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Structural Design and Performance Evaluation of a Mid-story Seismic Isolated High-Rise Building

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Abstract

This paper describes some of the challenges for structural design of a mid-story seismic isolated high-rise building, which is located near Tokyo station, completed in 2015. The building is a mixed-use complex and encompasses three volumes: one substructure including basement and lower floors, and a pair of seismic isolated superstructures on the substructure. One is a 136.5m high Main Tower (office use), and the other is a 98.5 m high South Tower (hotel use). The seismic isolation systems are arranged in the 3rd floor of the Main Tower and 5th floor of the South Tower, so that we call this isolation system as the mid-story seismic isolation. The primary goal of the structural design of this building was to secure high seismic safety against the largest earthquake expected in Tokyo. We adopted optimal seismic isolation equipment simulated by dynamic analysis to minimize building damage. On the other hand, wind-induced vibration of a seismic isolated high-rise building tends to be excited. To reduce the vibration, the following strategies were adopted respectively. In the Main Tower with a large wind receiving area, we adopted a mechanism that locks oil dampers at the isolation level during strong wind. In the South Tower, two tuned mass dampers (TMDs) are installed at the top of the building to control the vibration. In addition, our paper will also report the building performance evaluated for wind and seismic observation after completion of the building. In 2016, an earthquake of seismic intensity 3 (JMA scale) occurred twice in Tokyo. The acceleration reduction rate of the seismic isolation level due to these earthquakes was approximately 30 to 60%. These are also verified by dynamic analysis using observed acceleration data. Also, in April 2016, a strong wind exceeding the speed of 25m/s occurred in Tokyo. On the basis of the record at the strong wind, we confirmed that the locking mechanism of oil damper worked as designed.

Keywords: Mid-story seismic isolated high-rise building, Oil damper with locking mechanism, Wind and seismic observation, Tuned mass damper (TMD)

1. Introduction

Tekko Building is an ultra high-rise building with intermediate level seismic isolation, constructed on a narrow site more than 200 m long near Tokyo Station. It is a multi-purpose building having, the office function, the functions of commercial facilities in the basement and low-rise part and long-stay hotel (serviced apartments). The building also contains the limousine bus station for direct connections to Haneda and Narita Airports, and plays a role in the international economic activities of the city of Tokyo.

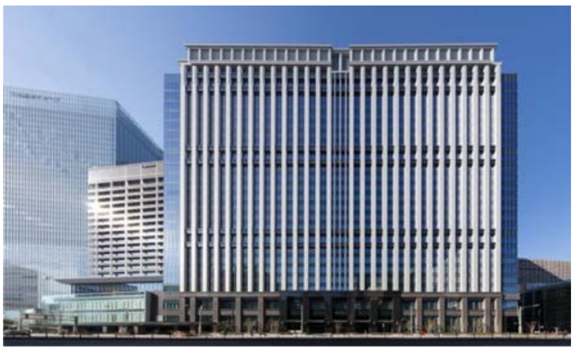

Photo 1. East view rendering.

2. Building Overview

The building includes a Main Building (office building) located on the north side of the site, and a South Tower (lively facilities building) located on the south side, integrated with the basement and the low-rise parts and the basement (Figs. 2 and 3).

The Main Building is 26 story above ground and 2-story

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Table 1. Summary of the building

Project Name:	New Tekko Building Reconstruction Project
Address:	Marunouchi 1-chome, Chiyoda-ku, Tokyo
Building Owner:	Tekko Building Co., Ltd.
Design and Supervision:	Mitsubishi Jisho Sekkei Inc.
Contractors:	Taisei-Masuoka Gumi Construction Joint Venture
Main Use:	Office, hotel, retail, car parking
Number of stories:	3-story basement, 26 (20) story above ground, 2-story (1) penthouse level
Maximum Height:	136.92 (99.18) m
Building Area:	5,534 m^2
Total Floor Area:	117,759 m^2

* Numbers within () refer to the South Building

Figure 2. Cross-section of the building.

Figure 3. Building layout.

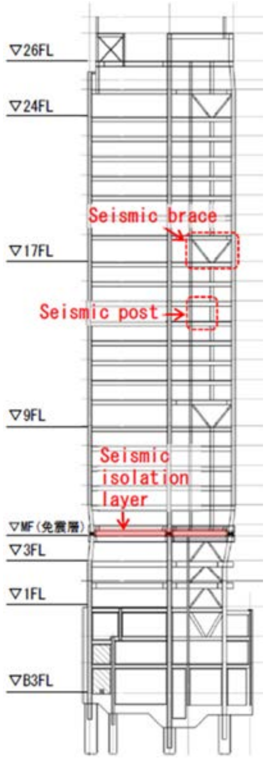

Figure 4. Frame elevation (South Building). **Figure 5.** Frame elevation (Main Building).

penthouse, the South Tower is 19 story above ground and 1-story penthouse level, sharing 3-story basement. The South Building consists of serviced apartments on the 6th floor are above, commercial facilities such as shops and restaurants in the low-rise part on the 5th floor and below, and a lounge that can be used as a resting area for users of limousine buses that operate to Haneda Airport 24 hours operating.

3. Structural Overview

3.1. Structural scheme

The building is so called "an intermediate-story seismic isolation structure", consisting of 2-seismic isolated buildings on an integrated lower part. The seismic isolation layers are located between the 3rd and the 4th stories of the Main building and at between the 5th and the 6th stories of the South Tower. The main structure is structural steel (with CFT columns) above ground and steel-framed reinforced concrete below ground, with combined foundation of piles and mat foundation to adopt top-down foundation construction method.

The site is very long and narrow, so that the Main building has a flat shape in plan with 100 m-long in long direction and 30 m-long in short direction. It also has a slender shape in elevation with high aspect ratio exceeding 4. A space with a long span of about 18 m with no columns is provided in the office area. Intermediate seismic columns are provided within the core in the short direction to ensure stiffness. Also, braces are provided where having high story-height (9F, 17F, 24F) to increase further stiffness (Fig. 5).

The South Building is a 2-span structure in the short direction above the seismic isolation layer. However the intermediate columns start from above the seismic isolation layer, so the seismic isolation layer has a single span structure (Fig. 4).

3.2. Seismic isolation scheme

The seismic isolation members on the Main Building are laminated natural rubber bearings, oil dampers and U-shaped steel dampers (Fig. 7).

The short direction is easily affected by strong winds, so oil dampers with a locking system are used to reduce the deformation of the elevators passing through the seismic isolation layer during strong winds.

The seismic isolation members on the South Tower are laminated natural rubber bearings, oil dampers and a TMD is installed on the top of the building.in order to increase the dwelling comfort during strong winds.

4. Outline of the Seismic Design

4.1. Seismic Design Policy

Seismic verification of this seismic isolated and ultra high-rise building was carried out by time history response analysis. The design seismic motions used in the time history response analysis included 3 measured waves from the past (El Centro 1940 NS, Taft 1952 EW, and Hachinohe 1968 NS), and 3 waves prescribed by the notification (Hachinohe, Kobe, and random phase), each of which were defined for Level 1 and Level 2. Also, 2 waves unique to the site were examined, assuming the Kanto earthquake and the Tokai/Tonankai/Nankai (3 coupled) earthquakes.

A coupled lumped-mass analysis model in which 2 buildings are arranged in parallel with a boundary below them is adopted for the vibration response analysis, as the

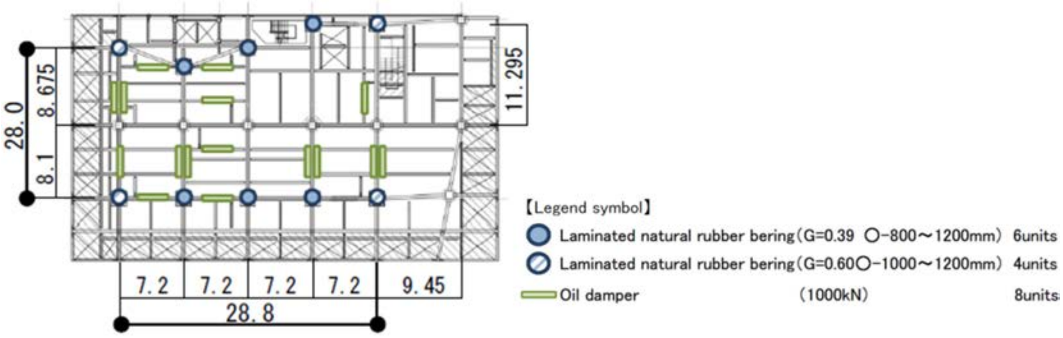

Figure 6. Seismic isolation plan of the South Building.

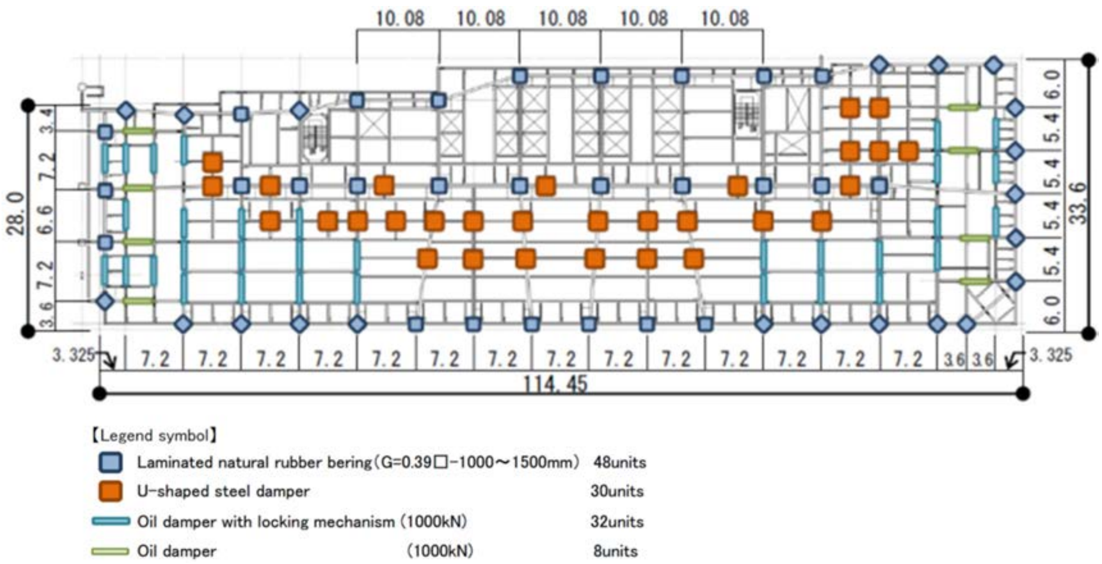

Figure 7. Seismic isolation plan of the Main Building.

Table 2. Target performance of the seismic design

Earthquake level	Level 1	Level 2
	Rarely occurring seismic motion	Extremely rarely occurring seismic motion
Above ground floors	Equal to the short term allowable stress or less Story drift ≤ 1/200	Equal to the elastic limit stress or less Story drift ≤ 1/100
Seismic isolation layer	Bearing shear strain 200% No tensile force	Bearing shear strain 267% or less Tensile surface stress less than 1.0 N/mm^2 of less Equal to the short term allowable surface pressure of less
Basement	Equal to the short term allowable stress or less	Equal to the elastic limit streff or less
Foundations, piles	Equal to the short term allowable stress or less	Equal to the ultimate stress or less

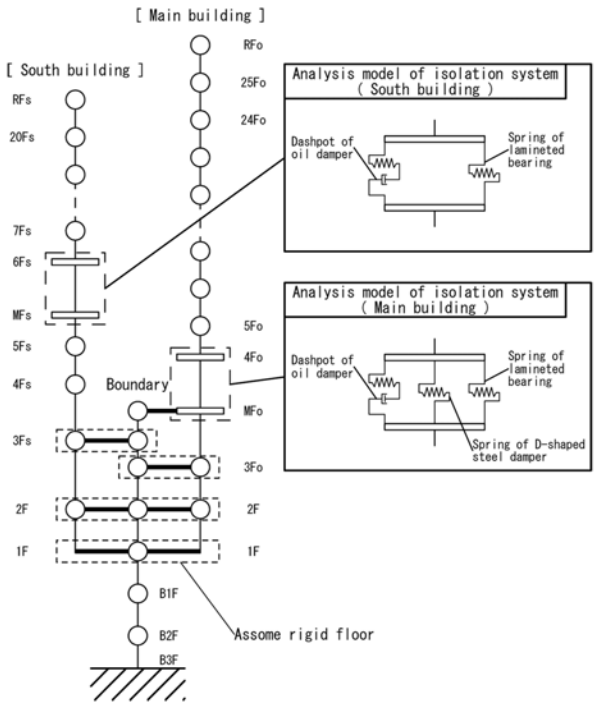

Figure 8. Vibration analysis model.

building is configured with 2 buildings and an integrated lower part. In the model, the B3 floor is assumed to be fixed on the earth with no displacement and each of the mass of the 3 basement floors is assumed to be integrated. The masses of the floors of 3 parts, the Main building, the South Tower and the boundary, from 1st to 3rd floor are arranged in parallel and the three of them are assumed to be rigid floor with the same displacement. The seismic isolation layers of the Main Building and the South Tower are placed below the 4th floor and 6th floor, respectively. Above those, the structure of the Main Building and the South Tower is modeled as 23 lumped masses and 16 lumped masses, respectively, with bending-shear spring.

4.2. Analysis results

From the results of the eigenvalue analysis, it was found that the primary natural period of the South Tower

Table 3. Natural period of building

		Natural period (sec)	
		Initial state	Deformatio at the time of 30 cm
X dir	1st (South building 1st)	5.68	5.68
	2nd (Main buliding 1st)	3.79	5.06
	3rd (Main building 2nd)	1.32	1.53
	4th (South building 2nd)	1.21	1.21
	5th (Main building 3rd)	0.79	0.84
Y dir	1st (South building 1st)	5.66	5.66
	2nd (Main buliding 1st)	4.24	5.38
	3rd (Main building 2nd)	1.44	1.71
	4th (South building 2nd)	1.11	1.11
	5th (Main building 3rd)	0.84	0.90

is 5.68 seconds, that of the Main Building with the initial stiffness was 4.24 seconds, and that with the equivalent stiffness when the deformation is 30 cm was 5.38 seconds. Parametric studies were carried out to investigate amplification of the response caused by resonance due to a coupling effect or variation in the level of the input seismic motions or equivalent stiffness, as the seismically isolated periods of the 2 buildings are close.

From the response analysis results, it was found that the maximum response of story drift under the Level 2 seismic motions was 1/184 for the Main Building (Y direction), and 1/173 for the South Tower (Y direction).

Also the displacement of the seismic isolation layer was 336 mm for the Main Building and 251 mm for the South Tower. Even if the variation in the seismic isolation devices was taken into consideration, the displacement was 376 mm for the Main Building and 285 mm for the South Tower, with shear strains of 185% and 183%, respectively.

From the response analysis results the design shear coefficient for the stories above the seismic isolation layer was 0.088 for the Main Building and 0.116 for the South Tower.

The surface pressures on the seismic isolation bearings were verified using the vertical response analysis results, which showed a maximum surface pressure of 27.7 N/mm^2 and a minimum surface pressure of -0.1 N/mm^2, which is within the allowable tensile stress.

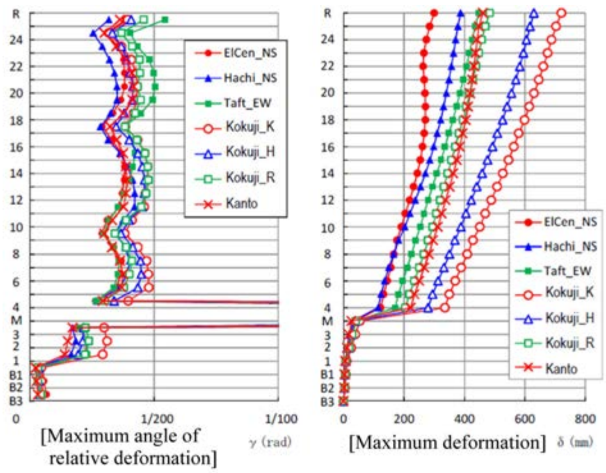

Figure 9. Result of vibration analysis (Main Building).

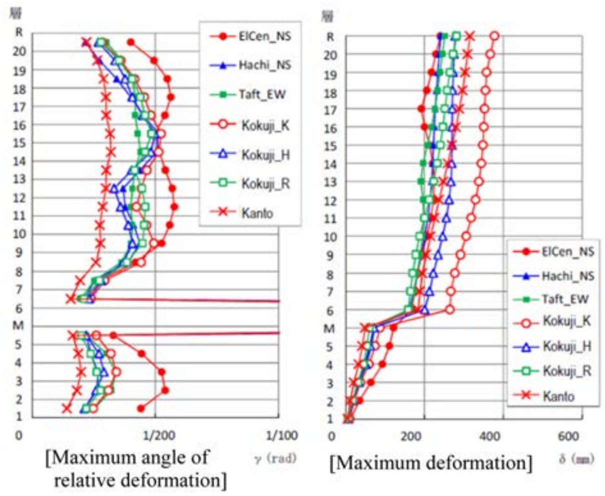

Figure 10. Result of vibration analysis (South Building).

5. Overview of the Wind Design

5.1. Wind design policy

The wind load is affected by various conditions such as the building shape, the surrounding environment, the building structural properties, etc., so the design wind loading was evaluated by carrying out wind tunnel tests. In the design of the building against wind, an analysis was carried out for 2 levels of wind loading.

The analysis was carried out for the safety of the structural frame and that of the seismic isolation layer under Level 2 wind load. The seismic isolation layer of the Main Building in the Y direction the elastic limit is exceeded under Level 2 wind loading, so elastic-plastic behaviour is exhibited for the fluctuating component about the steady load. Therefore time history response analysis was carried out taking into consideration the elastic-plastic properties of the seismic isolation members

Table 3-1. Target wind performance of the structural frame

	Story drift	Stress in structural frame members
Level 1 Level 2	Less than 1/200	Equal to the short term allowable stress or less

Table 3-2. Target wind performance of the seismic isolation layer

Load level	Seismic isolation layer
Level 2	• Deformation of seismic isolation layer ≤ seismic isolation clearance • There shall be no uplift on the seismic isolation bearings • There shall be no fatigue failure of steel dampers • Oil dampers shall maintain their integrity

and fatigue analysis of the steel dampers was carried out.

5.2. Response results

From the wind loading response analysis results, it was confirmed that the responses shear force for both the Main Building and the South Tower were less than the design shear force, and the shear stresses under the Level 2 wind load were less than the short term allowable stresses. Under the Level 2 wind load the shear forces in the story immediately above the seismic isolation layer as a ration to the design shear forces were 84% for the Main Building and 41% for the South Tower.

Also the maximum values of the deformation of the seismic isolation layer under Level 2 wind load were 98.7 mm for the Main Building and 269 mm for the South Tower. In addition, it was confirmed that the displacement of the Main Building under Level 1 wind loading was less than 20 mm, and the deformation at which the steel dampers yield was not reached. The maximum surface pressure on the seismic isolation bearings of the Main Building was about 26 N/mm^2 and the minimum pressure was about 0.5 N/mm^2, so there is sufficient margin with respect to compression and uplift.

5.3. Use of oil dampers with a locking mechanism

Elevators that pass through the seismic isolation layer are provided in the Main Building, which has a large area and is greatly affected by strong winds. Therefore, the elevators will stop when a large displacement occurs in the seismic isolation layer. Oil dampers with a locking mechanism have been adopted in this building so that under normal seasonal winds and strong winds such as typhoons, etc., the elevators can be operated with normal or low speed.

Under normal conditions the oil dampers with a locking mechanism function as normal oil dampers without locking, but during strong winds the oil dampers are locked using a solenoid valve. In this building the scheme is that the oil dampers are locked under wind loads with a return period of 4-5 years (wind velocity at

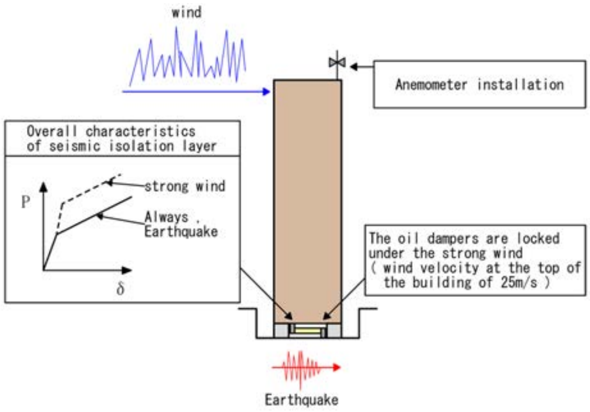

Figure 11. Use of damper with a locking mechanism.

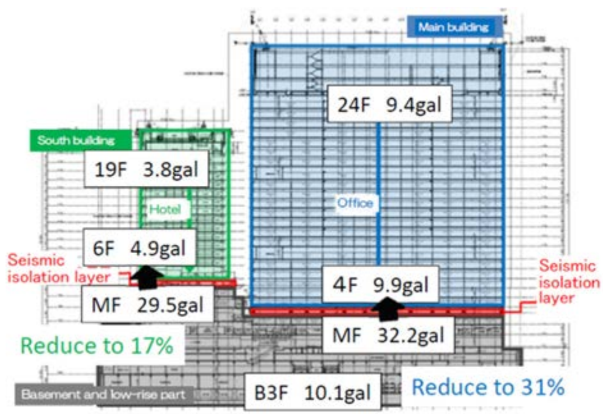

Figure 12. Observed max acceleration of May16, 2016.

Photo 2. Damper with a locking mechanism.

the top of the building of 25 m/s), the strong wind warning level of the Japan Meteorological Agency, based on measurements by a wind direction anemometer installed on the top of the building (Fig. 10).

The locking mechanism is released using a timer, so that the locking mechanism is released at a certain time after the locking mechanism has been activated, and also can be controlled manually.

When an earthquake occurs while the locking system is activated, there is a system whereby the lock is released based on accelerometer measurements. In addition, in order to verify safety seismic response analysis has also been carried out using the stiffness of the seismic isolation layer when locked, assuming a case in which the lock release function did not work normally.

6. Monitoring of the Building under Seismic and Wind Loading

After completion of the construction of the building, measurements of the building were carried out under seismic and wind load for a year. The objectives of the measurements were to confirm the seismic isolation effect through the seismic measurement and to confirm that the oil dumpers with the locking mechanism worked properly during strong winds through the wind measurement.

6.1. Building measurements during earthquakes

An earthquake of seismic intensity 3 was measured twice at the site after completion of the construction of the building. The first was an M5.5 earthquake on 16th May 2016 with an epicenter in the south of Ibaraki Prefecture and the second was an M7.4 earthquake on 22nd November 2016 with an epicenter in the sea off Fukushima Prefecture.

In the measurements of the earthquake with epicenter in the south of Ibaraki Prefecture, the maximum acceleration at the B3 floor was 10.1 gal, at the floor of below the seismic isolation layer of the Main Building (3M floor) it was 32.2 gal, at the 4th floor (above the seismic isolation layer of the Main Building) it was 9.9 gal, at the floor of below the seismic isolation layer of the South Tower (5M floor) it was 29.5 gal, and at the 6th floor (above the seismic isolation layer of the South Tower) it was 4.9 gal. It was confirmed that the effect of the seismic isolation was a major reduction of the maximum acceleration of the Main Building to 31% (32.2 gal → 9.9 gal). Also it was confirmed that there was a major reduction in the acceleration of the South Tower to 17% (29.5 gal → 4.9 gal) (Fig. 12).

In the measurements of the earthquake with epicenter in the sea off Fukushima Prefecture, the maximum acceleration at the B3 floor was 5.7 gal, at the 3M floor it was 18.3 gal, at the 4th floor it was 11.4 gal, at 5M it was 19.2 gal, and at the 6th floor it was 6.2 gal. Although the effect of the seismic isolation was a reduction of the maximum acceleration of the Main Building to 62% (18.3 gal → 11.4 gal), the percentage reduction was smaller than that for the earthquake with epicenter in the south of Ibaraki Prefecture. It is considered that this was because the magnitude of the earthquake, 7.4, was comparatively large, so the seismic isolation effect was reduced by the long period component of the seismic wave (Fig. 13). Figs. 14 and 15 show the time history acceleration responses as the earth-

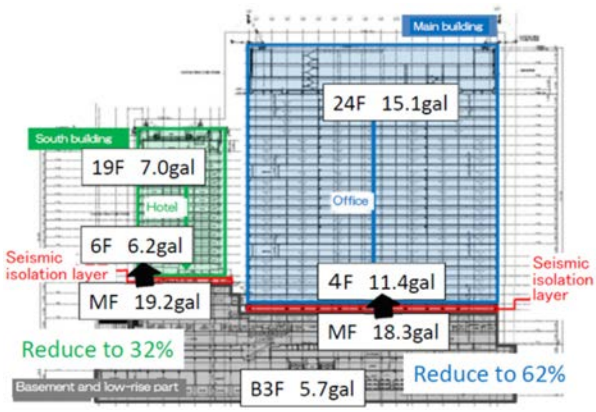

Figure 13. Observed max acceleration of Nov 22, 2016.

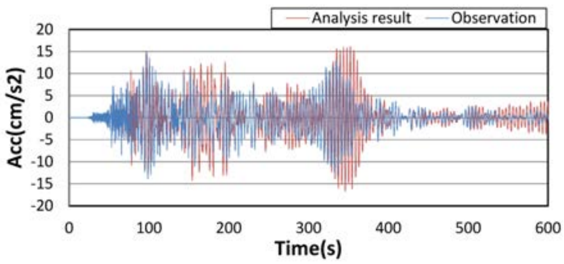

Figure 14. Time history acceleration of 24th floor (Main Building, Nov 22/2016).

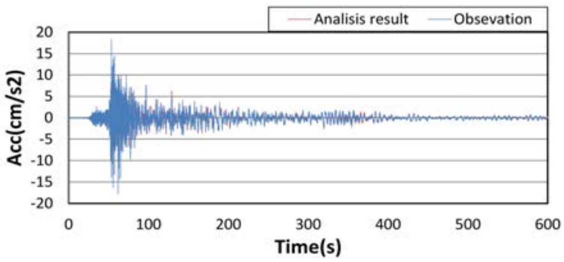

Figure 15. Time history acceleration of Seismic isolation layer (Main Building, Nov 22/2016).

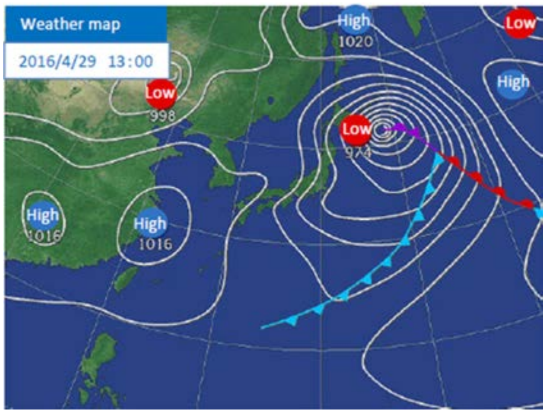

Figure 16. Weather map of April 29, 2016.

quake with epicenter in the sea off Fukushima Prefecture. Blue line indicates the observation and red line indicates the analysis result. There are large amplification from 330 seconds after occurrence of the earthquake for the long period component of the seismic wave. The observation and the result of analysis correspond well each other.

6.2. Building measurements during strong winds

Wind measurements were carried out on 2 days, 2017/4/17 and 2017/4/29 (Fig. 16), when the instantaneous maximum wind velocity exceeded 25 m/s and the oil damper locking mechanism was activated. In both cases this was due to seasonal winds. In the wind measurements on 2017/4/29 it was found that the instantaneous maximum wind velocity exceeded 25 m/s twice, with measured values of 30 m/s and 26 m/s (Fig. 17). When the locking mechanism of the oil dampers was activated, the acceleration response increased below the seismic isolation layer due to the wind pressure acting above the seismic isolation layer. As a result it was confirmed that the oil damper locking mechanism was activated properly (Fig. 18).

It was confirmed that there is no problem with dwelling comfort in the Main Building under strong winds when

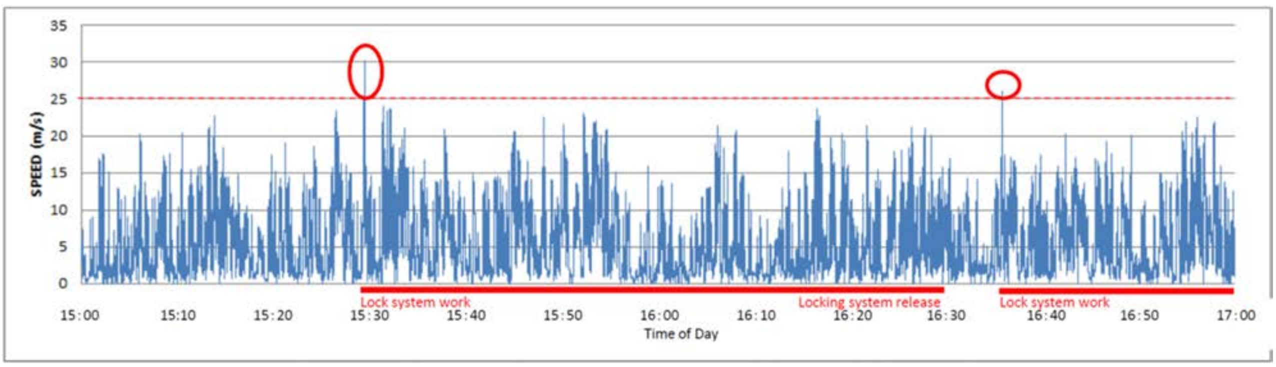

Figure 17. Observed max acceleration of Nov 22, 2016.

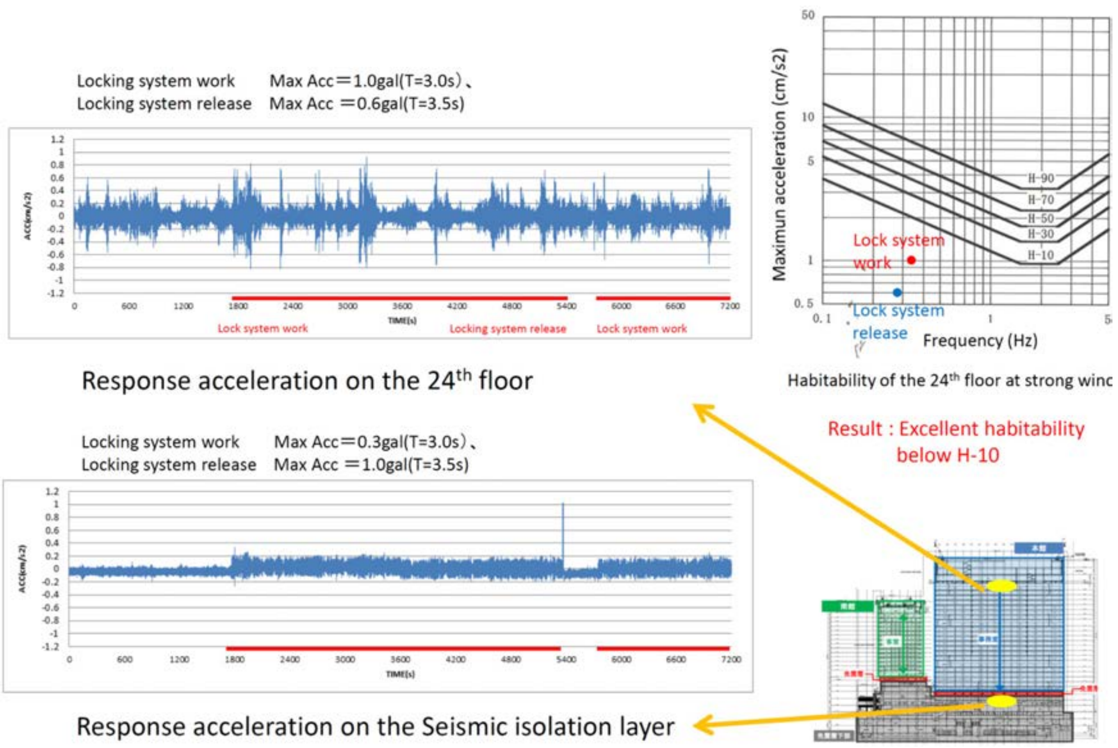

Figure 18. Response situation during strong wind (Main Building).

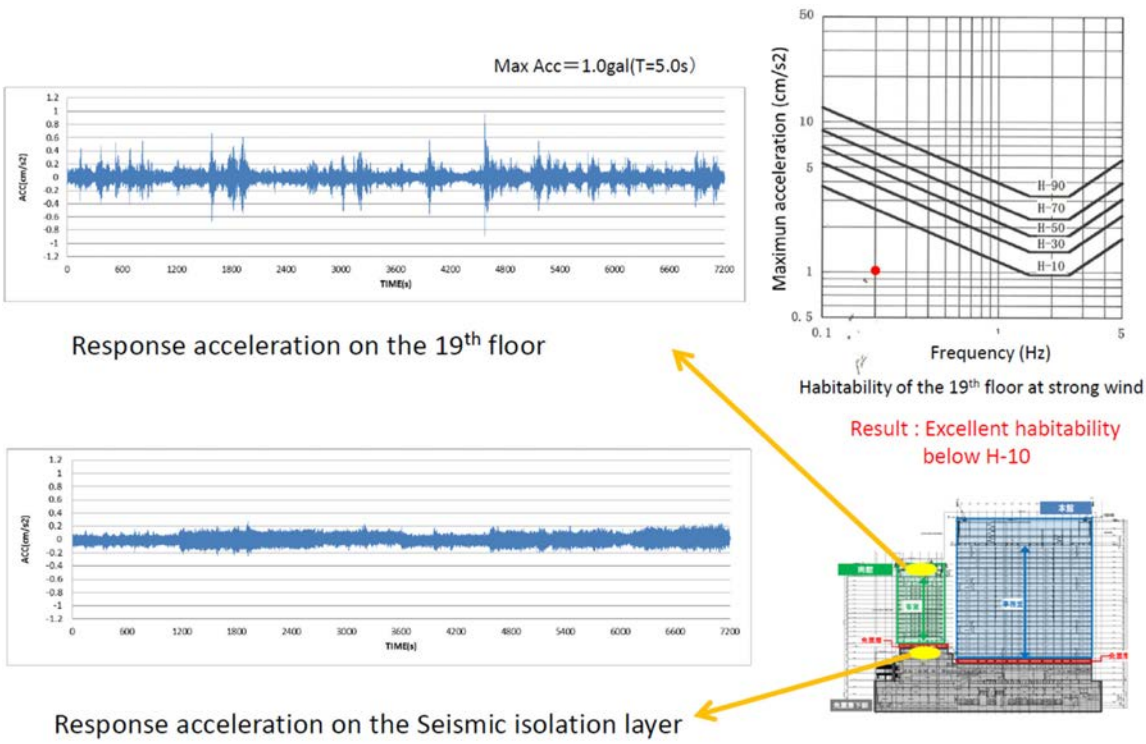

Figure 19. Response situation during strong wind (South Building).

the oil dampers are locked and unlocked.

Also, it was also confirmed that there is no problem with dwelling comfort in the South Tower under strong winds (Fig. 19).

7. Conclusions

In this paper the structural scheme has been described for the Tekko Building, in which 2 buildings with intermediate level seismic isolation structures are placed above the above-ground low-rise part. Because this is a twin seismically isolated structure, the design was carried out while checking that there are no resonance effects by analyzing the seismic isolation periods. The Main Building (office building) is easily affected by strong winds, so oil dampers with a locking mechanism were adopted to reduce the displacement of the seismic isolation layer during strong winds, to enable the seismic isolation elevators to be used as normal during strong winds.

After completion of construction, measurements of the building were carried out during earthquakes and wind. In the seismic measurements in the 1 year after completion of construction, earthquakes of seismic intensity 3 were measured twice, and in each earthquake the seismic isolation effect was confirmed. In the wind measurements in the 1 year after completion of construction, instantaneous maximum wind velocity exceeding 25 m/s on the top of the building was measured on 2 days, during which the locking mechanism of the oil dampers was activated. From the measured building response accelerations, it was confirmed that the locking mechanism of the oil dampers was activated normally.

The validity of the design was confirmed by the measurements, etc. We intend to continue the measurements, so that new knowledge can be reported.

Acknowledgements

This project is the first case that intermediate level seismic isolation was adopted on 2 buildings, and this was realized because of the high awareness of seismic safety of the building owner.

The authors express their deep gratitude to all those involved for their efforts, in particular to the building owner.

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