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Structural Design of High-Rise Building with RC Frame Using Core Wall and Damping Device; Toranomon-Azabudai Project (B2 Block)

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Abstract

This building has a slender shape with 54 floors above ground, height of 237.2 m, width of 39 m, and aspect ratio of 6.0 in the short side direction. The structure is greatly affected by bending deformation during an earthquake. Due to the small plane, it is necessary to design a structural that can control the bending deformation compactly and efficiently. In order to address these issues, a split wall damping system was proposed. Split wall damping system is a system that efficiently absorbs seismic energy with a velocity-dependent damper using the relative velocity generated when adjacent core walls motion both horizontally and vertically during earthquake. This mechanism was confirmed to be able to ensure high damping performance of the building (h = 2.2%) and contribute to deformation control effectively.

Keywords: Split wall damping system, Oil damper

1. Introduction

This building is located in the Toranomon / Azabudai District Type 1 Urban Redevelopment Project Area as the B-2 block of the Toranomon / Azabudai Project. The site is close to Kamiyacho Station on the Hibiya Subway Line and Roppongi 1-chome Station on the Namboku Line, made it highly convenient for transportation.

In this project, by applying a large-scale land use conversion through urban redevelopment projects, strengthening traffic node functions by improving roads and pedestrian networks in the area, and strengthening residence including hotel functions in order to meet diverse needs could be achieved. One goal of this project is to create a town that can be an international business and exchange base with an environment that helps foreigners to live comfortably.

The building explained is one of three skyscrapers in the whole project, composed of high-rise buildings such as condominiums, hotels and low-rise buildings as commercial facilities.

2. Outline of Architectur

Location:1-12,13 Azabudai,Minato-ku,Tokyo Building use: apartments, hotels, stores, meeting spaces, parking lots, etc.

Performer: Toranomon/Azabudai District Urban Redevelopment Association

Designer: Mori Building Co.,Ltd., Nihon Sekkei Co., Ltd.,

Shimizu Corporation (Underground Structure Design (joint design))

General Constructor: Shimizu Corporation Building area: 8,260.71 m^2

Gross Floor Area: 169,259.20 m^2

Number of floors: 5 basement floors, 54 floors above ground, 2 floors of penthouse

Building height: 237.20 m

Structural type: RC Structure (Partially S Structure, SRC Structure)

Foundation structure: Spread foundation

Seismic devices: Oil damper, viscous Wall damper

Others: Vibration control system using core wall (Split wall damping system)

3. Building plan

This building consists of a high-rise building and a low-rise building (2^{nd} to 5^{th} floors) that attached to the high-rise building, also a basement with depth of lower than 2 floors that covers the entire site.

The high-rise building consists of hotels at the lower floors, and apartments at the middle and higher floors. By switching the span of some columns on the boundary floor, an effective functional plan for both hotels and

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Fig. 1. All blocks perspective.

apartments could be realized.

The lower part is composed of a glass box that creates a lively atmosphere and an organic frame shape that expresses the undulations of the lush terrain as a design language that unifies the entire block. By arranging the greened low-rise part so as to surround the high-rise part, the oppression feeling to the surrounding area can be reduced and a lush landscape can be formed.

There is a level difference in the east-west direction of the site. The ground floor is from the 2nd floor above due to the relationship with the adjacent block.

4. Structural plan

4.1. Above-ground part structural plan

The plan shape of the high-rise part is about 39 m × 56 m, having a center core type. The standard span of 6.7 m and a short span of 3.9 m for the core and a long span of up to 10.65 m for the living room were designed in order to realize a highly flexible design plan. The aspect ratio in the short side direction is 6.0.

The outer peripheral columns were provided with large cross-section (1300 × 1800 to 2180 in the short side direction, 1300 × 2900 in the long side direction) in order to control the bending deformation during an earthquake, also the outstanding bending deformation caused by the high aspect ratio. The 2nd floor column is using Fc120 concrete with steel fibers contained to prevent the cover concrete from peeling off and ensuring a shear margin against unexpected earthquakes.

L-shaped walls (split walls, thickness 1200 mm to 1300 mm) are placed at the four corners of the core to improve seismic performance by preventing local layer rigidity of the building from decreasing and excessive deformation during an earthquake.

In addition to installing a viscous wall damper as a seismic damping device (4 devices at long side, 1 device at short side), energy absorption efficiency can be improved by connecting two split walls (start from the ground) with oil dampers arranged in parallel. This system is called a "Split wall vibration damping system". By adopting this

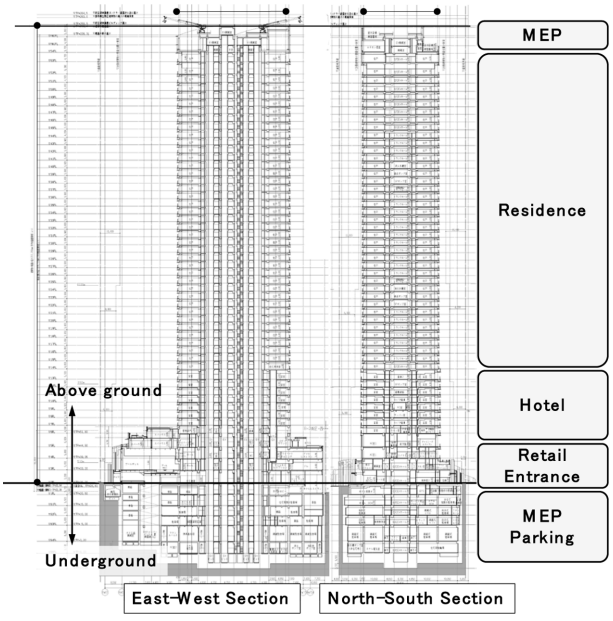


Fig. 2 Elevation and building use.

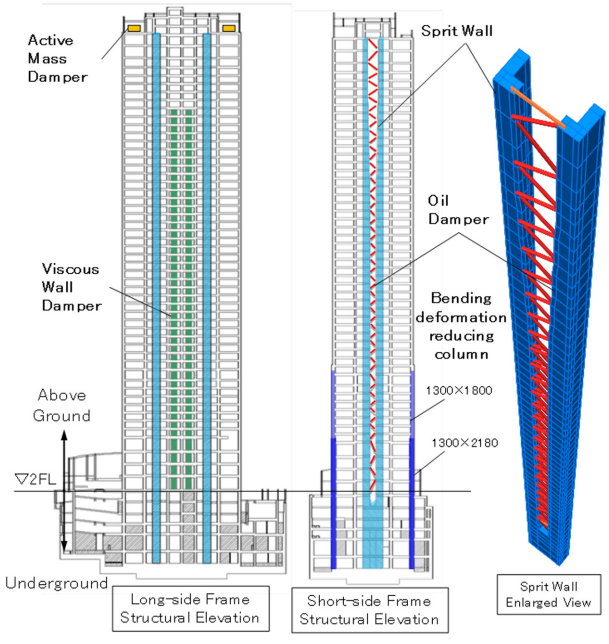


Fig. 3. Damping system and sprit wall.

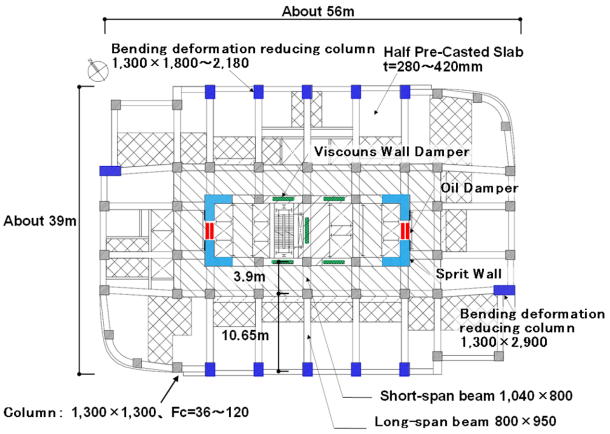


Fig. 4. Structural plan outline in floor plan.

system, the damage to the building during a large earthquake can be minimized, and almost no hinges will occur on the beam during a level 2 earthquake. It is also possible to suppress the damage and deformation even on the short side of the building with a large aspect ratio.

To resist the repeated deformation of the split wall, the short span beam connecting the sprit wall were designed with short depth to reduce the shear stress. In addition, to provide sufficient stiffness of the beam, concrete containing steel fibers were adopted.

This building is also designed by considering the livability level. In the living room, the sound insulation performance is improved by the half PCa void slab (partially solid slab) of up to 420 mm while reducing the vibration propagation to the adjacent dwelling unit and the dwelling units on the upper and lower floors by connecting the column and the girder. In addition, AMD is installed on the rooftop to improve the living performance against wind sway.

4.2. Split wall damping system

Two brace-shaped oil dampers (maximum damping force of 2000kN) are arranged in parallel on the split wall installed in the direction of the short side of the building. The oil damper was designed to exert damping performance efficiently and enhance the damping effect by generating horizontal and vertical relative velocities between the two walls that tend to split apart during an earthquake. A slit is provided between the split wall and the slab to ensure that the slab is structurally separated with the wall to prevent harmful slab cracks.

In case of a rigid beam provided between the split walls, the movement between the walls will be restrained and the energy absorption by the damper will decrease. Therefore, instead of providing a rigid beam, steel beams with pins on both ends are provided on the top and legs of the split wall to handle the reaction force of the damper.

Table 1 shows an excerpt of a case study in shape selection of the core wall.

When the core wall of Case 1 is a fully multi-layered

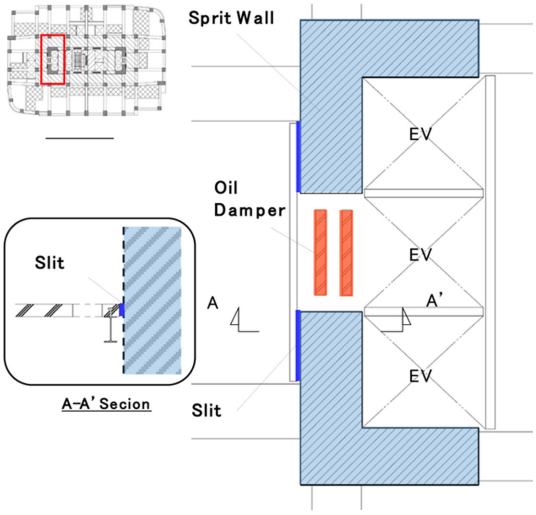


Fig. 5. Sprit wall in floor plan.

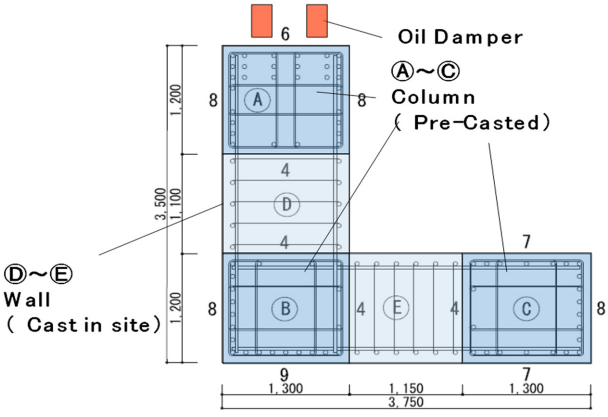


Fig. 6. Sprit wall detailed diagram.

Table 1. Case study of wall shapes

Case	0(Apply)	1	2
Wall Shape	Split Y Shape	No Sprit	Split Straight
Natural Period	5.15sec	4.94sec	5.16sec
① Interlayer deformation angle at 6th story	1.00 (benchmark)	0.90	1.05
② Effective period by response	6.6sec	6.4sec	7.0sec
③ Absorbed energy by damper / strain energy ratio	1.8	1.0	1.2

shear wall, the shearing force of the lower layer can be suppressed by the shearing force of the wall, but the

shearing force of the response layer itself increases due to the increase in horizontal rigidity, causing the damage control effect of the frame cannot be exhibited efficiently in this building. In addition, there are also some disadvantages, such as the difficulty in designing for the tensile force generated on the wall leg due to the increment of the horizontal rigidity, the amplification of acceleration on the top of building, etc.

When the damper is attached so that the space between the walls is widened and the horizontal direction is predominant as showed in Case 2, even though energy is well absorbed, the horizontal rigidity decrement is largely affected. The ideal shape is to increase the energy absorption efficiency while ensuring horizontal rigidity.

Based on the study above, the following three conditions were emphasized in the structural plan of this building.

(1) Suppressing the deformation of lower floors where stress increases as a condition for ensuring rigidity.
(2) Suppressing the elongation of the effective period of the building under seismic response condition (calculated by Fourier spectrum from the time history waveform after the maximum response deformation).
(3) Securing a larger additional damping (absorbed energy by the damping member) against damage (absorbed energy by strain) from the viewpoint of energy absorption.

In Case 0, the wall width is widened to the center of gravity of the building to ensure rigidity, and the wall width is reduced on the upper floors to control the deformation of the lower floors and the amplification of the upper floors.

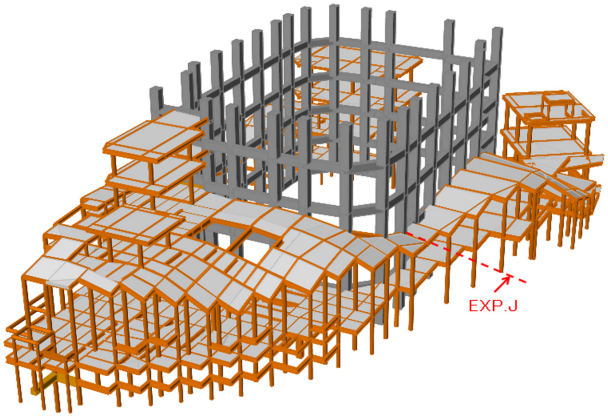


Fig. 7. Structural frame for surrounding low-rise areas.

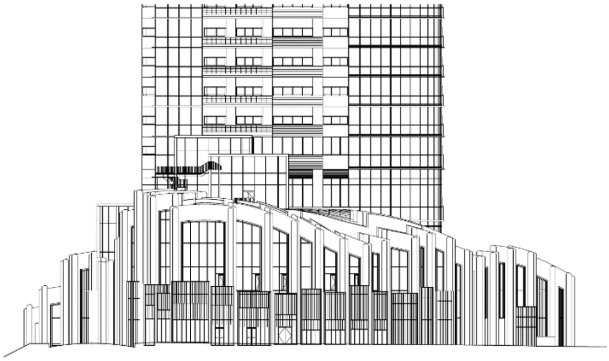


Fig. 8. low-rise areas Elevation

4.3. Surrounding low-rise areas structural plan

As shown in Fig. 7, the surrounding low-rise part draws a gentle curve and attaches the high-rise part at the 2nd to 5th floor levels. With the structure of pure rigid steel frame, connected to the high-rise part via slab, the low-rise building was designed to behave integrally with the high-rise part due to the surface rigidity of the slab during an earthquake. The roof has a curved surface that straddles some floors, and expansion joint is installed where the beams are brace shaped.

4.4. Basement and foundation structural plan

The basement has a flat shape of about 120 m in the east-west direction and about 70 m in the north-south direction with the curve along the road boundary as the outer line, and is composed of 5 basement floors. However, since the 2nd floor above ground is close to the exterior level, in the calculation, the basement is considered to be from the 5th basement floor to the 1st floor above ground.

The basement structural were designed as a rigid underground structure suitable for the 230 m-class high-rise buildings' basement. It has a rigid frame structure with bearing walls, mainly constructed with reinforced concrete. The thickness of the second floor above ground is set appropriately so that the seismic force of the upper floors can be transmitted to the seismic walls of the lower floors.

The foundation type is a spread foundation using a mat slab, and the area directly below the high-rise part and the 5th basement floor around it (foundation bottom = TP-14.7 m~17.2 m) are supporting the Kazusa layer with an N value of 50 or more. The 4th basement floor on the west side (foundation bottom = TP-7.7 m) is supporting the Tokyo layer with an N value of 30 or more. The long-term allowable bearing capacity was designed to be 1500 kN/m^s for the 5th basement floor and 800kN/m2 for the 4th basement floor. In addition, as confirmation of the bearing capacity, a deep load test and a flat plate load test are conducted.

5. Seismic response analysis

5.1. Seismic performance criteria and design input seismic wave

Table 2 shows the seismic performance criteria of this building. In addition to Level 2 design criteria, the design criteria for Level 2 × 1.5 times notifications and regional waves were set in order to achieve higher seismic performance.

For the design input seismic wave, observation waves,

Table 2. Seismic performance criteria

Seismic level	Rare Earthquake	Extremely Rare Earthquake	Earthquake for margin verification	
	Level 1	Level 2	Waves specific to the region and simulated wave	Level 2×1.5
	Recorded wave Notification wave	Recorded wave Notification wave Long-period wave	Specific wave (south-kanto, directly under the ground) BCJ-L2	Notification wave (Level 2) × 1.5
Building deformation ratio	Less than 1/360	Less than 1/180	Less than 1/120	Less than 1/120
Inter layer deformation ratio	Less than 1/300	Less than 1/150	Less than 1/100	Less than 1/100
Member plasticity ratio	Less than 1.0	Less than 2.0	Column : less than 2.0 Beam : less than 3.0	Column : less than 2.0 Beam : less than 3.5

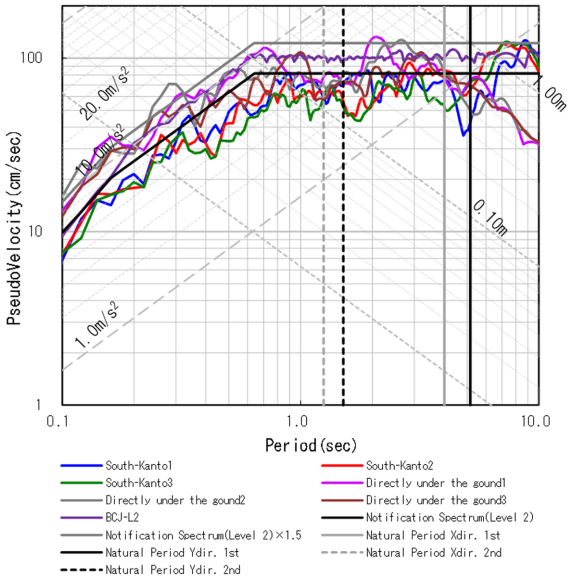


Fig. 9. Pseudo velocity response spectrum.

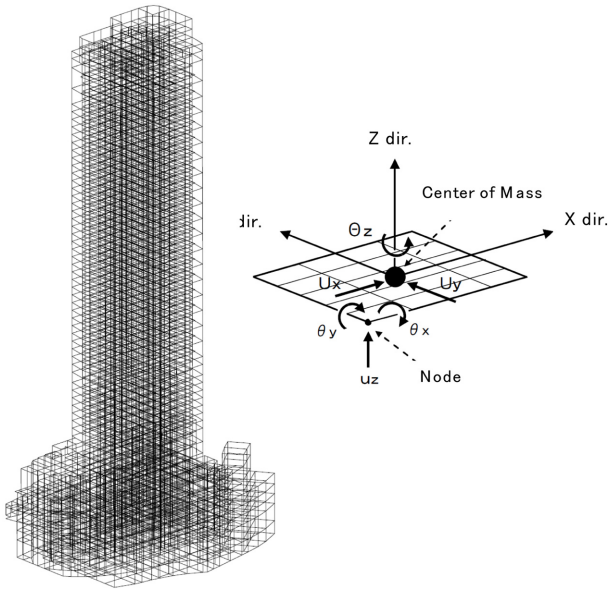


Fig. 10. Simulation model.

notification waves, BCJ waves, inland earthquakes, and regional waves assuming the Minami Kanto earthquake were adopted. Fig. 9 shows a pseudo-velocity response spectrum diagram of the design input seismic wave (seismic wave for margin verification).

5.2. Seismic analysis model

A three-dimensional skeleton analysis model was adopted as the seismic analysis model, modeled from basement, and seismic wave was input to the bottom of the foundation. The beam is modeled as a rigid plastic spring model at the end of the material, the column and split wall are modeled as an MS model, and the column-beam joint is modeled as a rigid region. The modeling of the split wall is examined in detail, and the validity of the modeling is confirmed by fitting the experiment and analysis using the model that holds the entire plane. The analysis is performed assuming each layer rigid floor. The primary

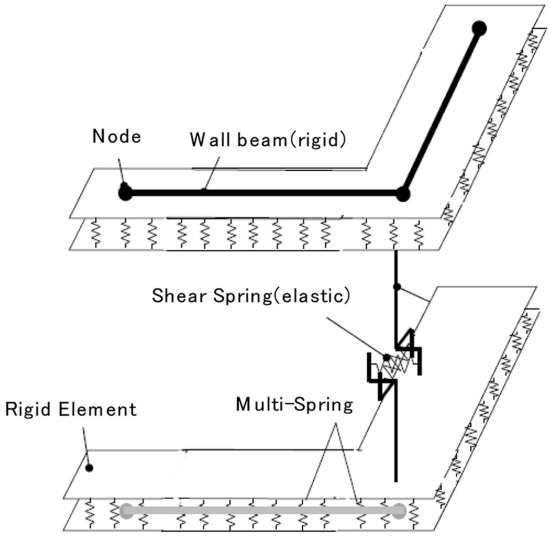


Fig. 11. Sprit wall simulation model.

natural period in each direction is 5.15 seconds in the short side direction and 4.01 seconds in the long side direction. The internal viscosity damping was h = 3.0%, and the instantaneous rigidity was proportional.

5.3. Seismic response analysis result

Figure 12 shows the response analysis results. The maximum interlayer deformation angle at level 2 is 1/201 in the long side direction and 1/187 in the short side direction, which satisfies the target value of 1/150. The maximum member plasticity rate is 1.29 in the long side direction, and there are no plasticized members in the short side direction, which is 2.0 or less as the target.

The maximum interlayer deformation angle at level 2 notification wave x1.5 is 1/120 in the long side direction and 1/115 in the short side direction, which satisfies 1/100 of the target value. The maximum member plasticity is 2.64 in the long side direction and 2.03 in the short side direction, which is 3.5 or less as the target.

The absorbed energy of the damping member is 36% in the long side direction (viscous wall damper) and 34% in the short side direction (viscous wall damper 7%, oil damper 27%). Since the internal damping energy is the equivalent viscous damping constant h = 3.0%, the damper absorption energy gives a large additional damping of about h = 2.6% in the long side direction and about 2.2% in the short side direction from the absorption energy ratio.

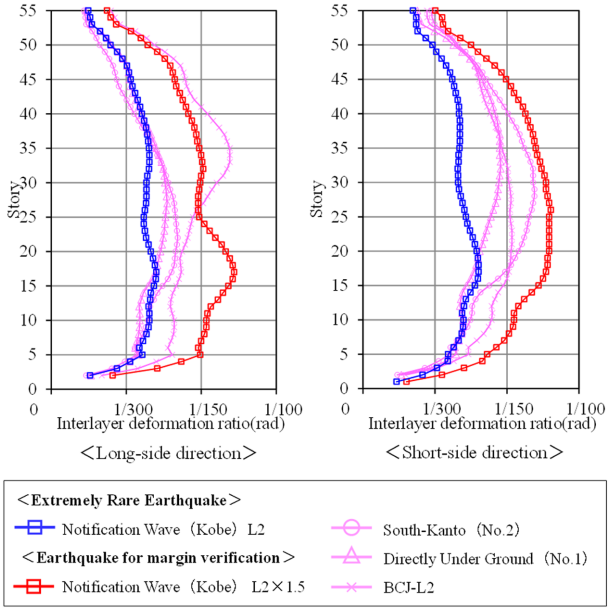


Fig. 12. Seismic Simulation (Interlayer deformation ratio).

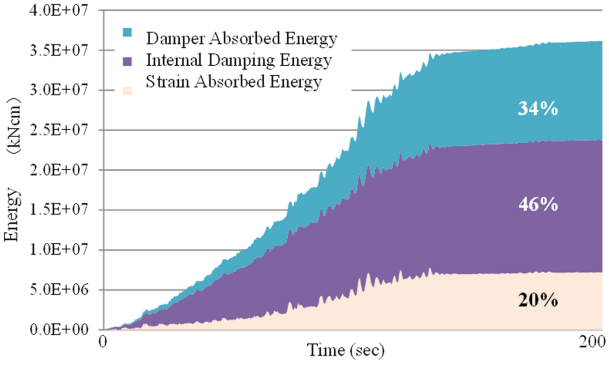


Fig. 13. Energy time history. (Notification wave (Kanto)).



Fig. 14. Wind tunnel test model.

Figure 15 shows the pseudo-velocity response spectrum for the rigid floor displacement after the maximum response deformation time. The effective period of the notification wave level 2 ×1.5 is 6.6 seconds, which is lower than 7 seconds, as the natural period of the Kanto Plain.

6. Wind-Resistant design

For the design wind velocity used were obtained by calculating the larger value between the wind velocity based on the Building Standards Law Enforcement Ordinance and the wind velocity based on the Load Design Guideline (reproduction period 100 years and 500 years). Using the adopted design wind velocity and the wind power obtained according to the wind load experiment, the design wind pressure (equivalent to level 2) is calculated using modal analysis in the frequency domain.

Since the building is structured by reinforced concrete, the columns and beams will crack as the deformation progresses due to external force, causing a decrease in rigidity. Therefore, the design wind pressure is calculated by obtaining the equivalent period (about 1.13 times the elastic natural period) when the wind pressure acts equivalent to level 2 by load increment analysis, and considering the effect of the wind pressure that is increasing due to the decrease in rigidity.

From the determined comparison of the design wind pressure and the design seismic force, the level 2 wind pressure in the short side direction is close to the design layer shear force (short-term design layer shear force to control the damage). Each structure member was designed within the short-term allowable stress under the level 2

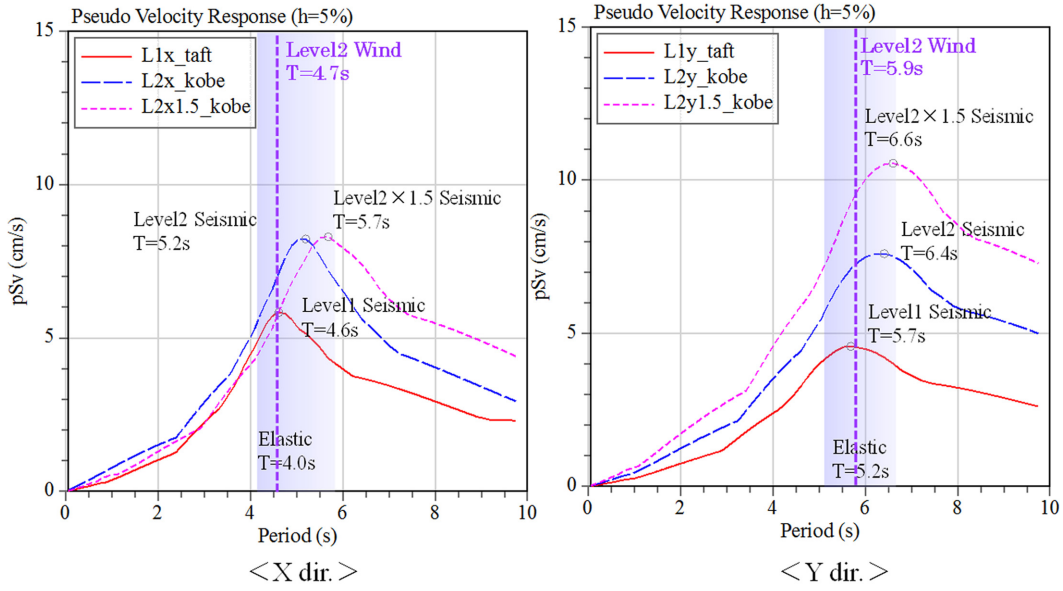


Fig. 15. Effective period after seismic and wind load.

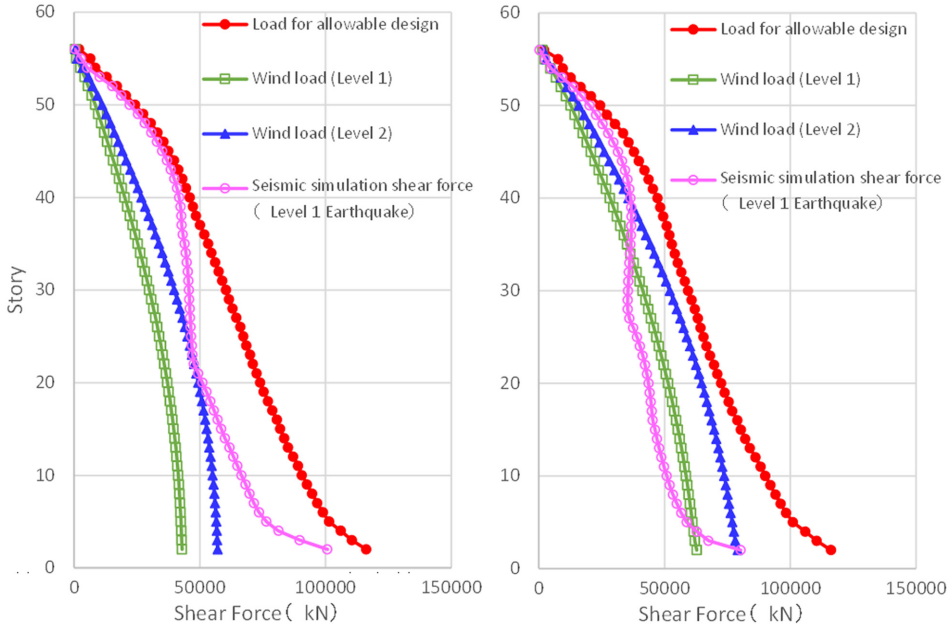


Fig. 16. Seismic and wind load by dynamic simulation.

wind pressure applied to each wind direction at the same time in the wind direction, the wind orthogonal direction, and the twisting direction. In addition, a rocking vibration experiment considering the influence of surrounding buildings was conducted, and the vortex excitation and buffeting is confirmed not to occur within the range of the design wind.

7. Study of creep deformation

In a super high-rise RC structure, the long-term axial force occurred on the column and the effect of creep increase the axial expansion and contraction of the column, which may also affect the increase in beam stress attached to the column and the fit of fittings and exteriors. In this building, the effects of gradual loading and creep during skeleton construction were analyzed, and the member stress was confirmed in consideration of the amount of axial deformation of the columns at the time of the upper building for 10 years and more. It has been confirmed that the maximum deformation difference occurs in the short span beam connected to the split wall, but the deformation angle of the beam is 1/1000 or less and the assumed stress is less than the long-term allowable

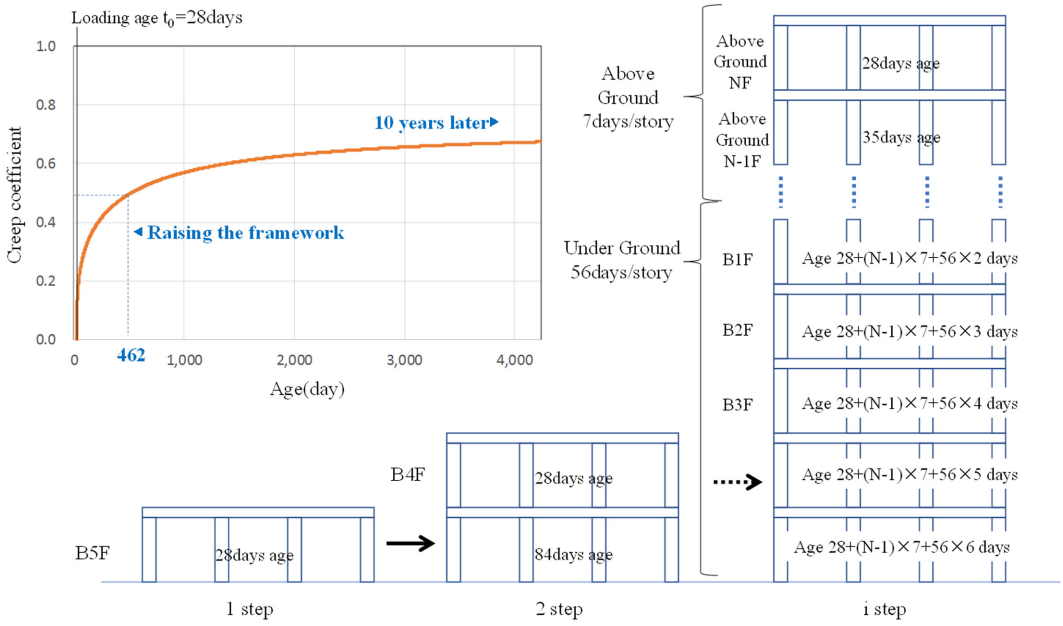


Fig. 17. Analysis steps and creep factors during construction of a building frame.

stress. The actual amount of creep deformation was planned to be monitored by installing a strain gauge on the column.

Conclusion

The split wall vibration damping system is a system that efficiently absorbs seismic energy with a speed-dependent damper using the relative velocity generated when adjacent core walls behave horizontally and vertically during an earthquake. It is confirmed that this mechanism ensured high damping performance of the building (h = 2.2%) and effectively contributed to deformation control.

Acknowledgments

The construction is now on progress of the second floor and is scheduled to be completed in 2023. Finally, Authors would like to express their sincere gratitude to all personals involved in this project for giving them the opportunity to design this project.