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Structural Design and Construction for Tall Damped Building with Irregularly-Shaped Plan and Elevation

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Abstract

This paper introduces three distinctive means for the use of a 189-meter high damped structure ensuring safety against earthquake:
1. *Realization of L-shaped elevational structural planning*: The bottom and top of the tower have belt trusses and hat trusses respectively to restrain the bending deformation. Furthermore, large-capacity oil dampers (damping force 6,000 kN) are installed in the middle part of the tower to restrain the higher-mode deformation.
2. *Realization of L-shaped planar structural planning*: We devised a means of matching the centers of gravity and rigidity by adjusting planar rigidity. Moreover, viscous damping devices are located at the edges of the L-shaped plan, where torsional deformation tends to be amplified. We call this the "Damping Tail" system.
3. *Composite foundation to equalize deformations under different loading conditions*: We studied the vertical and horizontal deformations using sway-rocking and 3D FEM models including the ground, and applied multi-stage diameter-enlarged piles to the tower and a mat foundation to the podium to keep the foundations from torsional deformations and ensure structural safety.

Keywords: "Damping Tail" system, High-capacity oil damper, Hat truss and belt truss, Composite foundation

1. Introduction

In recent years, skyscrapers with bizarre planar/elevational shapes have started to emerge worldwide. Demands for large-scale, complicated shaped skyscrapers are on the increase in Japan which has been hit by large-scale earthquakes during recent years. On the other hand, these types of buildings are likely to have larger deformations and stresses caused by horizontal loads due to earthquake or strong wind than regular-shaped buildings and therefore require a variety of considerations and cares in the designing process.

We have focused especially on three planning processes: the elevational structure planning of a high-rise (tower) section, the planar structure planning of a low-rise (podium) section, and the foundation structural planning, and thus secured the safety of a complicated shaped skyscraper in an efficient way. This paper describes the details of the process.

2. Overview of the Building

This is a project to rebuild a skyscraper complex which stands on the two sites across a road at the center of the Osaka-Umeda Terminal, the West Japan's largest terminal, serving an average of around 2.5 million people each day. We plan to build a 189-meter-skyscraper in the north site and a 54-meter-high tall building in the southeast site. Fig. 1 shows a concept rendering of a completed building. In terms of the building scale, the complex has 3 underground stories, 38 stories above ground and 2 penthouse levels, with a department store and a conference center in the low and mid-rise section, and offices in the high-rise section. The building configuration is featured by irregular shapes both in plan and in elevation. The building consists of an L-shaped plan vis-à-vis the urban center area and an

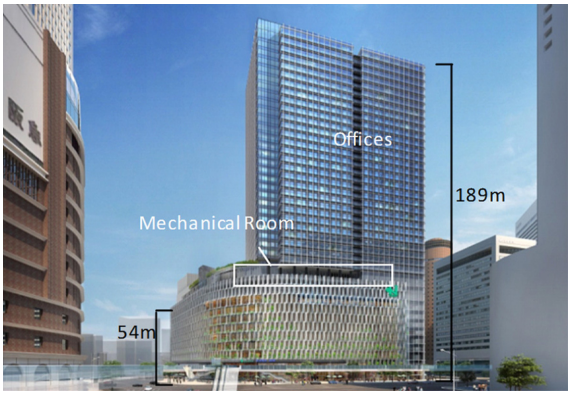


Figure 1. Concept rendering of completed building.

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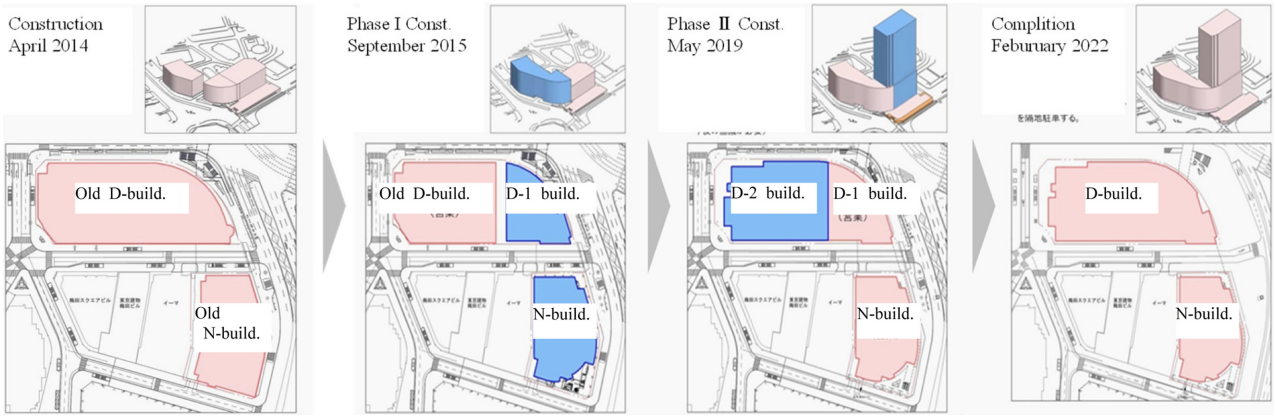


Figure 2. Step Diagram of Construction.

L-shaped elevation combining a commercial podium and an office tower.

Fig. 2 shows the step diagram of the construction. This construction started in April 2014 and will be completed in February 2022. In order not to halt operation of the department store during construction, we will divide it into phase I and II. This project will be carried out with demolition and new building repeating twice, and it will be a construction lasting about 8 years in its full term.

3. Overview of Structure

This building is steel structured above ground with steel and reinforced concrete structures at the underground level. Additionally, it has a damped structure to reduce shaking and structure damages in an earthquake and serve as a countermeasure against an earthquake on a scale exceeding the statutory level of earthquakes. Two types of damping devices are employed in this building to provide adequate bearing force and stiffness by installing hysteretic dampers and ensure redundancy by using both hysteretic and viscous dampers. Fig. 3 shows an illustration overview of the structural planning.

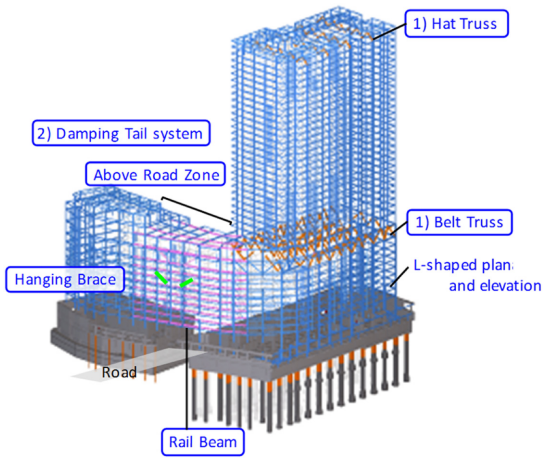


Figure 3. Overview of Structural Planning.

This building uses the following three major distinctive means in the structural planning to realize the characteristic shapes in plan and elevation and ensure effective and reliable safety. More details are described in Section 4 below.

1) Use of belt/hat trusses and high-capacity oil dampers to match the L-shaped elevation; and

2) Use of a “Damping Tail” system to match the L-shaped plan having eccentricity of loading.

3) Composite foundation plan to equalize vertical and horizontal deformations under different loading conditions.

4. Seismic Design Criteria

There are more and more social demands for and interest in ensuring a margin of structural performance to prepare for an earthquake beyond the statutory level after the Great East Japan Earthquake in 2011. Table 1 shows the seismic design criteria for this building which have been established as the result of our negotiations with the Client. We have performed validation of the Safety Level 3 as a measure against an earthquake on a scale exceeding the statutory level of earthquakes. Besides, these criteria have a margin of about 10% over the story drift angle criteria established for normal high-rise buildings in Japan to improve the performance of the existing design criteria. Moreover, the member strengths specified in the members design criteria are under the elastic limit strength against Level-2 earthquake motions in particularly critical areas: the belt truss, hanging braces above roads and overhead structures above roads.

5. Structural Planning

5.1. Realization of L-shaped Elevational Structural Planning of Tower

This building has an L-shaped elevation, with an

Table 1. Seismic Design Criteria and Safety Decision Criteria in Designing Superstructure Members

Outline of Earthquake Motions		Level 1 - Rare. - Recurrence interval: Approx. 50 year	Level 2 - Very rare. - Recurrence interval: Approx. 500 years	Level 3*1 - 1.5 times stronger than the Notification Level-2.
Super-structure	Story drift angle	4.55×10^{-3} rad. (1/220)	9.09×10^{-3} rad. (1/110)	13.4×10^{-3} rad. (1/75)
	Ductility factor of story	Allowable stress for short-term loading, or less	1.5 or less	3.0 or less
	Column	Allowable stress for short-term loading, or less	Less than ultimate strength*2	Less than ultimate strength*2
	Girder	Allowable stress for short-term loading, or less	Plastic hinges allowed	Plastic hinges?allowed
	Brace	Allowable stress for short-term loading, or less	Plastic hinges allowed	Plastic hinges allowed
	Belt Truss, Rail Beam, Hanging-Brace	Allowable stress for short-term loading, or less	Less than elastic limit strength	Less than ultimate strength*2
	Connection floor	$\tau < 0.38 \times \sigma_B^{0.5}$	$\tau < 0.56 \times \sigma_B^{0.5}$	$\tau < 0.75 \times \sigma_B^{0.5}$

τ: Shearing unit stress of slab (N/mm^2), σ_B: Specified design strength of concrete (N/mm^2).
*1 Seismic Safety Margin Analysis Level, *2 Formation of plastic hinges is allowed in some of the members.

approximately 135-meter tall tower (offices) erected on the top of a nearly 60-meter high podium accommodating a department store section. It is critical in structural planning for the prevention of whipping and torsional deformation of the tower.

In this project, the floor equipped with MEP machines, located between the podium and the tower, serves as an 8-meter high belt truss. Besides, the top floor is provided with a hat truss in the shorter-side north-south direction (Y) (Fig. 4). And moreover, the columns connected to those outriggers are made of CFT (concrete filled tube, max. FC = 80 N/mm^2) to improve the vertical stiffness and thereby restrain the tower section's bending deformation.

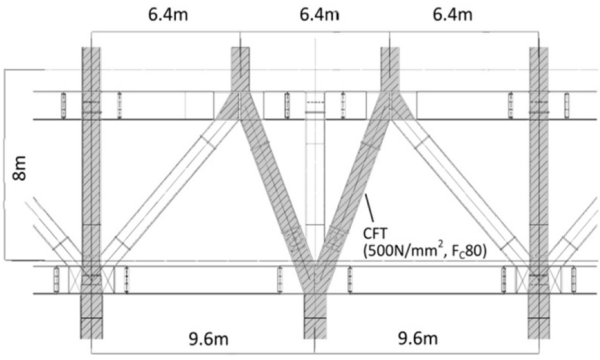


Figure 4. Detail of Belt Truss.

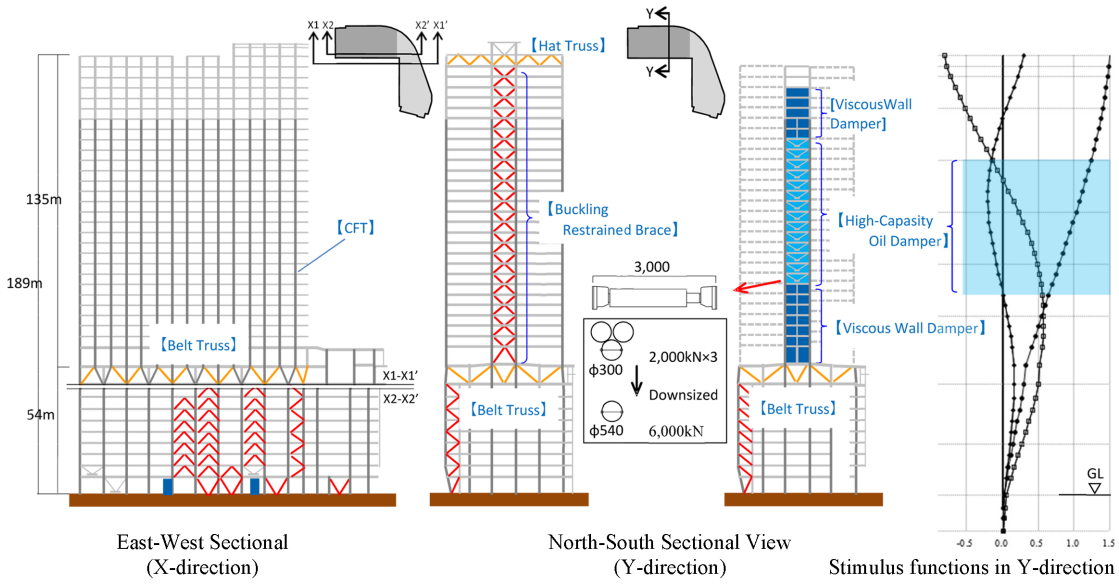


Figure 5. Structural Sectional View.

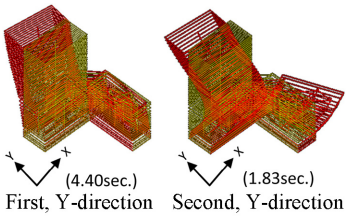


Figure 6. Natural modes of deformation.

The belt truss functions as a transfer truss that transforms the east-west span (in the X-direction) which is 9.6 meters for the podium into a 6.4 meter span for the tower. The colonnade along the outer perimeter of the tower increases the torsional stiffness of the tower and reduces the torsional deformation (Figs. 4 and 5).

Furthermore, high-capacity oil dampers with a damping force of 6,000 kN (Yamamoto et al., 2016) are installed to restrain the higher-order mode deformations in the middle part of the tower (Fig. 6). These are high-capacity slim dampers with smaller diameters achieved by a new mechanism while being arranged in the same way as the conventional parallel mechanism of three 2,000 kN dampers. We have developed this system because we often encounter difficulties in securing a space for installing dampers despite our desire to ensure high-capacity damping force in design.

5.2. Realization of L-Shaped Planar Structural Planning of Podium

The podium of this building is an L-shaped configuration measuring approximately 150 m by 150 m in plan. Besides, there is a tower only on the north side, one of the sides of the L shape, which yields a deviation between the centers of rigidity and gravity in the podium.

Consequently the building is prone to an increase in the torsional deformation of the whole podium when horizontal load is applied. It is critical to restrain the deformation.

In this project, we adjusted planar rigidity to achieve balance between the tower and the podium sections and match the centers of rigidity and gravity. Specifically, highly-rigid, buckling restrained braces are laid out throughout the tower, while the podium using a rigid-frame structure becomes relatively less rigid than the tower's lower part (Fig. 7). Moreover, viscous damping devices are intensively located mainly along two edges of the L-shaped plan of the podium section where torsional deformation tends to be amplified. We call this system "Damping Tail" system, aiming to restrain the podium section's deformation and absorb the seismic energy throughout the building at the "tail-shaped" portion attached to the tower (Fig. 8). Table 2 shows a list of the damping devices applied to this building.

In this building, it is important in structural planning to firmly integrate the tower section and the podium section. On the two ends of their connection installed are steel large-box-section beams called Rail Beams with the maximum thickness of 80 mm and yield a strength of 385 N/mm^2 each to bear the bending moment and axial force applied to the connection (Fig. 9).The shear force applied to the connection is borne by the slab (the maximum strength is FC=36 N/mm^2). The shearing unit stress of the slab is set so as to be lower than its cracking unit stress,

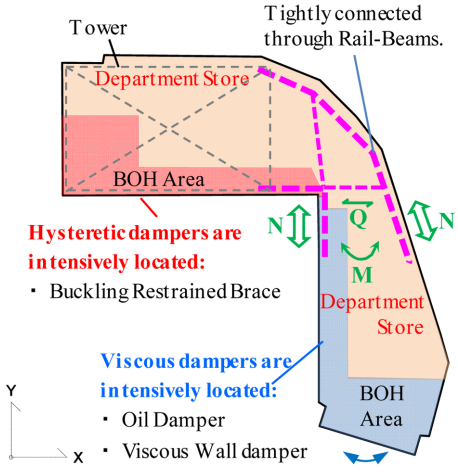


Figure 7. Layout of Damping Members in Lower Section of Tower and in Podium.

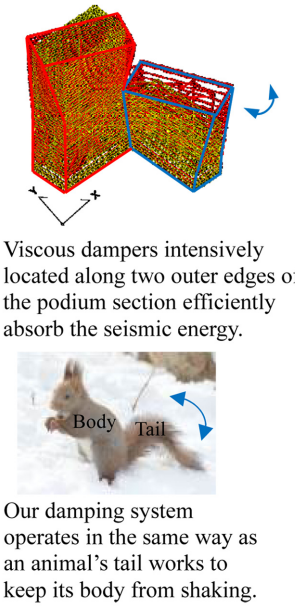


Figure 8. Overview of Damping Tail System.

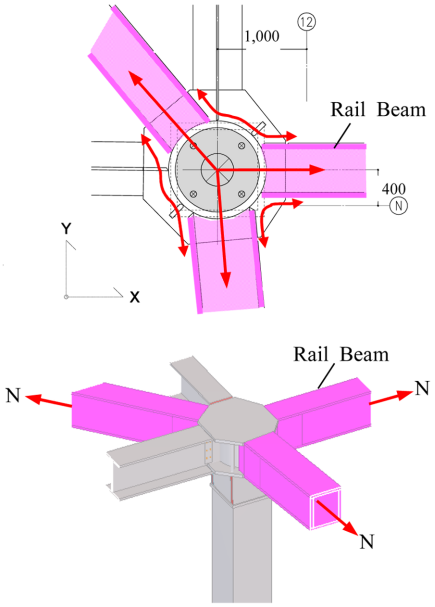
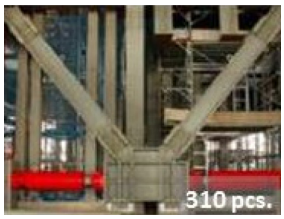


Figure 9. Detail of Rail Beam Joint.

Table 2. Damping Devices Applied to this Building

Hysteretic Dampers		Viscous Dampers	
Buckling Restrained Brace		Oil Damper	Viscous Wall Damper
			
Low yield steel braces having excellent deformation performance absorb seismic energy.		Oil in cylinders absorbs the shaking and impact on the building.	Viscous wall between steel plates absorbs the shaking and impact on the building.
Rigidity Matching the Weight of the Tower Area Ensured before Energy is Absorbed.		Seismic Energy Flexibly Absorbed Without Gibing Rigidity.	

thereby ensuring the transmission of shear force through the slab.

5.3. Composite Foundation Structure Planning to Equalize Vertical and Horizontal Deformations under Different Loading Conditions

The foundation structure mostly serves the tower section. The cast-in-place concrete piles are driven with the tip load bearing layer 50 meters below the ground level in the north area where the support reactions reach 40,000 to 50,000 kN. Our originally developed multi-stage diameter-enlarged cast-in-place concrete piles with their middle enlarged diameter parts additionally placed in the gravel layer near 27 meters below the ground level (Hirai et al., 2015) are used where the load is especially heavy or extraction force is applied to the piles (Fig. 10).

A mat foundation is applied to the podium in the southeast site, where the bearing layer is a gravel layer near 27

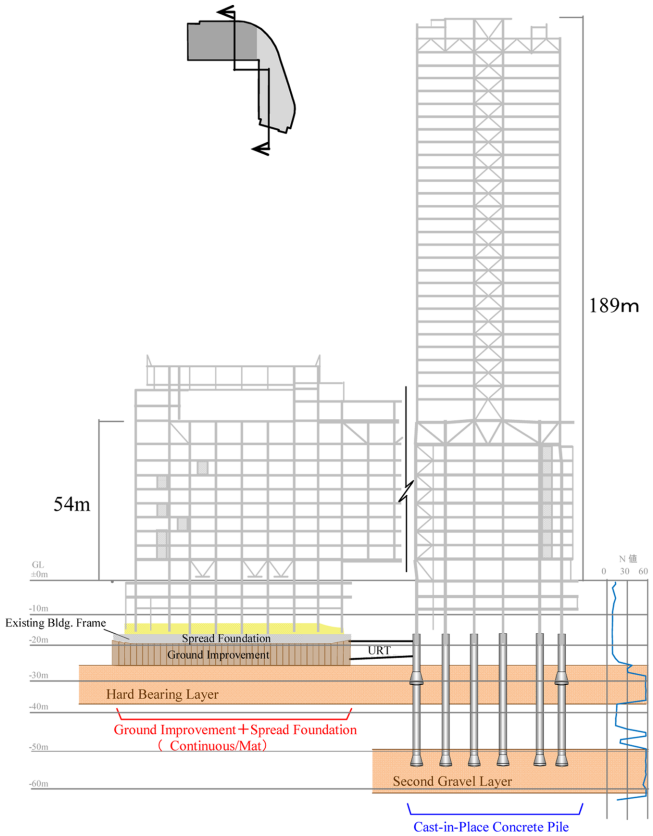


Figure 10. Illustration Overview of Foundations.

meters below the ground level. Under the foundation bottom 18.5 meters below the ground level, the existing frame, approximately 3.5 meters thick, remains down to 22 meters below the ground level. In order to ensure the safety during dismantling of the existing frame, the approximately 5 meter thick ground between the foundation bottom and bearing layer was improved by high-pressure jet, which was also used for ground improvement during new building construction.

The underground and foundation areas of the podium and the tower are divided by the road and underground mall. Therefore, we studied the vertical and horizontal displacements caused by sustained loading and earthquakes by using static and dynamic methods to keep the foundations from remarkable differences in deformations (Shiomi et al., 1998 and Satoh et al., 2010). The dynamic study uses different equivalent shear models, each equipped with sway springs and rocking springs, according to the foundation type, as elaborated in Chapter 6.

Application of the foundation types that firmly support the podium and the tower respectively is effective to keep the planar deformation angles of the podium's and the tower's underground portions in an earthquake as extremely small as up to 1/6,400 (Fig. 10) even against Level-2 earthquake motions. Besides, the difference in deformation under vertical loading between the foundations of the podium and the tower is as slight as 1/1,100. The behaviors of the underground portions in an earthquake have been separately validated by using a 3D FEM model (Fig. 11) (Shiomi et al., 1998 and Satoh et al., 2010).

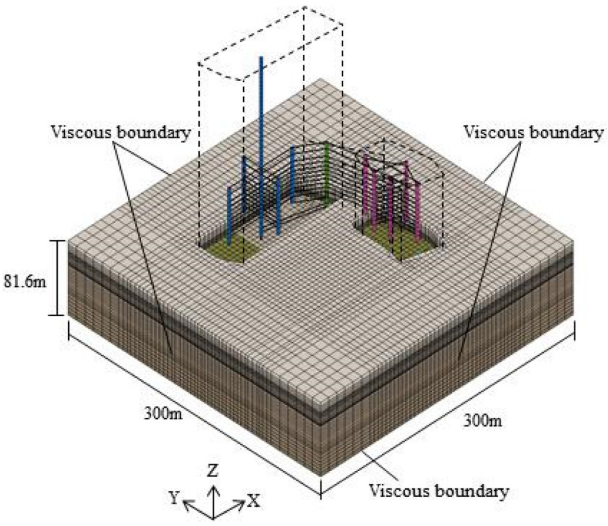


Figure 11. Three-Dimensional FEM Model.

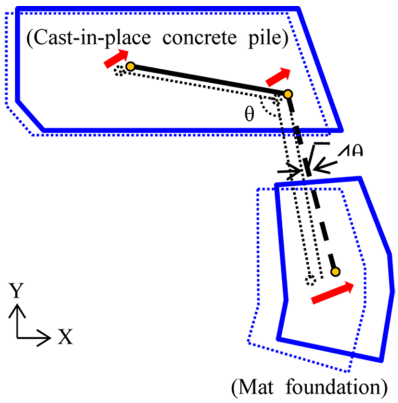


Figure 12. Torsional Deformation of Underground Portions in Earthquake.

6. Study of Seismic Response Analysis Results

6.1. Seismic Response Analysis Model

This building consists of a podium L-shaped in plan and a regular-shaped tower located at a biased position above the podium. Therefore, it is critical to grasp the building behaviors, considering the effects of the podium's eccentricity and torsion. We have conducted a 3D seismic response analysis using a full model to evaluate them. The full model contains as many as 53,000 mass points, which requires a lot of calculation time. Thus we used an equivalent shear model on the 11 blocks, into which the whole building is split, in the design development phase after confirming the compatibility of the two models. Moreover, the data of the 11 blocks were tallied in 3 areas according to the building configuration, the results of which were compiled. Fig. 13 shows the equivalent shear model used for the seismic response analysis.

Each of the blocks was provided with a mass point where the mass of the corresponding area was concentrated. Besides, the horizontal rigidity of the frame in each block was assessed using an equivalent shear plastic spring. The blocks were connected to one another by elements having the horizontal bending rigidity and shear rigidity in consideration of the thickness and minimum width of the slab connecting one block to another. The earthquake motions were input in position on the third basement floor. The sway springs and rocking springs in consideration of the dynamic interaction between the structure and the ground were set in position on the third basement floor. Concerning the internal viscous damping of the building, the damping constant of each building in the first mode was set to 2%, and the ground's damping was considered only for the rocking vibrations. Table 3 shows the natural periods of a mass system model.

6.2. Input Earthquake Motions

The input earthquake motions can be classified into three types as shown below in Table 4: (1) The earthquake motions provided for in the Japanese laws and the standard earthquake motions, (2) the earthquake motions beyond an expected level which are 1.5 times higher than the Level-2 earthquake motion accelerations on engineering

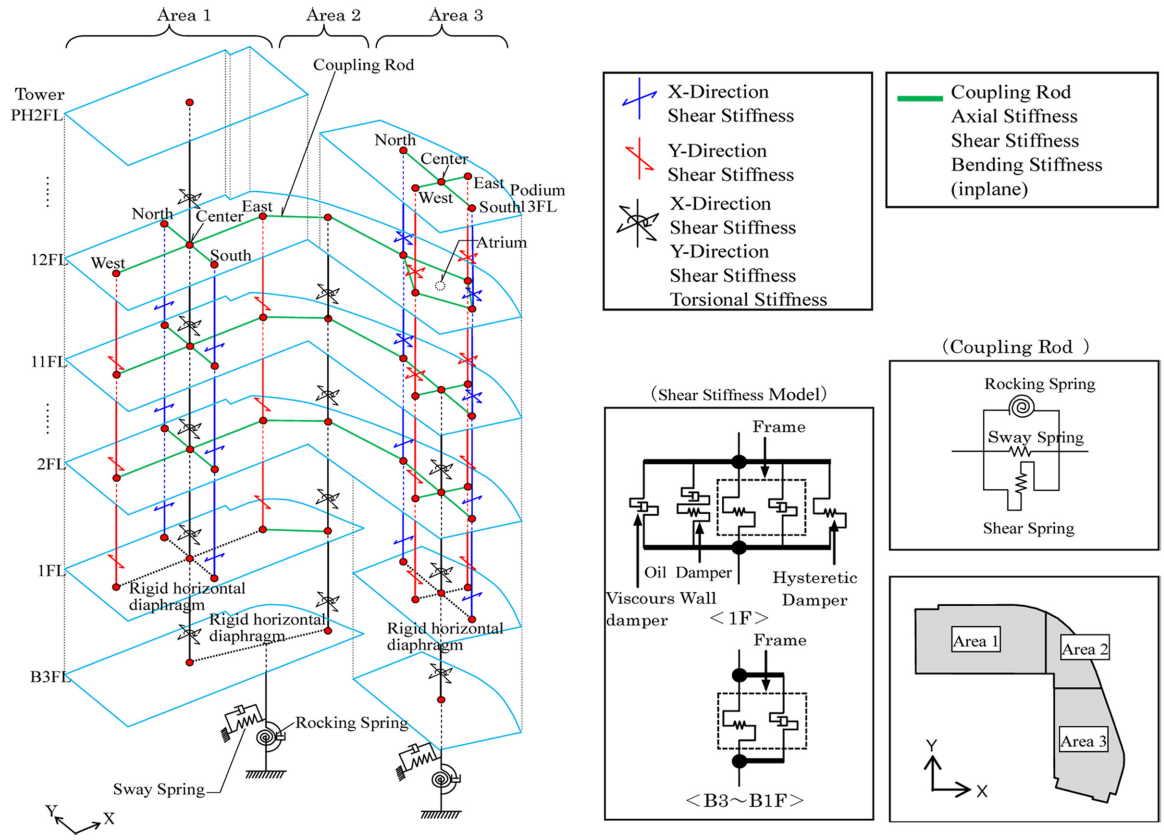


Figure 13. View of Analysis Model.

Table 3. Natural Periods (in seconds)

Entire mode order		1st	2nd	3rd	4th	5th	6th
Natural period (sec.)	Equivalent shear model	4.40	3.72	3.38	2.17	1.83	1.56
	Full model	4.33	3.60	3.38	2.08	1.65	1.47
Predominant mode		Tower Y: First	Tower X: First	Tower Torsion: First	Podium XY: First	Tower Y: 2nd	Tower X: 2nd

Table 4. Input earthquake motions for design purpose and seismic safety margin analysis

		Level 1		Level 2		Level 3*	
		Vmax (mm/s)	Amax (mm/s^2)	Vmax (mm/s)	Amax (mm/s^2)	Vmax (mm/s)	Amax (mm/s^2)
Standard Waves	Elcentro 1940 NS	(1) 250	2,555	500	5,110	-	-
	TAFT 1952 EW	250	2,485	500	4,970	-	-
	Hachinohe 1968 NS	250	1,669	500	3,338	-	-
Notification Waves	Notification Wave A	159	1,107	744	3,995	(2) 1,050	5,250
	Notification Wave B	132	996	714	4,278	1,065	6,075
	Notification Wave C	102	1,128	485	3,993	700	5,230
Regional Waves	Tokai/Tonankai/Nankai earthquake (average)	(3) -	-	304	1,916	-	-
	Tokai/Tonankai/Nankai earthquake (deviation)	-	-	-	-	494	2,956
	Hyuga/Tokai/Tonankai/Nankai earthquake (average)	-	-	-	-	430	2,313
	Uemachi fault zone (UFZ)	-	-	-	-	1,155	5,322

*Seismic Safety Margin Analysis Level

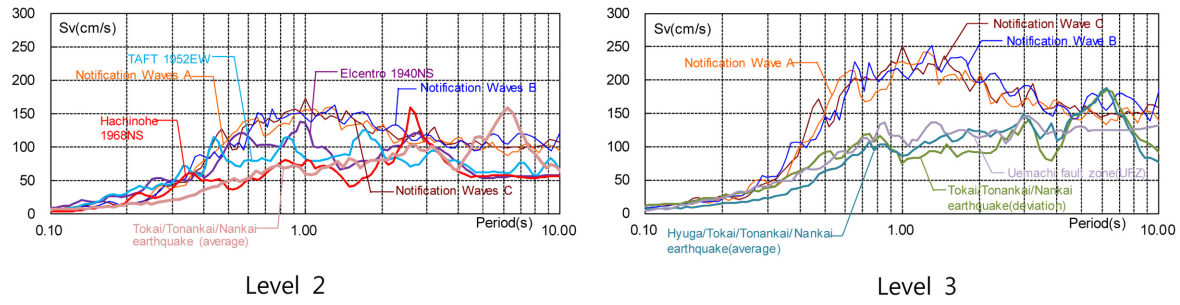


Figure 14. Velocity Response Spectra.

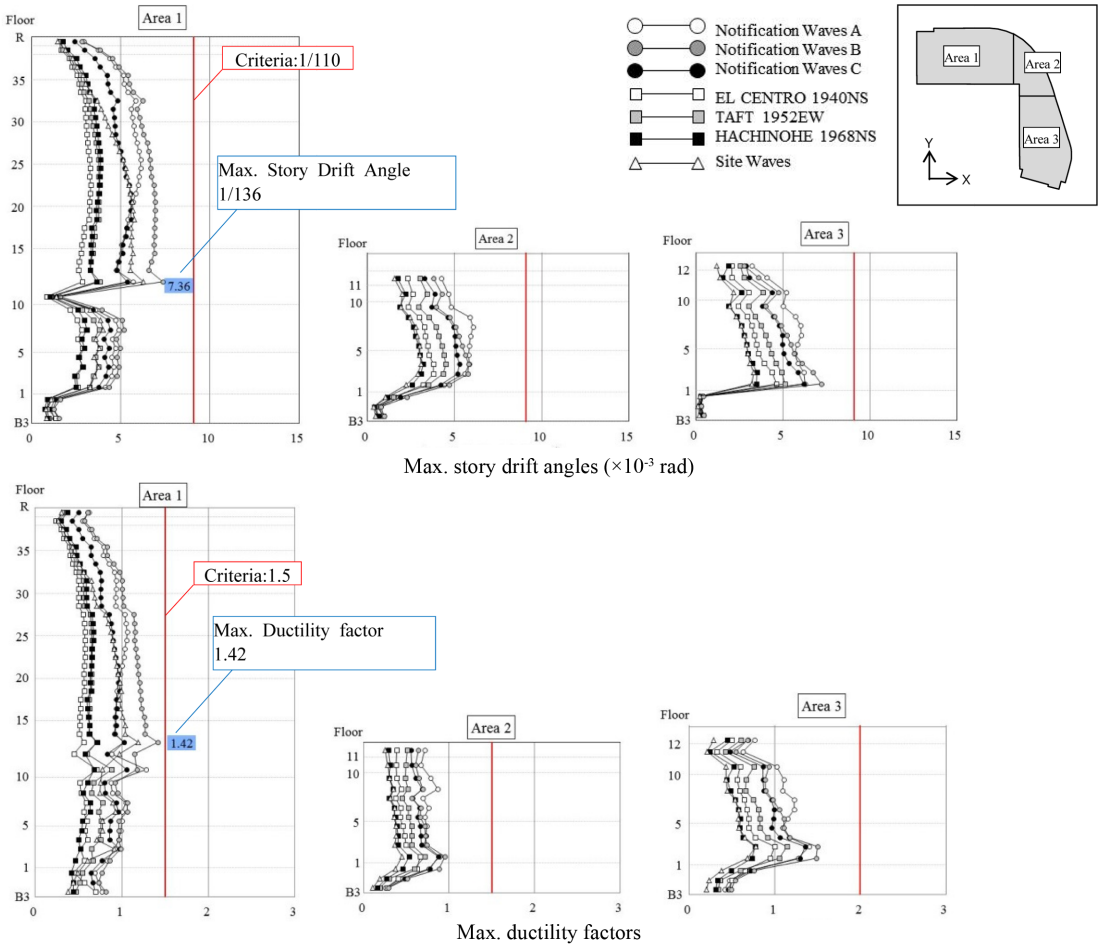


Figure 15. Results of Response Analysis of Level-2 Earthquake Motions (Y Direction).

bedrock and (3) the earthquake motions in consideration of regionality such as long-period earthquake motions (subduction zone) (Shiomi et al., 1998; Okawa et al., 2010) and epicentral earthquake motions. Fig. 14 shows the velocity response spectra of the input earthquake motions. We discussed the earthquake motions (2) and (3) above with the Client after March 11, 2011 (the date of the Great East Japan Earthquake) and decided to apply them to our analysis.

6.3. Results of Seismic Response Analysis of Level 2

Fig. 15 shows the results of the analysis of the responses to Level-2 earthquake motions, all of which meet the design criteria established in Section 4. These results indicate that the belt and hat trusses exhibited effects in the Area 1, showing a reduction of the story drift angles at the 10th and penthouse floor levels compared with those at the other floor levels.

Furthermore, installation of high-capacity dampers has

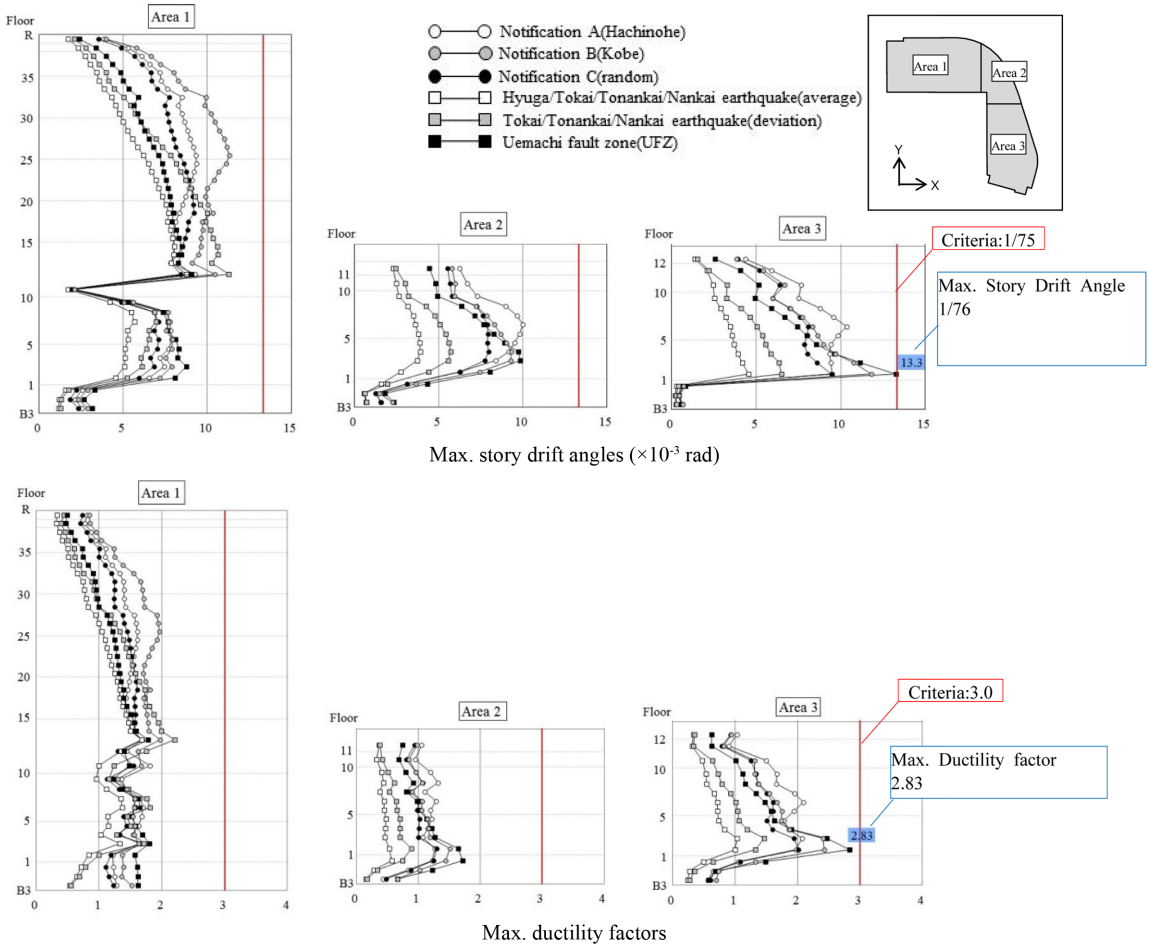


Figure 16. Results of Response Analysis of Level-3 Earthquake Motions (Y Direction).

caused a mitigation of the higher-order mode effects as demonstrated by the story drift angle values at the 18th to 31st floor levels which are not increased so much as those at the other floor levels. We have also confirmed that the responses to the Level-1 and Level-3 earthquake motions meet the design criteria.

6.4. Results of Seismic Response Analysis of Level 3 (Seismic Safety Margin Analysis evel)

The Great Hanshin-Awaji Earthquake (epicentral earthquake) in 1995 and the Great East Japan Earthquake (subduction-zone earthquake) in 2011 have led to an increased need for study of and preparedness for various types and scales of earthquakes in Japan.

This building is situated in the heart of a city and expected to be used by tens of thousands of people every day. The designers and Client have shared the importance of ensuring the safety of such many and unspecified users and of the building which was incorporated into the structural planning and design of the building.

Specifically, we have performed validations against an Uemachi Fault Zone Earthquake (epicentral) and a Nankai Trough Earthquake (subduction-zone) which are highly likely to affect this building, and furthermore against earthquakes on a scale which is 1.5 times larger than that of the statutory level of earthquake motions. Fig. 16 shows the results of these validations.

7. Conclusion

The skyscraper irregularly-shaped both in plan and in elevation has achieved the seismic performance beyond the conventional design criteria by using the following three distinctive means to ensure safety in a reliable and effective way: 1) framing system, 2) installation of damping devices, and 3) foundation system.

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