Effects of Seismically-Isolated Buildings during the Huge 2011 Earthquake in Japan

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SUMMARY

The Japan Society of Seismic Isolation (JSSI) investigated the behavior of seismically-isolated (SI) buildings in Japan, during and after "the 2011 off the Pacific Coast Tohoku Earthquake". The earthquake was followed by many aftershocks. In one month there were four M7-level aftershocks, forty-six M6 and two-hundred M5 aftershocks. The effects of SI were extremely good in SI buildings in the Tohoku area. There was no damage in structures with seismic isolation, and also SI effects were confirmed from records of seismographs that were installed in buildings and by perceptions of occupants in SI buildings. Nothing fell, nor was there any movement, such as of household-articles or of furniture in SI buildings. There was no problem regarding the business continuation in companies or factories which had adopted SI structures. They were able to continue with their business as usual after the earthquake.

Displacement of the SI layer was about 10 to 20 cm, on average, and 40 cm maximum in the Tohoku area; in the Kanto area it was 5 to 8 cm and 15 cm, respectively. Then, residual displacement was very small in both areas. The seismic isolation layers of two buildings were inundated by the tsunami, but there was no interruption of business.

All isolators for SI devices worked well, but hysteretic dampers made of steel or lead worked hard due to the many aftershocks. Some of these dampers were exchanged after so much consumption of energy resulting from earthquake vibrations. This was done in order to prepare for future earthquakes. This exchange of dampers was decided in consideration of how much energy absorbed by the dampers, or how much absorption capacity remained. Generally, SI buildings have covers of moat between the ground side and the SI building, mainly at entrances and exits, or expansion-joint parts between the other building and the SI building. These covers and parts in twenty-five percents of SI buildings investigated by JSSI were damaged. Technical views about devices such as dampers, covers of moat, and expected future problems in SI buildings will be shown in this paper.

Keywords: seismic-isolation, safety, isolator, damper, cover of moat

1. INTRODUCTION

The Japan Society of Seismic Isolation established an investigation committee of response-controlled buildings to study the behavior of seismically-isolated (SI) and vibration-controlled (VC) buildings in the earthquake that occurred on March 11, 2011.
The investigation issued a questionnaire on the behavior of SI and VC buildings for members of the Japan Society of Seismic Isolation. This committee is conducting research activities as follows.

2. OUTLINE OF INVESTIGATION

The subjects of the survey are mainly in the Tohoku and the Kanto areas where the earthquake had the most impact. The investigation items are as follows;[1)]

a.) Construction site, b.) Seismic intensity on the construction site,
c.) Existence of seismographs, d.) Behavior of the building, e.) Maximum displacement,
f.) Residual displacement, g.) Situation of devices for seismic isolation,
h.) Movement or overturning of furniture, equipment, appliances,
i.) The situation of finishing materials and the plumbing pipes,
j.) The situation of SI expansion joints, k.) Emergency inspections after earthquakes,
Questionnaires were returned for 327 buildings, details are in Table 1., below.

Table 1. Investigation of SI buildings (in each prefecture)

prefectures	number of buildings	Seismic intensity of JMA		
		>5 low	< 4	indistinct
Aomori	4	4		
Iwate	5	5		
Miyagi	60	60		
Fukushima	10	10		
Ibaraki	5	5		
Tochigi	1	1		
Gunma	1	1		
Saitama	9	8	1	
Chiba	28	27	1	
Tokyo	111	86	22	3
Kanagawa	52	20	19	13
Shizuoka	2		2	
Nagano	2		2	
Aichi	4		4	
Gifu	1		1	
Osaka	28		28	
Hyogo	3		3	
Other	1			1
Total	327	227	83	17

In the Tohoku district, seismic intensities of JMA ranged from lower five to seven, and in the Kanto district, they were four or less. [2)]

2.1. Maximum and residual displacements

The average of maximum displacements of the seismic isolation layer was around 5-10 cm in the Kanto district, which was 400 km from the epicenter, and around 10-20 cm, in Miyagi prefecture, which was 170 km from the epicenter. The maximum displacement was 15 cm and 41.5 cm, in Fukushima and Miyagi, respectively. It was 15 cm in Tokyo and in Kanagawa, which were far from the epicenter. The maximum residual displacement was around 2 cm. As a result, it seems that residual displacement was low, due to many aftershocks (Table 2.).

Table 2. Displacement of the seismic isolation layer (cm)

prefectures	maximum displacement	residual displacement
Aomori	1.0	0.2
Iwate	10.0	
Miyagi	41.5	2.0
Fukushima	15.0	1.5
Ibaraki	10.0	
Tochigi	18.0	
Gunma	6.0	0.5
Saitama	5.1	0.8
Chiba	13.0	1.0
Tokyo	15.0	1.9
Kanagawa	15.0	1.5
Shizuoka	0.9	
Nagano	1.0	
Aichi	3.0	
Gifu		1.0
Osaka	4.5	
Hyogo		

2.2. The behavior of these buildings

The behavior of the buildings was according to design objective. They showed SI performance, and none of them had damage in the main structure. Two of the returned questionnaires reported that the buildings were hit by the tsunami, but the SI layer was not damaged.

2.3. Situation of SI devices

There was no damage to the bearing system. Among hysteretic dampers, there were minor distortions in six buildings, some footing bolts loosened in a few buildings. The residual deformations of dampers occurred in Miyagi. In addition, there was one report that the footing of a damper was damaged.

There were cracks in lead dampers in five buildings. In Miyagi, where the displacements were big and seismic intensities were also large, there were no reports of cracked lead dampers. In the Kanto district, where displacement of the SI layer was around 10cm, and in Osaka, far from the epicenter, cracks were found.
"The Damper WG" performed more detailed surveys, analyses, and also suggested countermeasures. There were only two cases of damage to piping systems, these were plumbing pipes. There were three reports of movement of furniture with casters. In addition, falling tableware was rare in SI buildings.
In surveys on expansion joints, malfunctions occurred in 90 of the 327 buildings. "The Expansion-joint WG" was established to perform surveys and analyses, and then it suggested preventive measures against recurrences.

3. DAMAGE OF EXPANSION JOINTS AND COUNTERMEASURES FOR THEM

3.1. Situations of expansion joints as non-structural

In SI buildings, expansion joints clad the isolation moat to absorb big displacement during earthquakes. They are installed between the portion of SI building and the ground portion. [1)]
SI buildings are designed for the purpose of preventing major earthquakes. Moreover, the buildings are able to continue to function after an earthquake. However, in this survey, damage to expansion joints was reported for approximately a quarter of the 327 buildings. Damage occurred not only in the Tohoku area but also in the Kanto area.

3.2. Causes of damage to the expansion joints

Causes of damage are sorted by surveys as below;
a.) .Carelessness during construction, b.) Insufficient maintenance, c.) Problems with the function of the expansion joints themselves. Architects, construction engineers, manufacturers and building owners should have knowledge for movement of SI expansion joints, which are different from conventional expansion joints.

3.3. Measures to preventive recurrences

It is important that no person falls down, nor is caught in the moat or any part of it, during and after earthquake. The expansion joints must have range of movement up to design-movable displacement without being damaged. The design-movable displacement is decided by architects to have more than the quantity of displacement in case of an extremely-big earthquake. The expansion joints manufacturer must confirm that movability is maintained without any damage, up to the design-movable displacement confirmed through testing. Regarding the standard products, it is necessary to confirm the performance through a dynamic excitation test on a vibrating table.
The range of movement of the expansion joint is illustrated in drawings and specifications. It is prohibited for construction engineers to install anything in the movable zone. Providing a smooth and level in movable zone

is important.
It is imperative that the manufacturers explicitly state to architects and construction engineers that the movable zone must be smooth and level. Construction engineers must perform construction management based on that.
It is important to perform inspections of an expansion joints and their perimeter at the time of a periodic inspection.

4. INVESTIGATION AND COUNTERMEASURES FOR STEEL AND LEAD DAMPERS

4.1. Situation of dampers

The role of the damper in SI devices is to provide damping performance to SI buildings by energy absorption, and to limit excessive relative-displacement between the superstructure and the ground during earthquakes. [1)]
In not only the Tohoku and the Kanto areas, but also in Osaka, the seismic intensity reported by JMA was very small. Osaka was 750km away from the epicenter, but high-rise and SI buildings were shaken by long-period earthquake vibrations. Duration of the 2011 earthquake was unusually long so that SI devices endured many cyclic vibrations, but they performed very well according to survey results.
However, upon inspection of SI layers after the earthquake, loose bolts were found in steel dampers, and phenomena such as cracks in lead dampers were found. These phenomena were investigated by the committee.
Confirmation of residual capacity is important. As for steel dampers, there was correlation between shape deformation and the degree of cumulative damage determined in original tests. The rate of change of the rod-shape is provided as the management-standard value.
Fissuring of lead dampers occurred on the surface of the damper bodies. There was information for occurrence of cracks from approximately 30 buildings. These cracks were mainly caused by this earthquake, but before the earthquake, there were fissuring had already been occurred in several buildings. [3)]
Countermeasures for cracks of lead dampers are under development, but some countermeasure experiments have been pushed forward, at present. Regarding the cracking of lead dampers, residual capacity evaluation becomes important as well as residual one of steel damper. The management-standard value of the crack-depth of damper is provided from yield-load ratio, also, a method to confirm residual capacity was suggested.

4.2. Steel dampers

4.2.1. The residual deformation of damper-rods and technical views
The residual deformation of damper rod of steel damper was confirmed after the earthquake. This damper rod deformation had been recognized in previous tests in manufacturer. Steel dampers absorb energy transforming to plasticity of steel rods during an earthquake.
Residual deformation of damper rods shows how much damper absorbed energy during an earthquake. The deformation was similar to the test results of the residual capacity in a factory. By test results, it is confirmed that hysteresis loop after residual deformation is still stable for maintaining the energy absorption capacity, therefore, according to the level of transformation of damper rod, usage of dampers is possible or not by

confirming of their level referring to test results. If they have a crack, damper rod should exchange immediately, which a crack indicates fatigue degree.

4.2.2. Confirmation of residual capacity

When abnormality is not observed through inspection for confirmation of residual capacity, the SI performance of a building is still sufficient.

In the event of deformation of damper rods, a dimensional-gauge check must be carried out. If shape transformed-ratio of the rod height is less than 1.1, the capacity still remains. If this value is exceeded, residual capacity should be examined by using the approval methods shown below.

a.) An examination method by Miner's rule

b.) An examination method by the energy absorption factor

c.) A method to estimate from maximum displacement by orbiter

4.3. Lead dampers

4.3.1. One phenomenon about lead dampers after the 2011 earthquake

A phenomenon that occurred to lead dampers after the earthquake was cracking on the surface of lead dampers. About 13% of SI buildings in Japan use lead dampers. The total number of these in use is approximately 6,000. Lead dampers usually recrystallize themselves after deformation. Lead dampers have superior energy absorption capability. There was no knowledge of cracking initiated by the long-duration and cyclic-low amplitude excitation, such as wind responses. However, the quantitative tendency of cracking was recently revealed to the public. [4)]

4.3.2. Technical views

Cracks are caused by repetition of the micro-amplitude excitation, a kind of striation of which is characterized fatigue fracture was observed in sectional views of lead dampers (Photo 1.) by electronic microscope. [5)]

Photo 1. Lead damper used conventionally

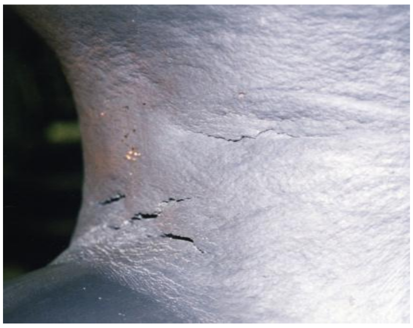


Photo 2. Cracks on the surface of lead damper

Even if fissuring occurs (shown in Photo 2.), the lead damper will not break immediately. It will not break until it undergoes by the repetition of 30 times - 40 times of the repeated time which cracks are produced.

The capacity of lead dampers in which cracks are produced, is equivalent to the effective area, what remains after subtracting the doughnut-shaped area by the crack depth assumed along circumference from total area. [6)]

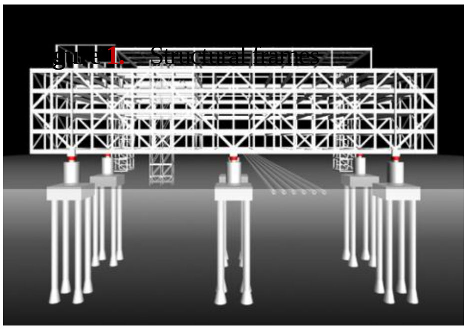
4.3.3. Confirmation of the residual capacity

When abnormality of lead dampers is not recognized by emergency inspections, it is assumed that the SI performance of the building is intact. Abnormalities were discovered, such as cracks on the surface of lead dampers. If the maximum depth of the crack is less than 10 mm: U180, 15mm: U2426, by crack-depth test, they have 90 % of residual capacity to the usual capacity.

The amplitude level was big in this earthquake, so shape transformation may have occurred. It is assumed that there was still 90% of residual capacity if changes the axial diameter were less than 200mm: U180, 280mm: U2426. If it had been beyond this value, it would have been necessary to check them to determine whether or not to change them.

5. BEHAVIOR OF SI BUILDINGS IN THE EARTHQUAKE

5.1. A piloti-building in Tokyo



This building is six stories with a column-top SI and steel structure of trussed cage shown in Fig. 1. It is located in Shimizu Research Institute, Kotoku Tokyo; it was built in 2003. The first floor of the building is the piloti area, which is 20 m x 80 m. It has laminated rubber (G0.39) bearings with a lead plug of 1,000 mm to 1,100 mm in diameter. The vertical stress is less than 15 N/mm^2. The natural period is four seconds at shear-strain of 200 % of the isolator. Accelerographs are installed and provide records. The relative displacement of the SI layer was observed by a displacement gauge. The accelerograph in the ground and one on the sixth floor are shown in Fig. 2. The maximum accelerations of the superstructure were reduced to about half, compared with the ground (shown in Table 3.).

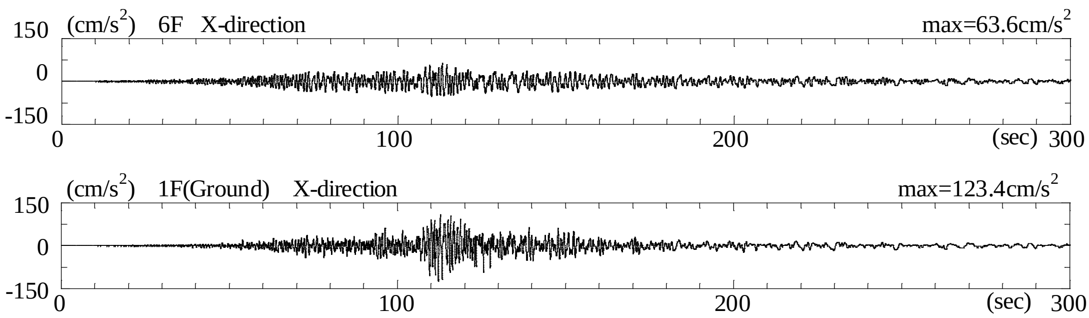


Figure 2. Observed acceleration of the sixth floor and the ground

Table 3. Maximum accelerations (cm/s^2)

location	X direction	Y direction
6	64	72
4	56	56
2	59	69
ground	123	132

The horizontal deformation of an LRB is shown in Fig. 3. The maximum was 8.6 cm. The transfer-functions of the observed accelerations on the sixth floor to those on the ground are shown in Fig. 4. [7)]

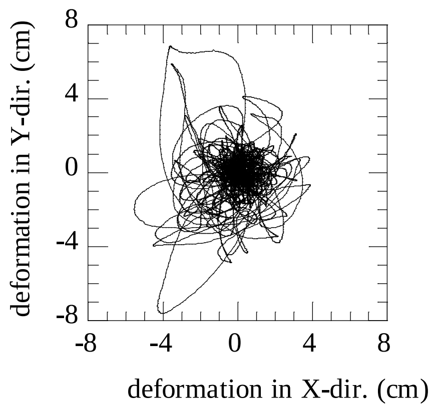


Figure 3. Deformation trace

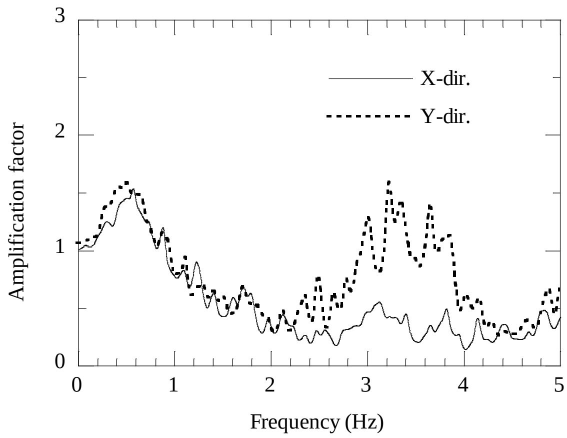


Figure 4. Transfer-function

5.2. A condominium in Tokyo

This building which is a seven-story RC structure with SI, is located in Katsushikaku, Tokyo.

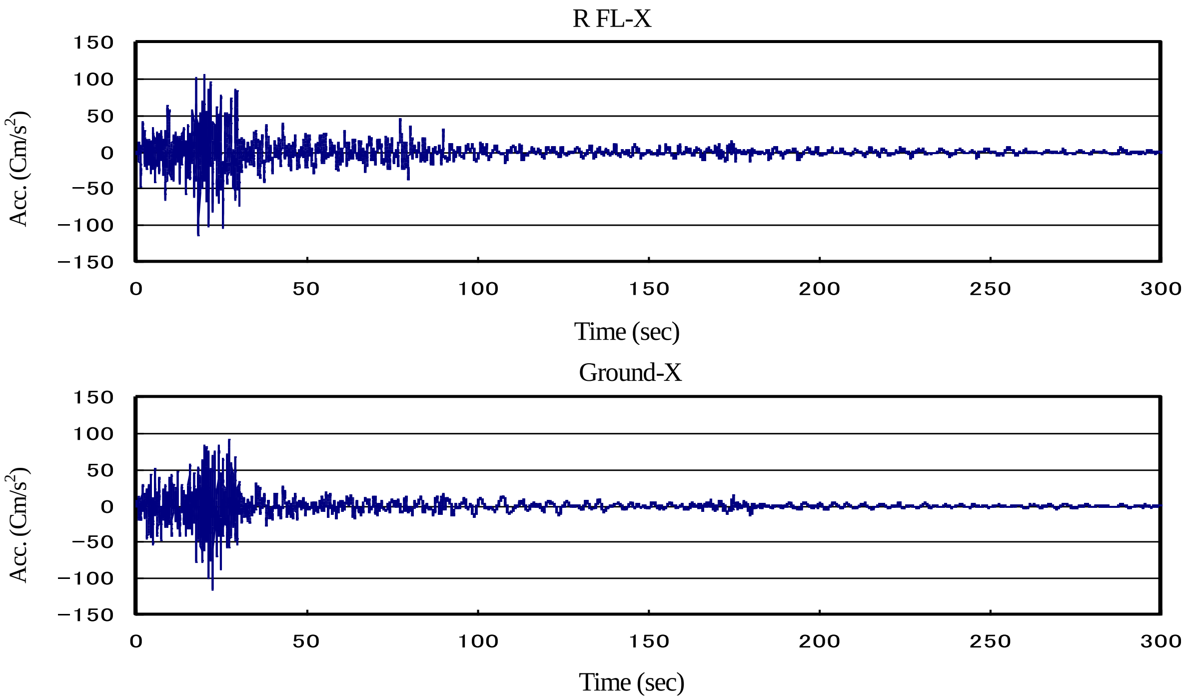


Figure 5. Observed acceleration of the roof floor and the ground

It was built in 1991 as a condominium, and is 12 m x50 m. The SI devices are natural rubber (G0.5) bearings of 1,000 mm to 1,200 mm in diameter. The vertical stress is less than 10 N/mm^2. It has steel dampers and oil dampers. Natural period is 2.5 seconds at shear-strain of 100 % of the isolator. Accelerographs are installed on the roof level, fifth floor, first floor and the ground.

Observed accelerations, such as on the roof level and on the ground are shown in Fig. 5. Table 4. indicates maximum accelerations. The maximum acceleration under the SI layer 115gal (the JMA seismic intensity was lower five), the acceleration of the superstructure of the first floor was 87 gal, and the roof level was 116 gal. The acceleration of the top floor was approximately at the same level as the ground.

Table 4. Maximum accelerations (cm/s^2)

location	X direction	Y direction
R	116	106
5	86	86
1	87	89
ground	115	110

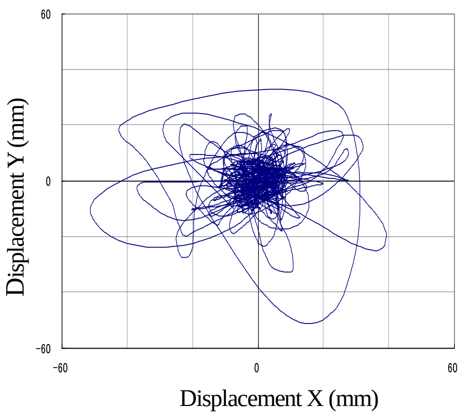


Figure 6. Displacement trace

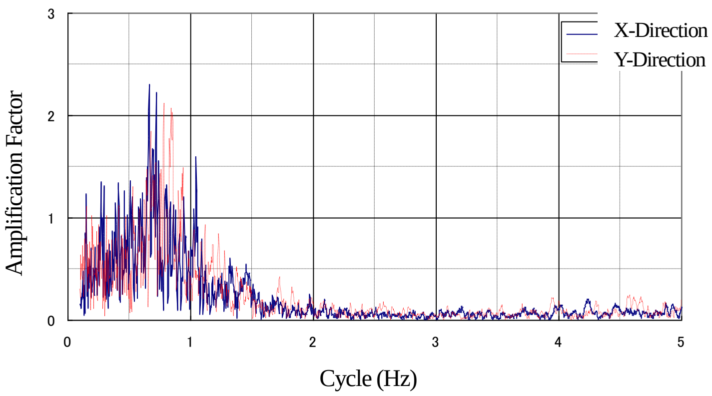


Figure 7. Transfer-function

A displacement graphic-meter is installed in the SI layer. The maximum amplitude of the SI layer was approximately 5cm (Fig. 6.).

The transfer-function amplitude from accelerations is shown in Fig. 7. In the first peak, it is thought that the natural period of the SI layer was approximately 0.7Hz. (1.5 seconds). This earthquake did not lead to the original seismically-isolated cycle for 0.4 Hz (2.5 seconds).

6. NEAR FUTURE PROBLEMS

For long-period and long-duration ground motion, such as the Tokai, the Tonankai and the Nankai, these earthquakes are predicted to occur sequentially along the Pacific offshore fault lines in the future. Damper systems should be prepared to be able to absorb vibration-energy, which is likely lager than the 2011 Tohoku Earthquake.

Hysteretic dampers, such as steel or lead will reduce the energy-absorption capacity in excitation over a long duration; It will be necessary for structural engineers to check the residual capacity of these devices.

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