Behavior of Seismically Isolated Buildings during the 2016 Kumamoto Earthquakes

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2017 NZSEE Conference

ABSTRACT: In Japan, Prof. Hideyuki Tada (title at the time) undertook research on laminated rubber bearings in 1978, and put it into practical use in 1981. The single family house at Yachiyodai, Chiba Prefecture is completed in 1983, it's the first seismically isolated building which is installed laminated rubber bearings in Japan. Afterward, this system was gradually adopted to mainly office buildings, like a research laboratory, a hospital, a computer center and other offices. In the 1994 Northridge earthquake and the 1995 Kobe earthquake and 2011 Tohoku Earthquake et al., seismically isolated buildings improved these good performances, and recently the number of the buildings has increased. The Kumamoto earthquake is an extremely rare case, because Magnitude 6.5 and 7.3 earthquakes struck Kumamoto and Oita Prefecture in succession within a 28-hour period. There are 24 seismically isolated buildings in Kumamoto Prefecture. 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 will report behavior of seismically isolated buildings during the 2016 Kumamoto earthquake.

1 INTRODUCTION

An earthquake of magnitude 6.5 struck the Kumamoto Region of Kumamoto Prefecture at a depth of 11 kilometers at 21:26 JST on April 14, 2016. Severe shaking was observed, with a seismic intensity of 7 (the Japan Meteorological Agency, JMA, seismic intensity scale is used throughout this paper) measured in the town of Mashiki and a seismic intensity of 6-lower measured over a wide area of Kumamoto City. Further, an earthquake of magnitude 7.3 struck the same region at a depth of 12 km at 01:25 JST on April 16, and the maximum seismic intensity of 7 was observed. It is extremely rare for an earthquake of seismic intensity 7 to be observed twice in succession within a 28-hour period. It was announced afterwards that the earthquake on April 14 was a foreshock and the earthquake on April 16 was the main shock. Commencing with these earthquakes, a wide area including the Kumamoto and Aso regions of Kumamoto Prefecture and the central part of Oita Prefecture has become seismically active, and 18 earthquakes with a maximum seismic intensity of 5-lower or above occurred up until April 30. Earthquakes regarded as aftershocks are still occurring frequently.

2 SEISMICALLY ISOLATED BUILDINGS IN KUMAMOTO PREFECTURE

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 1, which allow the movements of a building to be recorded by marking scratches on a metal plate, had been installed in 8 of the hospitals and offices, and this made it possible to confirm the movements of these buildings during the earthquakes. Table 3 shows the maximum amplitudes recorded on the scratch plates. A maximum single amplitude of 41 cm was recorded at the clinic building of Medical Facility **A** in Kumamoto City, and a single amplitude of 40 cm was recorded at Office **B** nearby. A maximum single amplitude of approximately 10 cm was recorded at Medical Facility **H** in Yamaga City, and a single amplitude of 33 cm was recorded at Warehouse **L** in the district of Kikuchi Gun. A maximum double amplitude of 90 cm and a maximum single amplitude of 46 cm were recorded at Medical Facility **M** in Aso City. 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.

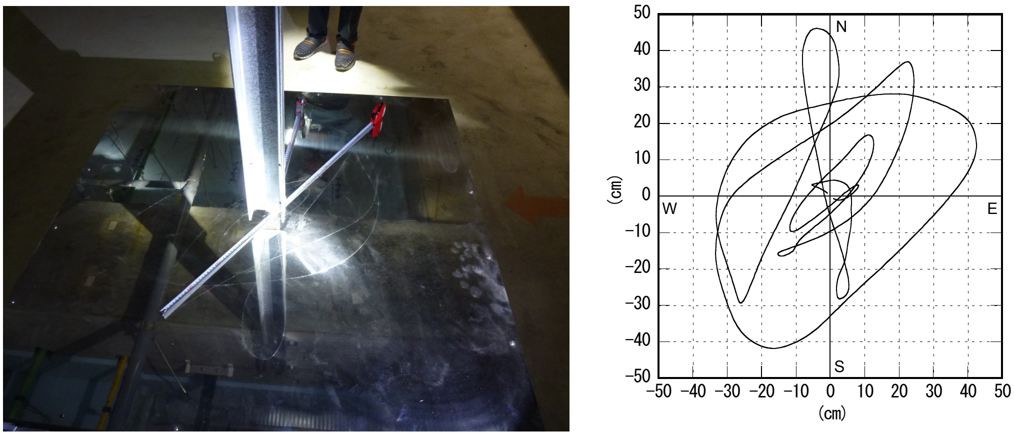

Figure 1. A scratch plate and an orbit of Medical Facility M

Table 1. A summary of the seismically isolated buildings in Kumamoto Prefecture

Uses	Apartment 12	Hospital 7	Office・Warehouse 5	
Story	1-4 stories 3	5-10 stories 6	11-15 stories 15	
City	Kumamoto 18	Yamaga 2	Yatsushiro 2	Others 2

Table 3. The 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	32.5
M	Medical facility	90	46

Table 2. A summary of the surveyed buildings

City		Uses	Built year	Struc-ture	Story	Seismically isolation members	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

3 EFFECTIVENESS OF SEISMICALLY ISOLATED BUILDINGS

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. Here, from among the seismically isolated buildings that we surveyed, we describe the seismic behavior of the medical facilities and apartment buildings.

3.1 Medical facilities

The seismograph station JMA Kumamoto, located close to Medical Facility **A** in Kumamoto City, measured a seismic intensity of 6-upper during the main shock. At this medical facility, there is a mixture of seismically isolated buildings and 2 types of seismic-resistant buildings. The Japanese Building Standards Law is revised in 1981. The buildings after 1981 is called new seismic-resistant buildings, and before 1981 is called old seismic-resistant buildings. Some of the old seismic-resistant buildings sustained major damage, while the new seismic-resistant buildings sustained damage to non-structural elements and contents. Due to repair work on these buildings they were closed until the following Monday, but patients arriving at the facility were treated. There are two seismically isolated buildings, an inpatient ward building and an outpatient clinic building, within the facility. 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 seismically isolated ward building. The seismically isolated clinic building was affected temporarily by water and power outages, but with external assistance and private power generation, the functionality of the hospital was maintained, and a system for accepting emergency cases was adopted immediately.

The seismograph station K-NET Yamaga, located close to Medical Facility **H** in Yamaga City, measured a seismic intensity of 5-lower during the main shock. In this facility, only the new ward building and clinic building are seismically isolated, while the waiting lounge and entrance hall are seismic-resistant buildings. The seismically isolated and seismic-resistant buildings are connected via internal expansion joints and gap covers. In an interview with the building manager, it was confirmed that none of the furniture or medical equipment in the seismically isolated buildings fell over, and normal business continued. Also, the facility accepted patients from hospitals that had sustained serious damage.

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, 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 in Aso City requires investigation.

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 very scared.

3.2 Apartment buildings

Roughly half of all the seismically isolated buildings in Kumamoto Prefecture are apartment buildings. The first of these, Apartment Building **D**, was built in 1998. In our survey of Apartment Building **D**, we estimated that the building had moved with a maximum single amplitude of about 30 cm, but apparently none of the furniture in the rooms had fallen over. A resident told us that when they purchased their apartment, they didn’t think that seismically isolated apartments were necessary in Kumamoto, but having experienced this earthquake, they were glad they had bought it. Also, the answers to a questionnaire targeting residents of seismically isolated Apartment Building **F**, a 15-story reinforced concrete structure also located in Kumamoto City, showed that the residents were satisfied with the performance of the structure—for example, furniture did not fall over, even slender cosmetic products that were standing up, everyday life could carry on as normal because essential utilities were not cut off, and relatives living nearby came to take refuge.

Yatsushiro City, away from the hypocenter, also has some seismically isolated apartment buildings. The seismograph station K-NET Yatsushiro measured a seismic intensity of 6-upper. A resident living on the top floor of Apartment Building **J** said that it felt as though the building swayed slowly for a long time during the main shock, but no furniture fell over and no damage was done to the superstructure, and they were able to continue living in the building without any problems. At a nearby 10-story accommodation facility with a seismic-resistant steel reinforced concrete structure, guests had to wait outside after the main shock until dawn when safety checks were finished.

Also, the answers to a questionnaire targeting residents of seismically isolated Apartment Building **K** in Yatsushiro City showed that 88% of residents knew that the building was seismically isolated, and 94% thought that the seismic resistance of the seismically isolated buildings was superior to that of conventional buildings during the Kumamoto earthquakes. The majority of the answers indicated that although the residents felt a bit scared by the slow swaying of the building during the main shock, they were able to continue living in the building without any problems, and they had come to realize the superiority of the seismically isolated structure.

4 FUTURE WORK

The Kumamoto earthquakes revealed several problems. In almost all of the buildings, we found that the expansion joints and gap covers connecting the seismically isolated building with seismic-resistant buildings were deformed. Figure 2 shows a deformed gap cover. During an earthquake, the expansion joints move without interfering with the movement of the seismically isolated building. However, when they are subject to large forces or move more than expected, the expansion joints and the gap covers may become deformed, although this does not impair the performance of the seismically isolated building. During the Kumamoto earthquakes, some of the joints showed greater deformation than expected, but there were no problems in terms of use.

Compared to when seismically isolated structures first started to be employed in buildings, the gap covers installed near building entrances have become more sophisticated. They allow completely barrier-free access, and recently many are designed to make it look as though the building is not seismically isolated at all. However, some of the expansion joints and gap covers appeared to have suffered excessive deformation due to a lack of consideration by the designers, who appeared to have forgotten that "during an earthquake, there will be relative movement between the seismically isolated building and the ground surface or the seismic-resistant building."

Figure 2. A deformed gap cover

5 SUMMARY

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. 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.

ACKNOWLEDGEMENTS

Our survey of seismically isolated buildings in the Kumamoto Region in 2016 was conducted in collaboration with the Disaster Investigation Committee of the Kyushu Branch of the Architectural Institute of Japan (AIJ) and the Japan Society of Seismic Isolation (JSSI). We received the cooperation of building managers and residents during the survey. Also, we were permitted to accompany investigators from the National Institute for Land and Infrastructure Management of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and the Building Research Institute. We would like to take this opportunity to express our gratitude.