STRUCTURAL DESIGN AND
PERFORMANCE EVALUATION OF A
HIGH-RISE SEISMIC ISOLATED
BUILDING

Masatoshi Tamari¹, Tadashi Yoshihara², Masato Miyashita³, Nobuyuki Ariyama⁴, Masataka Nonoyama⁵

ABSTRACT

In recent years, research and development of seismic isolation devices has advanced, and the adoption of seismic isolation devices for high-rise building is increasing. Seismic isolation systems are very effective in reducing building shaking during earthquakes; however, in high-rise buildings, the wind pressure increases, so vibration under strong winds may be a problem in high-rise seismic isolated buildings.

We designed a high-rise seismic isolated building with a height of over 100m located in Tokyo, and it was completed in 2015. The primary goal of the structural design of this building was to secure it greater safety against the largest earthquake expected in Tokyo. In addition to it, we adopted some strategies, which are oil dampers with locking mechanism and tuned mass dampers on the top of the building, to reduce wind-induced vibration.

After completion of the building, vibration of the building is continuously observed. On the basis of studies using observed acceleration records at earthquake and strong wind, we confirmed that the seismic isolation devices and the dampers for wind-induced vibration work effectively as designed.

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Structural Design and Performance Evaluation of a High-rise Seismic Isolated Building

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In recent years, research and development of seismic isolation devices has advanced, and the adoption of seismic isolation devices for high-rise building is increasing. A seismic isolation system is very effective in reducing building shaking during earthquakes; however, in high-rise buildings, the wind pressure increases, so vibration under strong winds may be a problem in high-rise seismic isolated buildings.

We designed a high-rise seismic isolated building with a height of over 100m located in Tokyo, and it was completed in 2015. The primary goal of the structural design of this building was to secure it greater safety against the largest earthquake expected in Tokyo. In addition to it, we adopted some strategies, which are oil dampers with locking mechanism and tuned mass dampers on the top of the building, to reduce wind-induced vibration.

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Introduction

The insertion of seismic isolation devices at the foot of a building structure is very effective under earthquakes. On the other hand, wind-induced vibration of a seismic isolated building tends to be excited. It can be noticeable in the case of high-rise building.

We designed a high-rise seismic isolated building, which 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 and the other is a 98.5 m high. [1] [2]
Firstly, this paper describes structural features of the building and a summary of structural design. We adopted optimal seismic isolation equipment simulated by dynamic analysis to minimize building damage. Secondly, a summary of the wind load design and strategies for wind-induced vibration reduction are explained. Lastly, this paper focuses on the building performance evaluated using observed acceleration records of the building on an earthquake and a strong wind. We carried out some studies using dynamic analysis and random decrement (RD) technique; we confirmed that the seismic shaking and wind-induced vibration were effectively reduced as designed.

**Building Overview**

The building consists of three volumes: one substructure, which includes basement and lower floors, and two superstructures. One is named Main Tower (office), and the other is South Tower (hotel). Seismic isolation layers are above the ground floor; we call it mid-story seismic isolation. Figure.1 shows the facade of the building and Figure.2 shows the section. Main Tower is 26 story above ground, the South Tower is 19 story above ground, sharing 3-story basement. The South Tower 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. Table.1 shows the facts and figures.

![Figure.1 Facade of the building](image1)

![Figure.2 Section of the building](image2)

### Table.1 Building facts and figures

<table>
<thead>
<tr>
<th>Facts</th>
<th>Figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Tekko Building</td>
</tr>
<tr>
<td>Main Function</td>
<td>Office(Main), Hotel(South)</td>
</tr>
<tr>
<td>Structural</td>
<td>Steel</td>
</tr>
<tr>
<td>Completion</td>
<td>2015</td>
</tr>
</tbody>
</table>
**Structural Overview**

**Structural feature**
Figure.3 shows the structural features. Both buildings are made of steel-frame above the ground, steel-reinforced-concrete under the ground, and the foundation is made of reinforced-concrete. Main Tower has studs and braces in the moment-frame to improve stiffness of the structure. South Tower has 3 columns in one frame, but the center column is floating on the seismic isolation layer. So the vertical load of center column is transferred to rubber bearing under outer column. It is effective to defuse seismic tensile stress applying to rubber bearings. On the top of South Tower, there are two Tuned Mass dampers to reduce wind-induced vibration.

![Figure.3 Structural features](image)

**Seismic isolation**
In Main Tower, 48 rubber bearings are set under each column. Rubber bearings are marked in blue. Two types of dampers are installed. One is a U-shaped steel damper indicated in red, and shown in this picture. The other is oil damper indicated in blue or green rectangle. 32 oil dampers out of 40 have a locking mechanism to reduce wind-induced vibration. South Tower is simpler than Main Tower’s. 10 rubber bearings and 8 oil dampers. (Figure.4)

![Figure.4 The configuration of seismic isolators](image)
Outline of the Seismic Design

Seismic design and dynamic analysis
Table 2 shows performance objectives. According to the Japanese Building Codes, seismic design carried out against 2-level earthquakes. These objectives mean almost no damage under level-1 earthquakes, and slight damage is allowed under level-2 earthquakes. But even under the level-2 earthquake, there will be almost no damage according to the results of our analysis.

We made non-linear multi-story vibration analysis models (Figure 5). The model is consisted of one substructure-part and two tower-parts. And seismic isolation layers have a rubber bearing spring and damper springs in parallel. Table 3 shows natural periods of the model. Ti stands for period where the seismic isolation layer has initial stiffness, and Teq stands for period where the seismic isolation layer has secant stiffness of 30cm lateral deformation. The 1st periods of Teq exceed 5 seconds using the seismic isolation.

![Figure 5 Vibration analysis model]

<table>
<thead>
<tr>
<th>Earthquake Hazard Level</th>
<th>Level-1 (50yrs Return Period)</th>
<th>Level-2 (475yrs Return Period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superstructure Frames</td>
<td>Remain Intact(*1)</td>
<td>No Yielding(*2)</td>
</tr>
<tr>
<td>Story Drift</td>
<td>0.5% Transient</td>
<td>1% Transient</td>
</tr>
<tr>
<td>Seismic Isolation (Rubber Bearing) Stress</td>
<td>No Tensile Stress</td>
<td>Tensile Stress less than 1.0N/mm²</td>
</tr>
<tr>
<td>Drift</td>
<td>200% Transient</td>
<td>267% Transient</td>
</tr>
<tr>
<td>Substructure Frames</td>
<td>Remain Intact(*1)</td>
<td>No Yielding(*2)</td>
</tr>
<tr>
<td>Story Drift</td>
<td>0.5% Transient</td>
<td>1% Transient</td>
</tr>
</tbody>
</table>

(*1) less than allowable stress,  (*2) less than elastic limit

![Table 3 Natural periods]

(M) Main Tower,  (S) South Tower
Condition of isolation system is …
(*1) initial stiffness
(*2) secant stiffness under 30cm deformation
Figure 6 is the results of Main Tower analyses in the case of Level 2 earthquakes. From the response analysis results, it was found that the maximum response of story drift was 1/184 for the Main Tower (Y direction). Also, the displacement of the seismic isolation layer was 336 mm for the Main Tower. It is found that most of all drift angles are almost less than 0.5%, and it is nearly half of the Level 2 criterion of 1%. The displacements of the isolation layer are in the range of 15 to 35 cm. And displacements of the substructure are very small; it means the substructure has almost no damage under the Level 2 earthquakes. The result values of South Tower are almost as same as Main Tower, so that the details of South Tower are skipped in this paper.

Wind load design
The wind load is affected by various conditions such as the building shape, the surrounding environment, and the building structural properties. Design wind speeds are determined according to the Japanese Building Codes. Wind load design carried out with 2 levels strong wind. The maximum design wind speed of level 1 is 34 m/s and that of level 2 is 42.5 m/s in Tokyo. We carried out wind tunnel tests to determine design wind load. Design issues for wind loads are; structural frame, seismic isolation system, occupants’ comfort in the hotel, and elevator availability in Main Tower. Design issues and criteria are summarized in Table 4. Structural frames and seismic isolation members are designed not to be damaged under level-2 wind. We set a target vibration value for occupants’ comfort according to a guideline, and set target displacements for elevator availability under strong wind.

**Outline of the Wind load Design**
Table.4 Performance objectives in wind load design

<table>
<thead>
<tr>
<th>Design issue</th>
<th>Wind Level</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Frame</td>
<td>Level 2 (500yr RP.)</td>
<td>Stress : less than allowable stress</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Drift : less than 0.5%</td>
</tr>
<tr>
<td>Seismic Isolation System</td>
<td>Level 2 (500yr RP.)</td>
<td>Drift : less than design clearance (60cm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Isolator : no tensile stress</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damper : no fatigue failure, remain intact</td>
</tr>
<tr>
<td>Occupants’ Comfort (South Tower)</td>
<td>1yr RP.</td>
<td>H-30 (Guidelines of Architectural Institute of Japan)</td>
</tr>
<tr>
<td>Elevator Availability (drift of Isolation Layer)</td>
<td>Level 1 (50yr RP.)</td>
<td>Operational (less than 4cm drift)</td>
</tr>
<tr>
<td></td>
<td>100yr RP.</td>
<td>Operable after inspection (less than 25cm drift)</td>
</tr>
<tr>
<td>(Main Tower)</td>
<td>Level 2 (500yr RP.)</td>
<td>Loss of use. Operable after repairing. (less than 40cm drift)</td>
</tr>
</tbody>
</table>

**Tuned mass damper (TMD)**

Two tuned mass dampers (TMD) are installed on the top of South Tower. They are expected to reduce wind-induced vibration. The TMD is a single pendulum; it is made up of a 30 ton weight and small rubber bearings. (Figure.7)

Figure.8 shows the results of numerical studies of wind-induced vibration. The black line shows the vibration without TMDs. Red line indicates the case with 30 ton TMDs, and blue line indicates the case with 50 ton TMDs. Maximum acceleration is reduced from 5.4 to 2.0 cm/s². It is almost 40% reduction, and the difference between red line and blue line is small. So we adopted 30 ton TMDs.

Figure.7 Section of the TMD

Figure.8 Dynamic analysis under 1yr return period wind load (1/3 octave band analysis)
Oil damper with locking mechanism (ODLM)

In Main Tower, which has a large area affected by strong wind, the elevators pass through the seismic isolation layer. They are controlled to be out of service when the displacement of the seismic isolation layer exceeds 4cm. The elevators want being available under a certain strong wind, so the displacement needs keeping down as small as possible. Therefore ODLM was adopted. ODLM are locked using a solenoid valve during strong winds. They are set to be locked to be locked in case that 25m/s or more wind speed detects at the top of the building, and to be unlocked after being below 25m/s for 1 consecutive hour.

Unlocked and locked state is described in Figure.9. Normally a piston rod moves with a certain damping. This is unlocked state. In case the anemometer detects 25m/s-or-more-wind-speed on the top of the building, all inner valves are shut to lock the damper.

Table.5 shows the results of numerical simulations. We confirmed that the elevators are available even if 100 year return period wind occurs in Tokyo.

![Figure.9 Unlocked and locked state of ODLM](image)

Table.5 Results of numerical simulations

<table>
<thead>
<tr>
<th>Return period</th>
<th>Max. wind speed</th>
<th>Disp. of isolation layer</th>
<th>ODLM</th>
<th>Elevator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 year</td>
<td>17m/s</td>
<td>Less than 2cm</td>
<td>Unlocked</td>
<td>Service</td>
</tr>
<tr>
<td>4 to 5 years</td>
<td>20 to 25m/s</td>
<td>Less than 2cm</td>
<td>Unlocked</td>
<td>Service</td>
</tr>
<tr>
<td>50 years</td>
<td>34m/s</td>
<td>1.5cm</td>
<td>Locked</td>
<td>Service</td>
</tr>
<tr>
<td>100 years</td>
<td>38m/s</td>
<td>1.9cm</td>
<td>Locked</td>
<td>Service</td>
</tr>
<tr>
<td>500 years</td>
<td>42.5m/s</td>
<td>12.3cm</td>
<td>Locked</td>
<td>Out of service</td>
</tr>
</tbody>
</table>

Performance Evaluation of the Building under Earthquake and Strong Wind

After completion of the building, the vibration of the building has been observed under earthquake and strong wind. The objectives of the observation are to evaluate the effect of the seismic isolation and to confirm that ODLM works properly during strong wind. Some numerical studies were carried out using observed acceleration data as follows.
Performance evaluation under earthquake

A M7.4 earthquake with the epicenter in offshore Fukushima Prefecture occurred on November 22nd, 2016. The seismic intensity in Tokyo was 3 (JMA scale). Figure 10 shows the observed acceleration in the building. The maximum accelerations were; 19.2 cm/s² (5F) and 7.0 cm/s² (19F) in South Tower, 18.3 cm/s² (3F) and 15.1 cm/s² (24F) in Main Tower. In South Tower, comparing the acceleration wave of 19th floor and 5th floor, we can see that the main shock in 50 to 100 seconds was reduced because of the effect of the seismic isolation. On the other hand, in Main Tower, although the main shock had been reduced, it had been shaking long after that. It is considered that the seismic acceleration was not so strong as to start to work the oil dampers.

In order to compare the observed vibration and the analytical result, a numerical study is carried out using dynamic analysis model and observed records. First of all, natural periods are determined by the response spectra ratio. Figure 11 shows the results. Next, the damping factors of the structure are identified by ARX model [3]. According to these analyses, the 1st mode period and damping factor are determined 4.1 seconds and 2.1 %, respectively.

The dynamic analysis is carried out using these vibration characteristics. Figure 12 shows the time history acceleration responses under the earthquake. Black line indicates the observed and red line indicates the analysis result. There is large amplification from 330 seconds after occurrence of the earthquake for the long period component of the seismic wave. From the point of view of the maximum value, the observation records roughly correspond to the result of analysis well.
Performance evaluation under strong wind

A relatively big typhoon passed around near Tokyo on October 23, 2017. The upper chart in Figure.13 shows the observed wind speed at the top of the building. And ODLM state is also indicated. In time within red line, ODLM were locked just after wind speed exceeded 25m/s. Figure.13 also shows the observed floor acceleration in 24th floor in Main Tower and 19th floor in South Tower. The chart of Main Tower indicates that the maximum floor acceleration was within 2cm/s² during ODLM was locked. And in South Tower, the maximum floor acceleration was also within 2cm/s².

Using these acceleration data, the first natural periods and damping factors are evaluated by the random decrement (RD) technique. The RD technique is applied for evaluation of the damping ratio of full-scale buildings, and it is said to be very useful for evaluation of the damping ratios of actual building under random excitation like wind loads. [4].

The first natural periods and damping factors are evaluated each of the towers. Figure.14 shows the free vibration wave calculated by the RD technique. The damping factors are estimated to be 5.5% for Main Tower and 11.1% for South Tower by the least-squared-method fitting. The damping factor of Main Tower is the value when ODLM are locked. Compared to that, the damping factor of South Tower is almost twice that of Main Tower. It is considered that the oil dampers and TMD in South Tower were very effective in the strong wind.

![Observed records on Oct. 23, 2017 (from 4:00 to 6:00)](image)

![Evaluation of damping ratio under the strong wind](image)
Conclusions

This paper described the structural features and design of the high-rise seismic isolated building, which 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. The primary goal of the structural design of this building was to secure greater safety against the largest earthquake expected in Tokyo. In addition, we adopted some strategies, which are oil dampers with locking mechanism installed in the Main Tower and tuned mass dampers on the top of South Tower, to reduce wind-induced vibration.

After completion of the building, the vibration of the building has been observed under earthquake and strong wind. In 2016, a seismic acceleration of seismic intensity 3 was observed. The dynamic analysis is carried out using observed acceleration. We confirmed that the observation records roughly correspond to the result of analysis well. In October, 2017, a relatively big typhoon passed around near Tokyo. Using the wind-induced acceleration data, the first natural periods and damping factors are evaluated by the random decrement (RD) technique. According to the data and the analysis it is confirmed that the oil dampers and TMD in South Tower were very effective in the strong wind.

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

Acknowledgments

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.

References


