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A Seismic Control Structure that Reduces the Seismic Response of the Entire Building by Absorbing Seismic Energy Intensively in the Seismic Isolation Layer Installed on the Middle Floor of Tall Building

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Abstract The base-isolation system is one of the structural systems with the best seismic performance. In Japan, seismic isolation structures have been used in many buildings after the Great Hanshin-Awaji Earthquake, partly due to the development of various devices. In addition, seismic isolation bearings are becoming larger in diameter, resulting in an increasing number of seismic isolated tall buildings exceeding 100 meters in height. On the other hand, there are cases in which the intermediate floors are seismically isolated because the axial force that can be supported is limited by the bearing diameter. This report presents a case study of a 43-story tall building over 200 meters in height, consisting of a hotel, offices, and other multiple uses, in which a seismic isolation layer was installed on the 38th floor, and dampers were intensively placed to provide both functionality and high seismic safety.

Keywords Tall building, Seismic control system, Seismic isolation layer, Period, Damping

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1. Introduction

Various architectural and structural design restrictions arise when installing seismic isolation layers on intermediate floors. The seismic isolation layer is limited to the floor compatible with the architectural plan, and it is necessary to secure horizontal clearances and accommodate vertical flow lines for elevators and other equipment. Structurally, the weight balance of structures above and below the seismic isolation layer is inevitably determined by which story the isolation layer is installed, and given that weight balance, the design of period and damping of the isolation layer is essential. The structures above and below the seismic isolation layer are also important. This paper introduces key points in the structural system for a case study of a tall building in Tokyo with a height of over 200 m.

2. Outline of Building

The tall building consists of 43 floors above ground and 3 floors below ground, 210 meters high, consisting of offices, a hotel, residences, stores, an exhibition hall, and a parking lot. Figure 1 shows a projected exterior view of the building, and Figure 2 shows a cross-sectional view of the building. The 5th to 36th floors is offices, the 38th to 43rd floors are a hotel, the 1st to 3rd floors are stores and



Figure 1. Projected Exterior View.

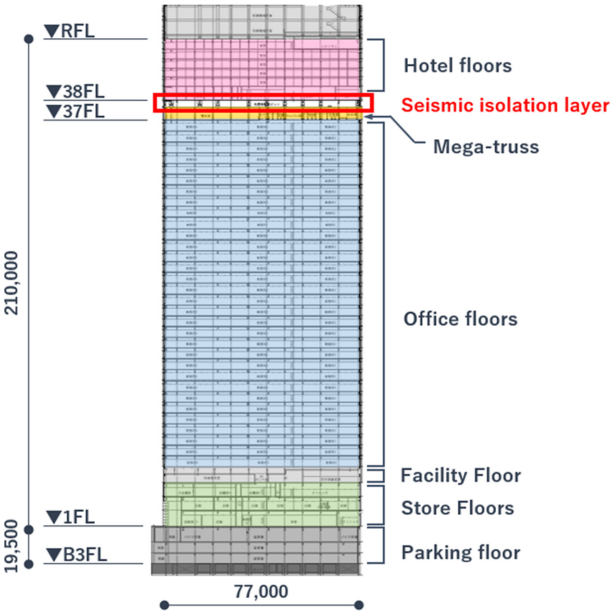


Figure 2. Usage Configuration.

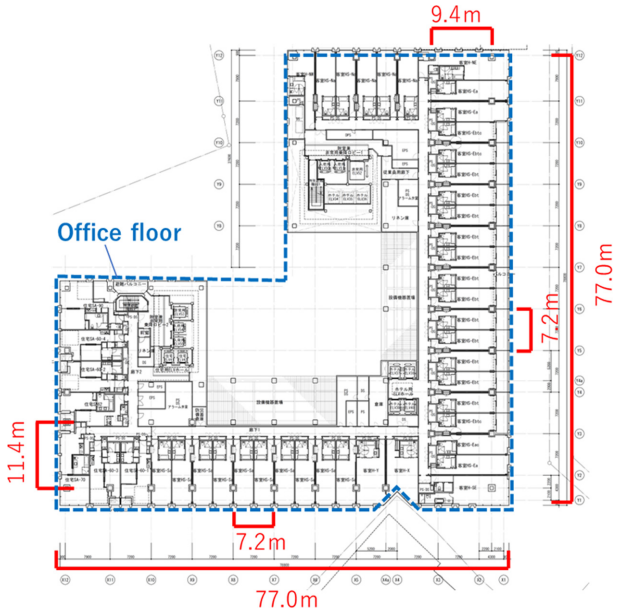


Figure 4. Typical Hotel Floor Plan.

exhibition facilities, and the 1st to 3rd basement floors are a parking lot.

The floor plan is L-shaped, with the basement part measuring approximately 100 m × 97 m and the above-ground part 77 m × 77 m. The column spacing for the office floors are 21.6 × 7.2 m (Figure 3), and the typical floor height is 4.3 m. The column spacing for the hotel floor is 9.4 m × 7.2 m and 11.4 m × 7.2 m (Figure 4), and the typical floor height is 3.6 m. As mentioned above, the floor between the office floors and the hotel floors is a seismic isolation layer, and the machine rooms and hotel backyard are planned to be on the 37th floor directly below the seismic isolation layer.

Location: Minato-ku, Tokyo

Building Use: Offices, Hotel/Residential, Retail, Exhibition space, Parking place

Building Area: 6,732.22 m^2

Floor Area: 208,354.12 m^2

Typical Floor Area: 4,277.56 m^2

Number of Floors: 3 floors below ground, 43 floors above ground, 2 floors of penthouse

Building Height: GL+210.5 m

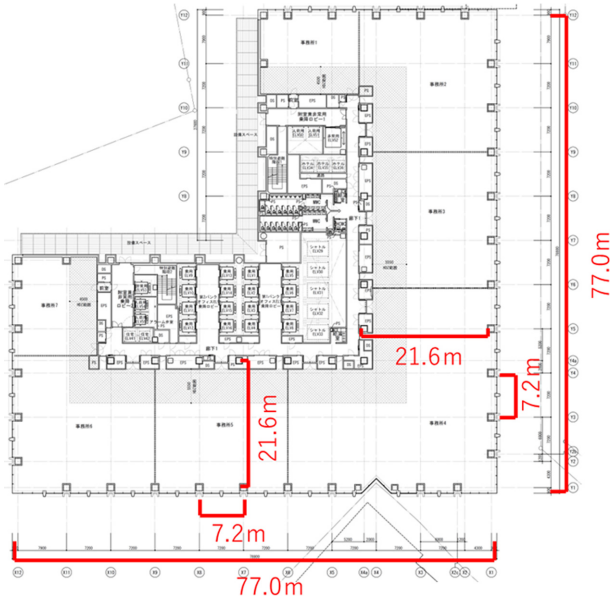


Figure 3. Typical Office Floor Plan.

3. Outline of Structural Design

The main structure of the superstructure is a steel frame, and CFT columns are adopted to the structural framing below the seismic isolation layer. Figure 5 shows the overall structural system. As the seismic control system, the seismic isolation layer installed on the 38th floor, between the office floors and hotel floors, is critical in controlling seismic behavior. This seismic control system reduces the seismic response of the entire building by absorbing seismic energy intensively in the seismic isolation layer. The seismic isolation system consists of laminated natural rubber bearings and oil dampers. Details are described below in Section 4.3. The mega-truss structure directly below the isolation layer is designed to accommodate different column spacing on upper and lower floors and increase the rigidity of the lower structure. Multi-layered braces are placed below the seismic isolation layer on all stories to prevent deformation from concentrating in a particular layer. Short-span beams connected to the multi-layered braces are low-yield steel. During earthquakes, these short-span beams are designed to yield ahead of the main structure

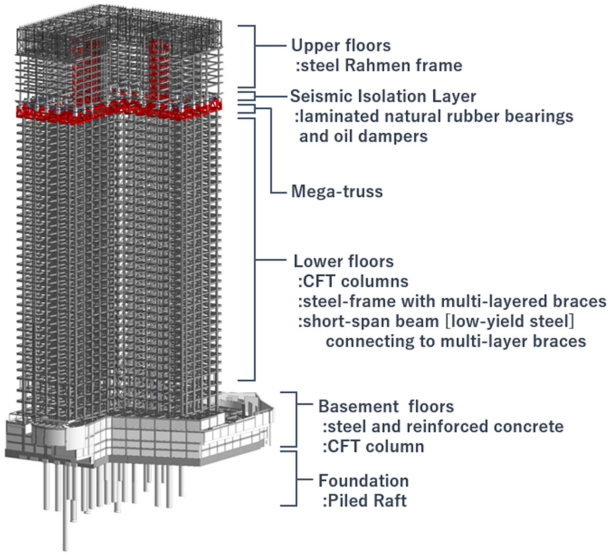


Figure 5. Structural System.

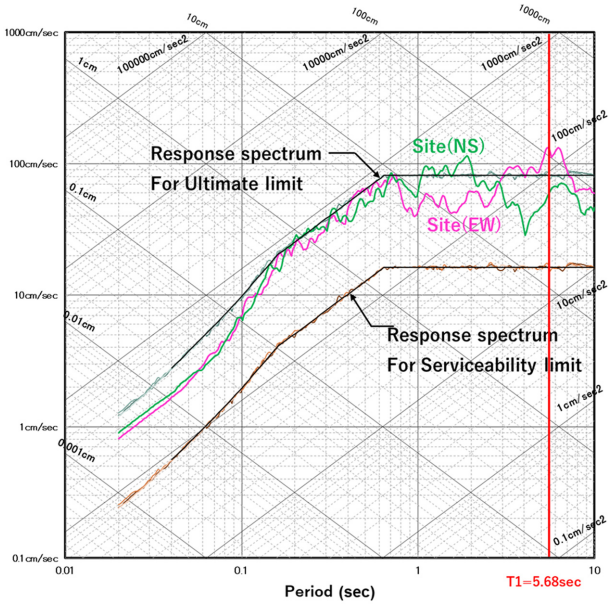


Figure 6. Response spectra of seismic load.

to keep the main structure elastic. The structure above the seismic isolation layer is a steel Rahmen frame that flexibly accommodate hotel guest room plans. The elevator shaft penetrating the seismic isolation layer is designed to be self-supporting from the mega-truss structure. This elevator shaft is a steel-braced frame to minimize deformation during earthquakes, and sufficient clearance is provided at the boundary between the elevator shaft frame and the seismically isolated upper frame.

3.1. Seismic Design

3.1.1. Seismic Loads

Seismic loads for ultimate limit state design are broadly classified into two types: the seismic load based on the response spectrum of 500-year return period shown in the standard, and the seismic load based on the site's characteristics. Seismic loads for serviceability limit state design are based on the response spectrum of 50-year return period shown in the standard. (Figure 6)

These seismic loads are defined as follows.

(1) Ultimate Limit State
  1. Standard Seismic Load [return period: 500-year]
  2. Site Seismic Load

(2) Serviceability Limit State
  1. Standard Seismic Load [return period: 50-year]

3.1.2. Seismic Design Criteria

Seismic design criteria are defined as follows.

(1) Ultimate Limit State Design
  Structural Elements: within allowable stress [above isolation layer]
  within elastic limit [below isolation layer]
  the degree of cumulative damage < 0.2 [low-yield steel]
  Rubber Bearing: within allowable stress, shear strain ratio < 250%
  Story Drift Angle: < 1/200 [above isolation layer], < 1/150 [below isolation layer]

(2) Serviceability Limit State Design
  Structural Elements: within allowable stress
  Rubber Bearing: within allowable stress, shear strain ratio < 200%
  Story Drift Angle: < 1/300

3.2. Wind Design

3.2.1. Wind loads

Wind loads can be affected by various factors, such as the shape of the building, the environment around the building, and the structural characteristics of the building. Therefore, wind design loads were evaluated based on the wind tunnel test. Wind design pressure is based on the time history data of wind force coefficients obtained by the wind tunnel test. In Japanese standards, two levels of wind loads, 500-year return period for ultimate limit state design and 50-year return period for serviceability limit state design, are required. In this project, the wind design criteria for ultimate limit state are set close to the seismic design criteria for serviceability limit state design. Therefore, the wind load of 50-year return period is omitted. In addition, the wind velocity of 1-year return period was adopted for the evaluation of habitability.

These adopted wind velocities are as follows.

(1) Ultimate Limit State: v = 62.0 m/sec
(2) Habitability Limit State: v = 28.3 m/sec

3.2.2. Wind Design Criteria

The wind design criteria are defined as follows.

(1) Ultimate Limit State
  Structural Elements: within allowable stress
  Rubber Bearing: within allowable stress, shear strain

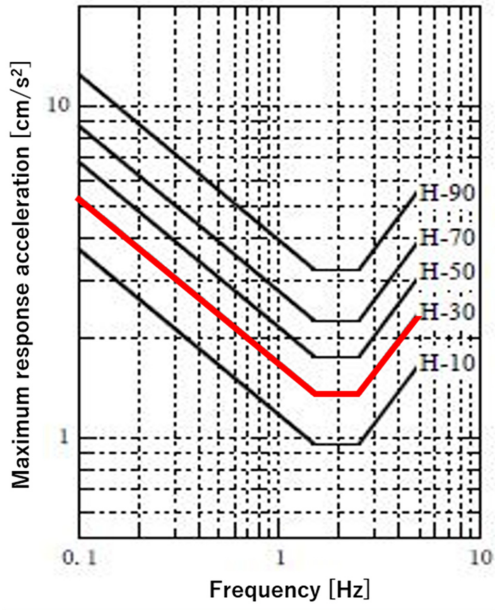


Figure 7. The curve of performance evaluation for horizontal vibration [1].

ratio < 250%
Story Drift Angle: < 1/300

(2) Habitability Design
The degree of habitability: < H-30
The curve of performance evaluation for horizontal vibration is shown below (Figure 7). "H-30" indicates a performance level at which 30 percent of people feel vibrations.

4. Overview of Seismic Response Control System

The seismic control system used in this building features a seismic isolation layer in the middle of the tall building to control the vibration characteristics of the entire building, and dampers which are concentrated in the isolation layer to absorb seismic energy and enhance earthquake resistance efficiently. Therefore, the design of the seismic isolation layer, i.e., the period and damping of the seismic isolation layer are essential. Each of these points is discussed below.

4.1. Period of Seismic Isolation Layer

This project introduces the seismic isolation layer on the relatively high 38th floor of the 43-story building above ground. As a result, the weight ratio of the upper and lower structures is approximately 2:8. As for the periodic characteristics, the primary period of the upper structure is 1.2 sec for a height of roughly 25 m, and the primary period of the lower structure is 3.9 sec for a height of roughly 170 m. The Kanto Plain[1)], where the

[1)] the most extensive lowland in Japan, located in central Honshu including Tokyo, facing the Pacific Ocean.

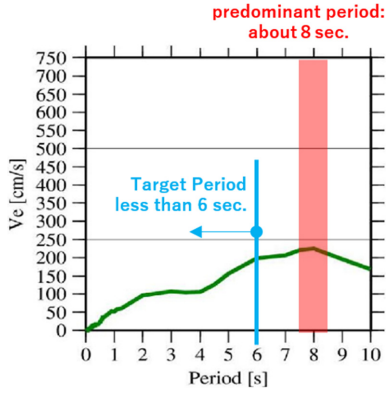


Figure 8. Response spectra of the site wave (South Kanto earthquake).

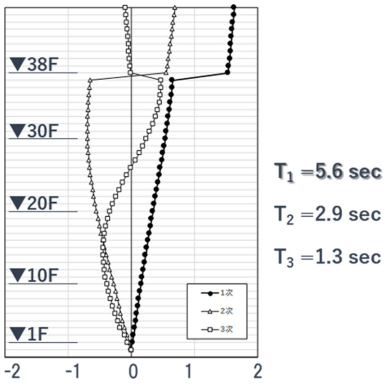


Figure 9. Modal Participation Function.

building is located, has the characteristic of having a predominant period of around 8.0 sec due to its geological formation. Therefore, the target period of the seismic isolation layer should be set to 4.0 sec to keep the primary period of the entire building, including the seismic isolation layer, less than 6 sec (Figure 8).

Figure 9 shows the modal participation function of the entire building when the seismic isolation layer's period is set to 4.0 sec [provided the weight ratio of the upper and lower structures (upper: lower = 2:8) and the primary period (upper:1 sec, lower:4 sec)]. The primary period T1 of the entire building is 5.6 sec, which satisfies the target period.

4.2. Damping of seismic isolation layer

In setting the damping value of the seismic isolation layer, the effects of the damping on the response shear of the entire building and the response displacement of the seismic isolation layer were studied. In this study, the building was replaced with a two-mass model consisting of the upper structure and lower structure, and the response analysis was conducted using the damping of the isolation layer as a parameter. The damping value α is defined as the ratio of the total maximum damping force of the seismic isolation layer damper to the weight of the

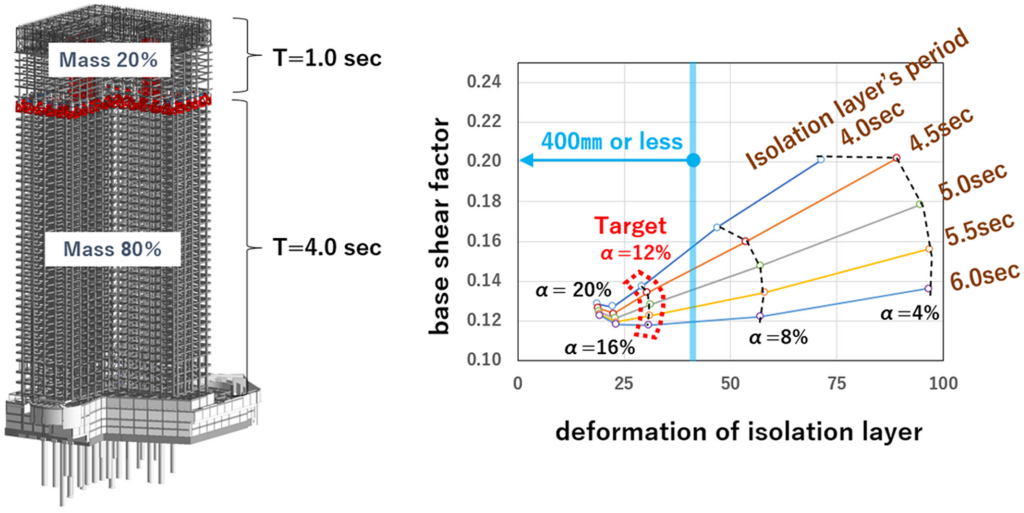


Figure 10. Response Results.

superstructure, as follows

α = (Total maximum damping force of seismic isolation layer)/(Weight of superstructure)

For reference, five cases of the seismic isolation layer's period [4.0s, 4.5s, 5.0s, 5.5s, 6.0s] were also assumed, and the effect of the seismic isolation layer's period was also verified at the same time.

Figure 10 shows the response results for the ultimate limit state seismic load. Each case is plotted with the horizontal axis as the maximum deformation of the seismic isolation layer and the vertical axis as the base shear factor of the first floor of the building. The damping value significantly affects the maximum deformation of the seismic isolation layer, while the impact of the seismic isolation layer's period is relatively small. The base shear factor of the first floor tends to decrease with a longer period of the seismic isolation layer, but the difference is less pronounced when the damping value is higher.

In this study, the criteria for deformation of the seismic isolation layer at the ultimate limit state is defined as 400 mm or less, within which the seismic isolation layer can behave stably, and α = 12% is set as the target damping value that satisfy this criterion with a margin.

4.3. Design of seismic isolation layer

The seismic isolation layer is designed for the target values described in Sections 4.1 and 4.2. Figure 11 shows the layout of seismic isolation devices. A total of 68 seismic isolation bearings were used, all of which were laminated natural rubber bearings and two bearing diameters φ800 and φ900. A total of 80 oil dampers were used, 40 in both the X and Y directions.

The oil dampers system consists of two types: standard oil dampers with a single damping characteristic and

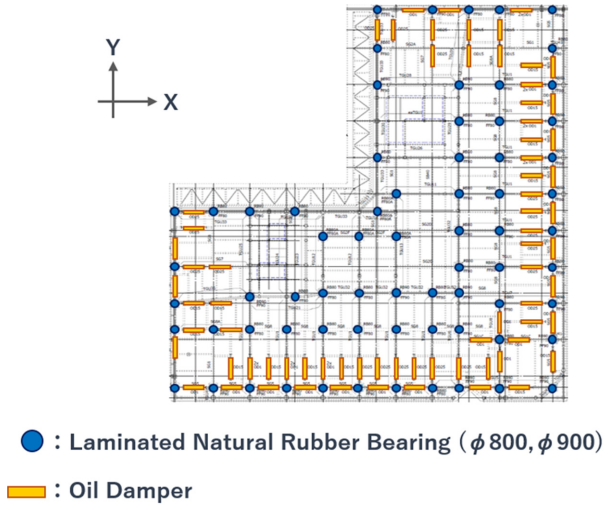


Figure 11. Layout plan of seismic isolation layer.

variable dampers with two damping characteristics, equally introduced in each direction. The variable dampers are set to switch from a low-damping mode to a high-damping mode when the deformation exceeds a set value (Figure 12). This is intended to reduce excessive deformation of the seismic isolation layer by providing higher damping in the event of a larger-than-expected earthquake.

4.4. Design of Lower Structure

In a typical tall building, there are many cases where dampers are placed across all layers of the building. In this building, however, dampers placed in the seismic isolation layer already absorb seismic energy intensively, eliminating the need for dampers in each layer. Instead, multi-layered steel braces are placed on all layers to increase the stiffness of the lower structure as much as possible. The connecting beams between the multi-layered braces and the surrounding frames are steel dampers, and

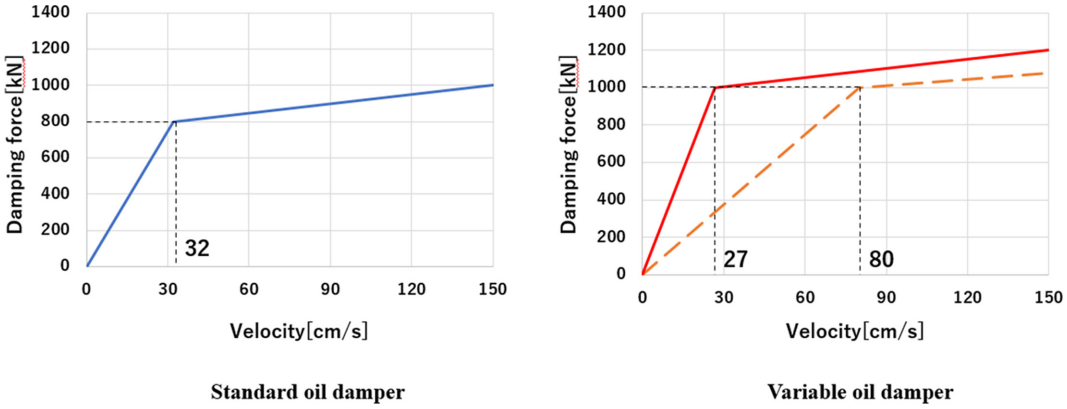


Figure 12. Damping force characteristics.

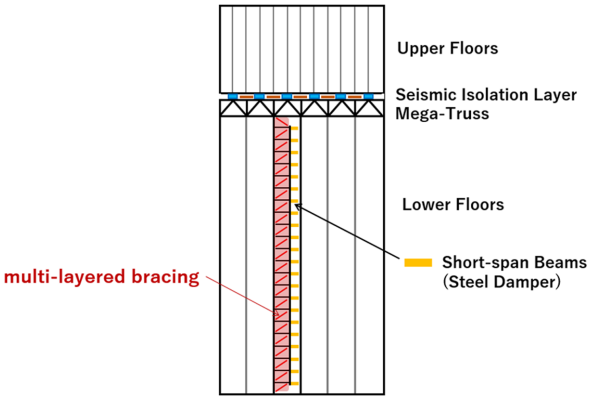


Figure 13. Structural concept of the lower frame.

these beams are designed to yield in advance so that multi-layered braces remain elastic and keep the entire structure almost elastic in the event of an earthquake above the ultimate limit state. Figure 13 shows a conceptual diagram of the lower structure. As a result of the above, the building possesses extremely high seismic performance.

4.5. Verification of Seismic Performance by Seismic Response Analysis

To minimize damage to the building in the event of a larger-than-expected earthquake, the inter-story drift angle criteria for the ultimate limit state design is set to 1/150 or less for the office floors below the isolation layers and 1/200 or less for the hotel floors. Furthermore, all members except for the steel damper on the office floors are set within their elastic limit capacity. This is an extremely high seismic performance compared to the standard inter-story drift angle, 1/100 or less for a standard tall building.

The performance of the above criteria was verified by

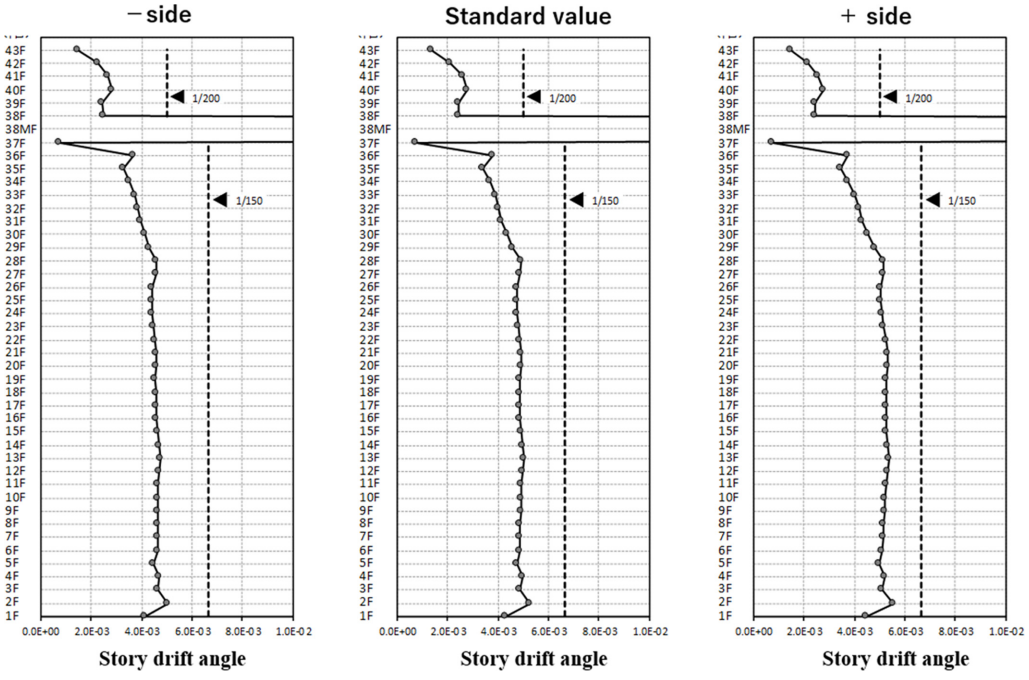


Figure 14. Maximum inter-story drift angle.

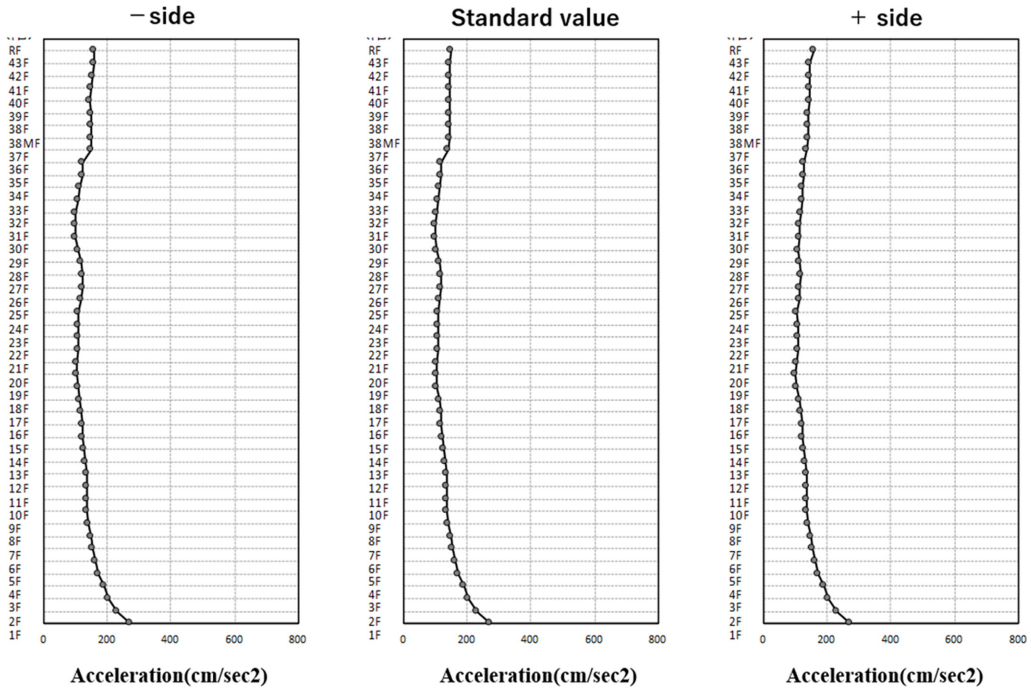


Figure 15. Maximum response acceleration.

time-history response analysis using a three-dimensional model. As a representative case, the response results of a site wave (South Kanto earthquake), created by considering the seismic environment of the planned site among the ultimate limit state earthquake ground motions, are shown. Figures 14 and 15 show the maximum inter-story drift angle and maximum response accelerations, respectively, for a total of three cases, considering the standard values of the seismic isolation bearings and oil dampers and the variations on the + and - sides. In all cases, the values are sufficiently small compared to the criteria, verifying the high seismic safety of the building.

5. Overview of Wind Design

5.1. Comparison of Seismic and Wind Loads

As mentioned in section 3.2, because the building is taller than 200 meters and has an L-shaped plan, wind tunnel tests were conducted to evaluate the wind loads in detail. Specifically, wind pressure was calculated based

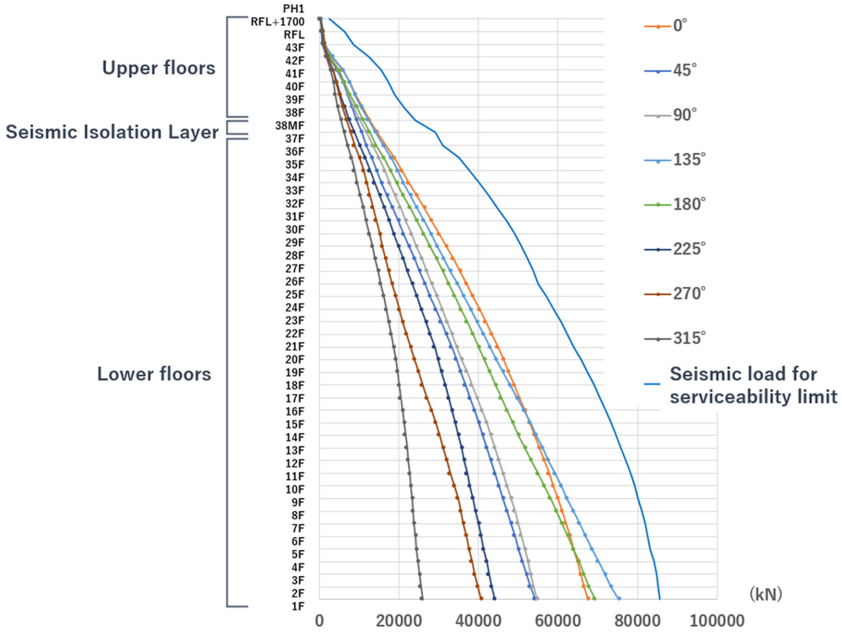


Figure 16. Comparison of seismic load and wind loads.

on the wind force coefficient obtained from the wind tunnel test results, and a time-history response analysis was conducted for all 72 wind directions at a pitch of 5 degrees. Figure 16 shows the maximum response shear force for the ultimate limit state wind loads and the design shear force for the serviceability limit state seismic loads. The design shear force refers to the enveloped shear force of the maximum response shear force in all seismic loads. In all cases, the ultimate limit state wind loads were less than the serviceability limit state seismic loads, indicating that the seismic loads govern the design.

As a verification of habitability performance, the vibration level was evaluated based on the response analysis results for wind loads based on 1-year return period, as shown in Section 3.2.2. As mentioned above, seismic loads govern the design of this building, and a considerable number of dampers are required in the seismic isolation layer. Therefore, as a result, the vibration performance for habitability limit state wind load is verified to be lower than the target vibration level H-30.

6. Conclusions

This paper introduces the design of a seismic isolation layer in the middle of a tall building over 200 m and mainly introduces the key points of the structural design. As shown in this case study, by designing appropriately the period and damping of the seismic isolation layer, the periodic characteristics and damping performance of the entire building can be controlled, enabling buildings to have extremely high seismic performance. The system that absorbs energy intensively in the seismic isolation layer is rational and versatile and can be adapted to various building sizes and structural types. More applications can be expected in the future.

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