committee (chaired by Kenji Kikuchi, Prof. of Oita University) and Disaster Committee (chaired by M. Takayama) of the AIJ Kyushu Chapter. Largely, the Disaster Survey Committee organized survey teams for each type of structure and surveyed building damage in coordination with the AIJ Central Committee. Aside from these undertakings, the committee conducted a comprehensive survey (a survey of all building structures) in Mashiki Town, which had heavily damaged wood-frame houses, around areas that were hit particularly hard.

While serious damage to buildings was confirmed in many places in Kumamoto and Oita prefectures, buildings with seismically isolated structures, seismically isolated buildings, kept residents and users safe, and could continue to be used without any problems after the earthquakes. When the Kumamoto earthquakes occurred, there were 24 seismically isolated buildings, including 4 under construction, in Kumamoto Prefecture.

We introduce the behavior of seismically isolated buildings, and the lessons learned from these surveys are discussed here.

Summary of the Earthquake

A magnitude (M) 6.5 earthquake struck at 21:26 JST on April 14, 2016 at a depth of about 10 km beneath the Kumamoto region in Kumamoto Prefecture. Another M 6.4 earthquake occurred at 00:03 midnight on

April 15, and another M 7.3 earthquake struck at 1:25 JST on April 16. The April 14 earthquake was later pronounced as a "foreshock" earthquake while the April 16 ground motion was the "mainshock." A maximum intensity of 7 (on the Japan Meteorological Agency, JMA, Seismic intensity scale) was recorded in Kumamoto Prefecture from these earthquakes, and tremendous damage was caused. The areas close to the active fault zone of the Kumamoto Earthquakes: Mashiki Town, Nishihara Village and Minamiaso Village, in particular, incurred severe damage.

Figure 1 shows the epicenters of the Kumamoto Earthquakes and the distribution of fissures appearing on the ground surface. Most of the fissures occurred along the Futagawa fault zone. The largest earthquake on April 16th is believed to have been caused by activity in the Futagawa fault zone. The probability of an earthquake occurring within the next 30 years in this zone had been assessed to be between 0% - 0.9%. According to announcements by the Kumamoto Prefecture (as of January 13, 2017), 50 people lost their lives due to causes such as building collapse, and if deaths from related causes such as the burden of living in shelters are included, a total of 181 people died from the series of earthquakes in Kumamoto. For residential structures, 8,373 completely collapsed, 32,593 partially collapsed, and 139,637 were partially damaged. The number of evacuees peaked at 183,882 on April 17, 2016.

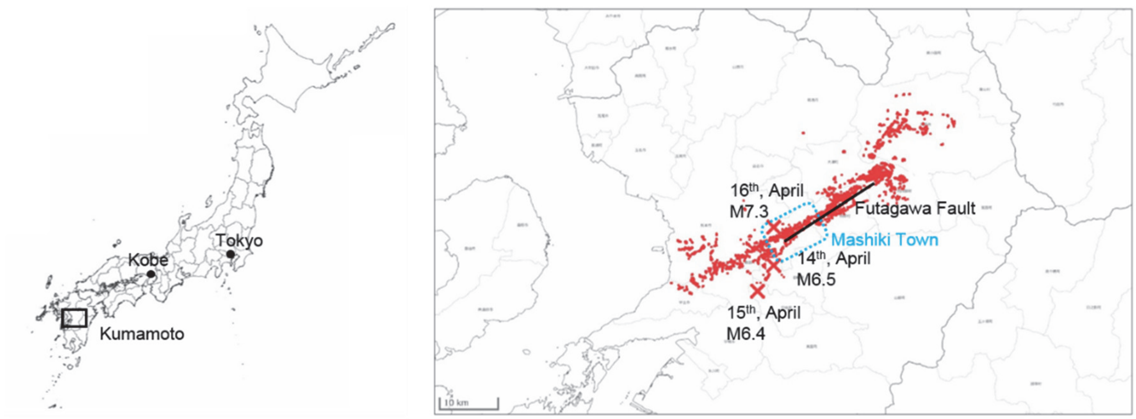


Figure 1. Epicenters of the Kumamoto Earthquakes and distribution of fissures appearing on the ground surface (processed Geospatial Information Authority of Japan (GSI) data [1]).

Figure 2 is the acceleration response spectrum (at 5% damping) based on the mainshock (EW component) records measured at Mashiki Town [2]. In the figure, MTO is a seismograph installed at the Mashiki Town Office, while KiK-net Mashiki (KIK), which is operated and maintained by the National Research Institute for Earth Science and Disaster Resilience (NIED), is installed around 650 m north of Mashiki Town Office. TMP1, TMP2 and TMP3 are observation points temporarily set up by Hata et al., and were able to record the April 16 ground motion [3].The solid black line shows the Building Standards Law spectrum specified for engineering bedrock, while the dotted black line is the same spectrum multiplied by 2 for ground surface equivalent to ground type 2 (zoning coefficient Z = 1.0). The observation record for TMP3, was taken in a district where the building collapse rate was high. Based on this spectrum, it can be seen that larger tremors were measured in a southward direction from KIK to TMP1, and then to TMP3. Also, it can be seen that large input seismic motion occurred at Mashiki Town, exceeding the ground motion given in the Building Standards Law.

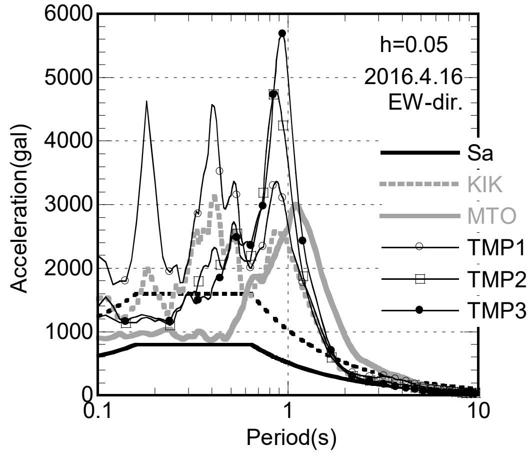


Figure 2. Acceleration response spectrum for observation records at Mashiki Town [2][3] (April 16 mainshock record, EW component).

Response of Seismically Isolated Buildings

While serious damage to buildings was confirmed in many places in Kumamoto and Oita prefectures, buildings with seismically isolated structures, seismically isolated buildings, kept residents and users safe, and could continue to be used without any problems after the earthquakes. Most of the buildings with seismic-resistant structures, seismic-resistant buildings, avoided collapse, but sustained damage such as furniture falling over, light fixtures falling down, service pipes rupturing, and cracks appearing in columns, beams, and walls.

When the Kumamoto earthquakes occurred, there were 24 seismically isolated buildings, including 4 under construction, in Kumamoto Prefecture, and we surveyed 17 of these. Table 1 shows a summary of the seismically isolated buildings in Kumamoto Prefecture, and Table 2 shows a summary of the surveyed buildings. Most are apartment buildings, followed by medical facilities, offices, and warehouses. There are some seismically isolated single-family houses in Kumamoto Prefecture. But, unfortunately, we could not identify any of them. We visually checked the inside and outside of the building and the isolation level, and at the same time, interviewed the building's users and managers.

During the earthquakes of seismic intensity 7 that occurred in succession in Kumamoto, the seismically isolated buildings demonstrated their capabilities by functioning extremely well. A scratch plate, like a Figure 4, which allow the movements of a building to be recorded by marking scratches on a metal plate, had been installed in 8 of the buildings, and this made it possible to confirm the movements of these buildings during the earthquakes.

Table 3 shows maximum amplitudes of recorded on the scratch plates. A maximum double amplitude of 90 cm and a maximum single amplitude of 46 cm were recorded at Medical Facility **M** in Aso City as shown in Figure 3. Figure 5 show the orbit recorded by mainshock of the earthquake. The amount of deformation recorded at Medical Facility **M** is the largest for a seismically isolated building so far. There was almost no residual deformation in any of the buildings, and no defects were identified in the seismic isolation devices.

Table 1. A Summary of the Seismically Isolated Buildings in Kumamoto Prefecture

<table>
<tr><td>Uses</td><td colspan="3">Apartment
12</td><td colspan="2">Hospital
7</td><td colspan="2">Office or Warehouse
5</td></tr>
<tr><td>Story</td><td>1-4 stories
3</td><td>5-10 stories
6</td><td colspan="5">11-15 stories
15</td></tr>
<tr><td>Location (City)</td><td colspan="4">Kumamoto
18</td><td>Yamaga
2</td><td>Yatsushiro
2</td><td>Others
2</td></tr>
</table>

*Figure 3. Photo of Medical Facility **M**.*

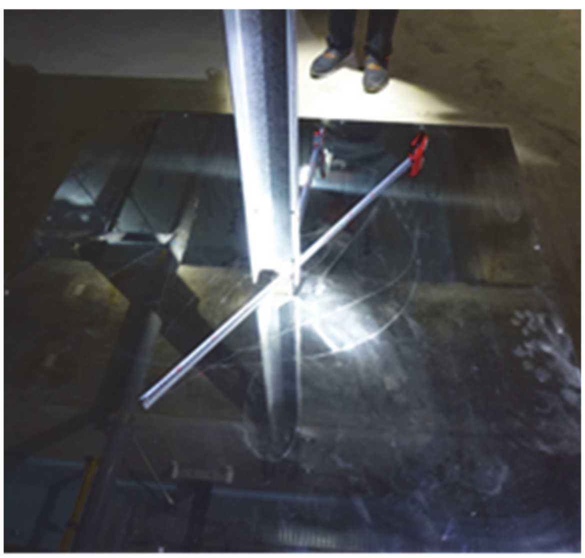


Figure 4. Photo of scratch plate.

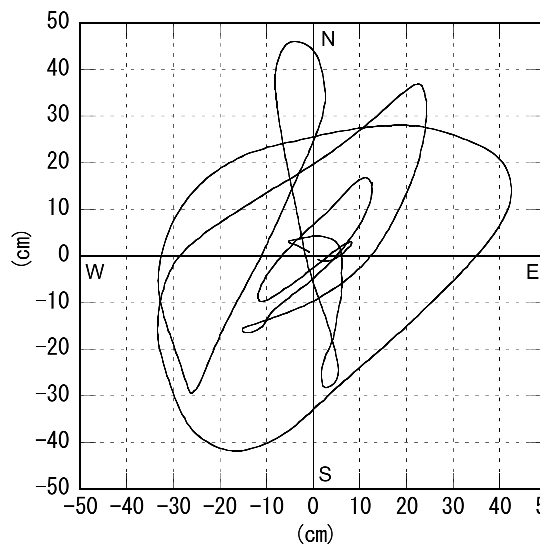
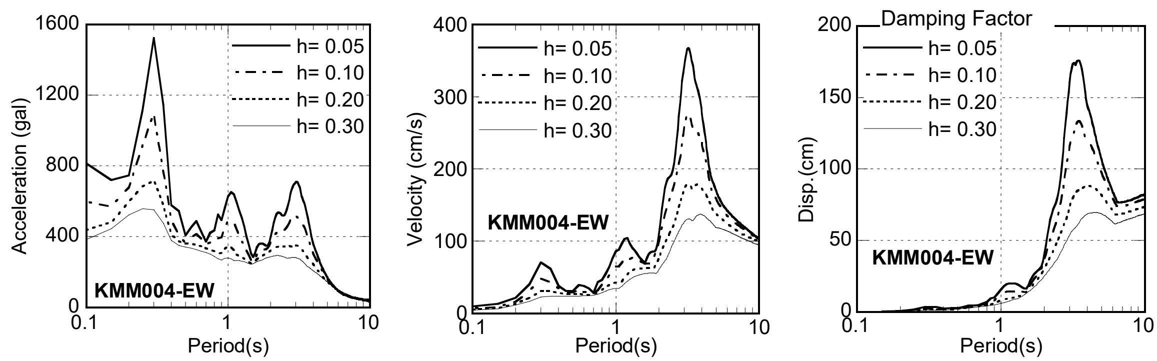


*Figure 5. Orbit recorded at Medical Facility **M**.*

The seismograph station K-NET Ichinomiya, located close to Medical Facility **M** in Aso City, measured a seismic intensity of 6-lower during the main shock. The record on the scratch plate in the isolation level of Medical Facility M immediately after the foreshock showed a locus smaller than 5 mm in diameter. A single amplitude of 46 cm was recorded during the main shock, which indicates its severity. Also, the dominant period of the seismic motion measured at K-NET Ichinomiya was 3 seconds as shown in Figure 6, and the amount of deformation of the isolation level estimated from the displacement response spectrum was well over 1 m. The large difference between this and the response deformation at the medical facility **M** in Aso City requires investigation.



(a) Acceleration *(b) Velocity* *(c) Displacement*

Figure 6. Response spectrum for observation record at K-NET Ichinomiya (EW component) [2].

Table 2. A Summary of the Surveyed Buildings

City		Uses	Built year	Structure	Story	Seismically isolation devices	Gap size (cm)	Scratch plate
Kuma-moto	**A**	Inpatient Ward	2002	SRC	13+B1	NRB,LRB,SD,CLB	50	○
			2010	SRC	13+B1	NRB,LRB,SD	50	○
		Outpatient Clinic	2006	SRC	7+B1	LRB	55	○
	B	Office	2015	S+SRC	7+B1	NRB,USD,SnRB	65	○
	C	Hotel	2002	RC	12	HDR,OD	45	
	D	Apartment	1998	RC	14	HDR	43	
				RC	11	HDR	43	
	E	Apartment	2002	RC	14	NRB,HDR	60	
				RC	14	NRB,HDR	60	
	F	Apartment	2008	RC	15	NRB,USD,LD	60	
	G	Apartment	2008	RC	13	NRB,USD,LD		
Yamaga	**H**	Medical facility	2011	RC	5	HDR	60	○
	I	Office	2014	S+CFT	5+B1	NRB,LRB,ESD,USD	60	○
Yatsu-shiro	**J**	Apartment	2008	RC	15	HDR,ESD,USD	60	(○)*1
	K	Apartment	2008	RC	14	NRB,USD,LD	55	
Kikuchi -gun	**L**	Warehouse	2013	S+SRC	2	NRB,LRB,ESD	58	○
Aso	**M**	Medical facility	2014	RC	4	NRB,LRB	50	○

*1: Valid data were not taken at this time

Structures RC: Reinforced concrete structure, S: Steel structure, SRC: Steel reinforced concrete structure, CFT: Concrete-filled steel tube structure

Seismic isolation devices NRB: Natural rubber bearing, LRB: Lead-plug rubber bearing, HDR: High damping rubber bearing, SnRB: Tin-plug rubber bearing, ESD: Sliding with elastomer, CLB: Roller bearing, OD: Oil damper, SD: Steel damper, USD: U-shaped steel damper, LD: Lead damper

Table 3. Maximum Amplitudes Recorded on the Scratch Plates

	Uses	A maximum **double** amplitude (cm)	A maximum **single** amplitude (cm)
A	Inpatient ward	60	38
	Outpatient clinic	72	41
B	Office	74	40
H	Medical facility	19	10
I	Office	16	8
L	Warehouse	50	33
M	Medical facility	90	46

In an interview with the building manager, it was confirmed that the seismically isolated buildings were undamaged, and normal business continued without even any furniture or medical equipment falling over. Patients were not evacuated from the Medical Facility **M**. And this hospital accepted a total number of around 70,000 patients from 13 damaged hospitals with seismic-resistant structure.

A hotel with a seismic-resistant structure located about 1.4 km from Medical Facility **M** was closed after the earthquake disaster until its safety could be confirmed. A member of staff who was on the third floor of the hotel at the time of the main shock said that the building shook so violently that paper sliding doors, the shoji, in the Japanese-style room came out of place and he was so scared.

The seismically isolated buildings in Kumamoto Prefecture include apartment buildings, medical facilities, accommodation facilities, offices, and warehouses. All of these buildings displayed a seismic isolation effect, and the functionality of the buildings was maintained even immediately after the earthquake.

Conclusions

Seismically isolated buildings fully exhibited their function during the Southern Hyogo Prefecture Earthquake in 1995, the Fukuoka Prefecture Western Offshore Earthquakes in 2005, and the Tohoku Region Pacific Coast Earthquake in 2011. The Kumamoto earthquakes revealed some future work to be done, but the seismically isolated buildings could continue to be used immediately after the earthquakes, with no loss of building functionality. We confirmed that the users and managers of the seismically isolated buildings were fully satisfied with the performance of the buildings.

Unfortunately, seismometers were not installed in the seismically isolated buildings surveyed in this study. Also, scratch plates were not installed in most of the apartment buildings. Measurements from seismometers are useful for confirming the soundness of seismic isolation devices after an earthquake. If installing a seismometer is difficult, a scratch plate should be installed at the very least. The scratch plate records confirm the movement of the isolation level during an earthquake, and then provide a benchmark for reconfirming the soundness of the seismic isolation device. After the Kumamoto earthquakes, the amount of deformation of the seismic isolation devices in the seismically isolated buildings with scratch plates installed was confirmed based on the scratch plate records, and the buildings were quickly evaluated to be safe to continue using. The judgment could be made with reference to experimental data accumulated in the past, rather than just a superficial visual check. Also, the accumulation of these kinds of records stored every time an earthquake occurs is expected to help in improving the performance of seismically isolated buildings.

Promoting the use of seismically isolated structures that exhibit high safety and maintain their functionality during earthquakes is considered to be an effective way of reducing earthquake damage. However, the earthquakes observed recently have gradually come to be larger than before, and it is important that sufficient allowances are also made in the design of seismically isolated structures.

Acknowledgement

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References

[1] Geospatial Information Authority of Japan (GSI), http://www.gsi.go.jp/ENGLISH/Bulletin64_00001.html, *Bulletin of the GSI*, **64** (2016)

[2] K-NET, KiK-net Strong Motion Network of the National Research Institute for Earth Science and Disaster Prevention, http://www.kyoshin.bosai.go.jp/kyoshin/docs/overview_kyoshin_index_en.html

[3] Hata, Y. & Goto, H. & Yoshimi, M., "Preliminary Analysis of Strong Ground Motions in the Heavily Damaged Zone in Mashiki Town, Kumamoto, Japan, during the Main Shock of the 2016 Kumamoto Earthquake (Mw7.0) Observed by a Dense Seismic Array", *Seismological Research Letters*, **87**(5), pp.1044-1049 (2016)