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Structural Design of Nakanoshima Festival Tower West that Achieved High-Grade Seismic Performance

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Abstract

This paper summarizes the structural concept and design of the "Nakanoshima Festival Tower West" in Osaka, Japan, which is 200m high and has a super-high damping system. Its superstructure is mainly composed of a central core and outer tube frames. It has a bottom truss structure at the boundary between the low-rise and mid-rise sections of the building, where the column arrangement is changed. Besides, the high-rise section of the building has a neck truss structure. These truss structures smoothly transfer the axial forces of the columns and reduce the flexural deformations induced by horizontal loads. Oil dampers with extremely high damping capacity are installed in the rigid walls named the "Big Wall Frames" of the low-rise section. Moreover, many braces and damping devices are well arranged in the center core of each story. The damping effects of these devices ensure that all structural members are remain within the elastic range and that story drifts are within 1/150 in large earthquakes. This super-high damping structure in the low-rise section is named the "Damping Layer". The whole structural system is named the "Super Damping Structure". The whole structural systems enhance the building's safety, comfort and Business Continuity Planning (BCP) under large earthquakes.

Keywords: Structural design, Super damping structure, Big wall frames, Central core and outer tube frames

1. Introduction

The Nakanoshima area of Osaka is a symbol zone of Osaka, a city of waterways, and has flourished as an economic and cultural center of Osaka for a long time, where the Nakanoshima Festival Tower (hereinafter the "East District") constructed in 2012 attracted attention as a complex building that contains a theatrical hall (Festival Hall) with a capacity of 2,700 people and offices for rent which are excellent in Business Continuity Plan (BCP) performance and environmental performance.

This building, paired with the East District across the Yotsubashisuji Avenue, is positioned in the second phase of the twin tower project. The building's name is the Nakanoshima Festival Tower West (hereinafter the "West District"), and the whole block is called "Festival City".

The building discussed in this paper is a complex of facilities consisting of offices for rent, a luxury hotel, cultural exchange facilities, commercial facilities, etc. These two towers will become gigantic facilities where 12 thousand people will work, appreciate music and arts and enjoy the foods of Osaka.

In this reconstruction project, the existing buildings, Osaka Asahi Building and Asahi Shimbun Building, were demolished, leaving only the part supporting the Hanshin Expressway (hereinafter the "Building Under Hanshin Expressway") as it was, and new skyscrapers were constructed on the empty land. The Building Under Hanshin Expressway was seismically retrofitted.

Fig. 1 shows the picture of the whole appearance of the

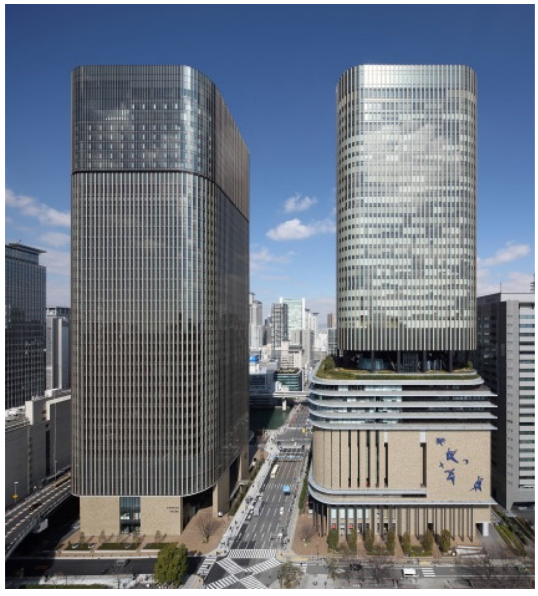
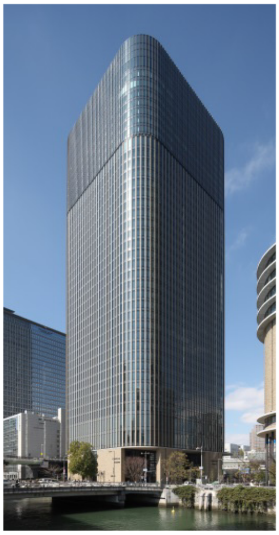


Figure 1. Picture of whole Festival City.

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Building name:
Nakanoshima Festival Tower West
Owners:
The Asahi Shimbun Company and Takenaka Corporation
Designed & supervised by:
Nikken Sekkei Ltd. (Structural and MEP designs: Cooperation provided by Takenaka Corporation)
Location of building site:
3-Chome, Nakanoshima, Kita-ku, Osaka
Uses:
Offices, hotel, cultural exchange facilities, retails, etc.
Site area:
Approx. 8,400 sq.m.
Gross floor area
Approx. 150,000 sq.m.
Number of stories:
41 stories above the ground and 4 below
Building height:
Approx. 200 meters
Construction period:
From July 2014 to March 2017 (33 months)

Figure 2. Façade picture and outline of building.

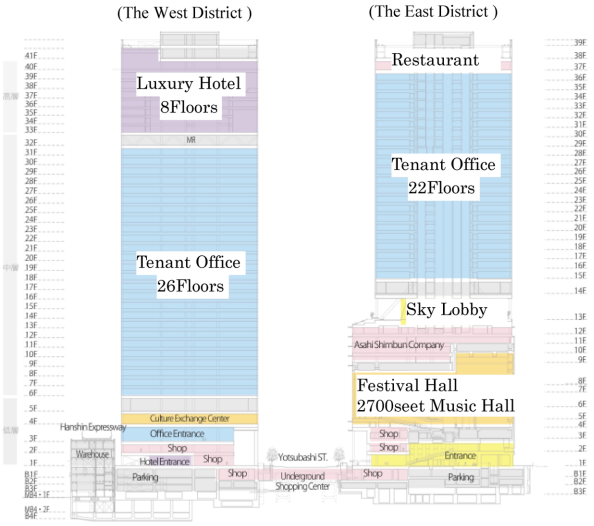


Figure 3. Sectional view of both West and East Districts.

Festival City. The heights of the both buildings are equal, approximately 200 meters, and the completed buildings are Japan's largest scale twin towers which are equal in height, floor plan configuration and exterior cladding finish.

2. Overview of Building

Fig. 2 shows the façade picture and outline of this building, and Fig. 3 shows the sectional view of both the West and East Districts standing side by side.

The superstructure of the West District mainly consists of 3 functions: The commercial and cultural exchange facilities at the first to fourth floor levels; the offices for rent at the 6th to 31st floor levels; and the hotel at the

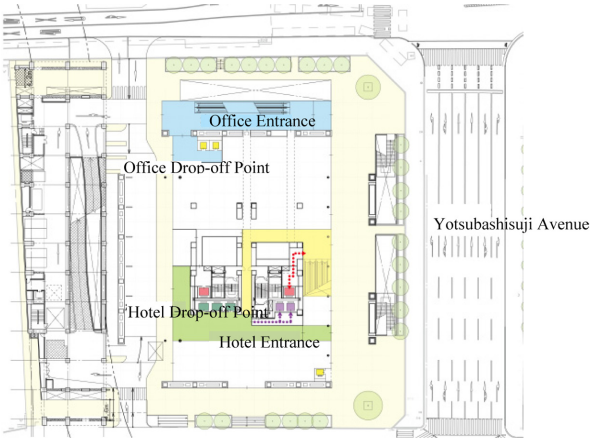


Figure 4. Ground floor plan.

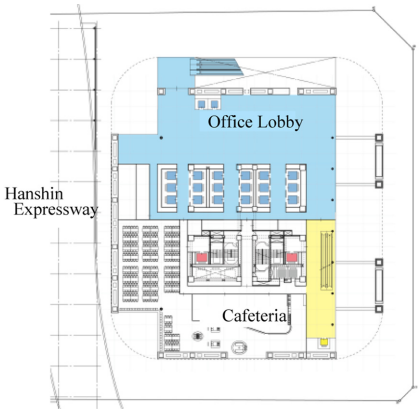


Figure 5. Floor plan, Level 3.

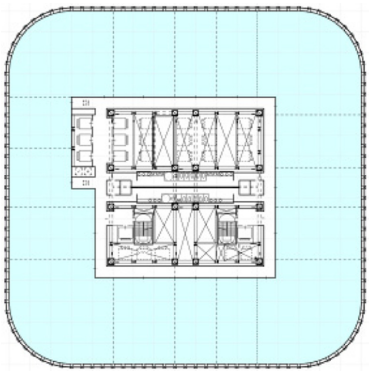


Figure 6. Typical low-rise office floor plan.

33rd to 40th floor levels. Fig. 4 shows the ground floor plan, Fig. 5 shows the third floor plan, and Fig. 6 shows the typical low-rise office floor plan.

The rental office floors are regular-shaped, central-core type floors having the same configuration with those of the East District. The circulation planning shows a flow starting at the north entrance on the ground floor and

moving by escalator to the office lobby on the 3rd floor and then to each floor. Since the West District has more office floors than the East District, the West District has 3 banks of elevators by adding one more bank to those of the East District.

The top floors are occupied by the luxury-branded hotel, and the shuttle elevators guide the visitors to the hotel lobby directly from the ground floor.

The cultural exchange facilities have Nakanoshima Kosetsu Museum of Art and a multipurpose hall (Nakanoshima Kaikan Hall) with a capacity of about 300 people.

For the exterior finishing, we applied three types of claddings according to the major functions: A curtain wall system with tiles on the columns, like the East District, is used for the exterior walls of the offices; A glass curtain wall system is applied to the hotel walls for continuity from the walls below; and bricks are used for the exterior cladding and interior finishing of the low-rise section. The office section's curtain walls and the low-rise brick walls provide a facade integrity with the East District.

The Building Under Hanshin Expressway was seismically retrofitted and is currently used for a reserve storage, a drive way and a machine room.

3. Structural Planning - Structural Systems

The Owners requested us to provide the structural systems with the following features in the structural planning of the West District:

- High seismic performance equivalent to the East District; and
- Use of seismic isolation well received at the East District.

Concerning the use of a seismically isolated structure, the second issue above, we conducted various types of architectural and structural studies, the result of which led us to make a decision to achieve an equivalent level of seismic performance by applying high-grade vibration control because we anticipated that the aspect ratio of the West District's isolation layer would be larger than that of the East District judging from the physical restrictions that allow an isolation layer to be mounted at a level only lower in the West District than that of the East District.

Under the circumstances, we had an eye on finishing the exterior low-rise walls into huge brick-covered walls in order to achieve an equivalent level of seismic performance to the East District. It was verified that installation of oil dampers which have great damping force in the low-rise walls while keeping the low-rise section sufficiently stiff would bring about equivalent performance to the East District, which means that the elastic story drifts of the members will not exceed 1/150 under the Level-2 ground motions. Fig. 7 illustrates the framing structure of the whole building which was

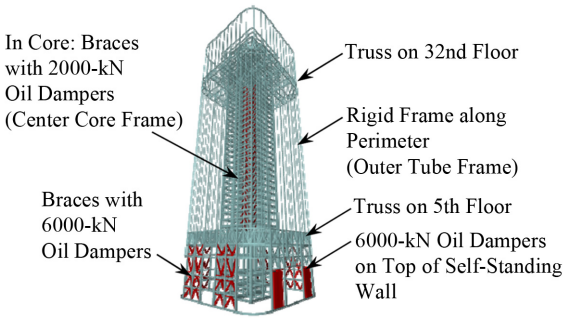


Figure 7. Rendering of framing structure.

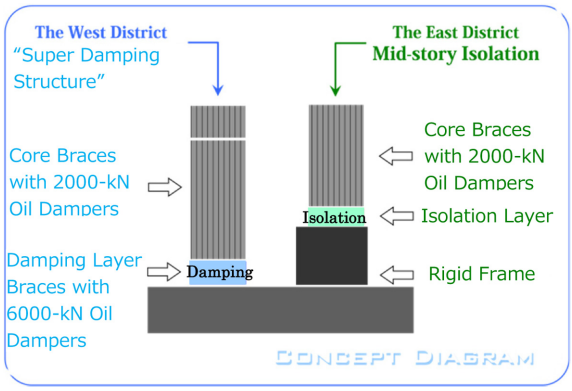


Figure 8. Concept diagram of structural planning.

established by applying such dampers. This vibration control component of the low-rise section is called the "Damping Layer", and the whole structural system is called the "Super Damping Structure". Fig. 8 shows a concept diagram of the structural planning of the West District in comparison with the mid-story isolation of the East District.

Figs. 9 and 10 show the sectional view of the framing structure and the typical floor framing plan respectively. As shown by the rendering of the framing structure (Fig. 7) and its sectional view, the spacing of the outer columns varies according to the intended use of the building component: 7.2 to 18.0 meters at the ground to 4th floor levels; 3.6 meters at the 6th to 31st floor levels; and 4.5 meters at the 33rd and higher floor levels. The machine rooms are located on the 5th and 32nd floors, which are the boundary stories where the column arrangements are changed as stated above, where truss structures are provided along the outer perimeters to adjust the column spans, and furthermore, to make connections between the cores and outer perimeters and reduce the flexural deformations induced at the cores.

A typical floor (Fig. 10) ensures horizontal stiffness by using the combination of an outer rigid tube frame made of the concrete filled tube (CFT) columns spaced at 3.6 meters and h-shaped steel beams, and a rigid, center core

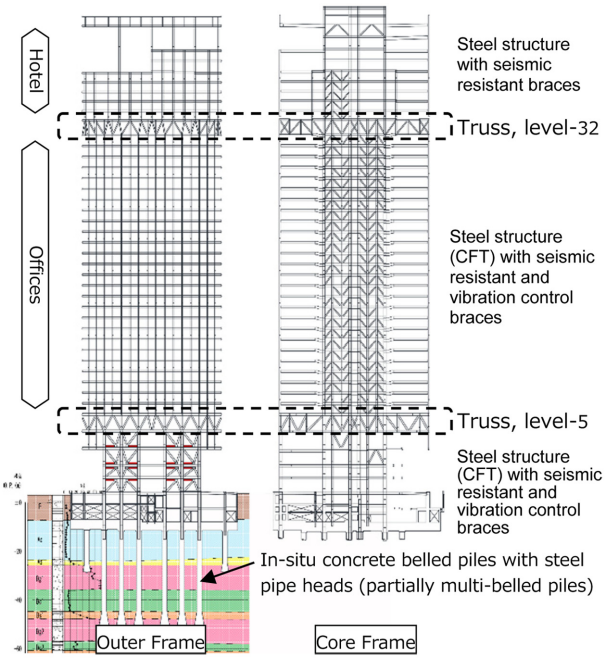


Figure 9. Sectional view of framing structure.

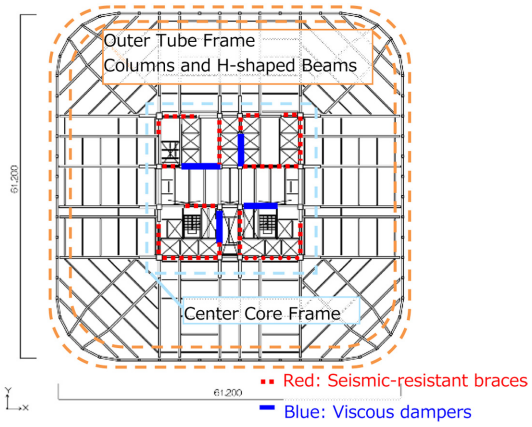


Figure 10. Typical floor framing plan.

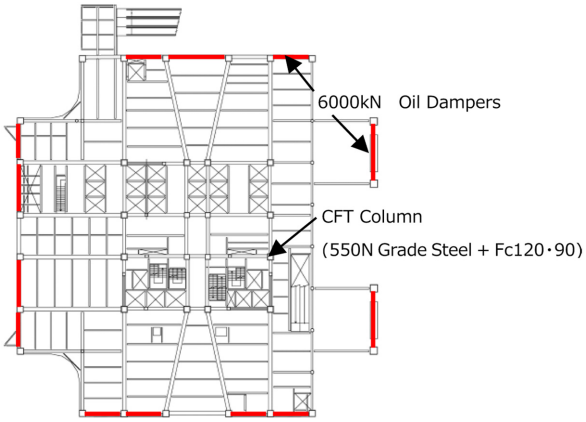


Figure 11. Framing plan, level 3.

frame with seismic resistant and vibration control braces at the core. The horizontal force bearing ratios are as follows: The outer tube frames bear approximately 15% of the horizontal loads and the center core frames bear the remaining approximately 85%.

The lower floors (Fig. 11) have a rigid frame structure with seismic resistant and vibration control braces, equipped with Japan's largest class 6000-kN dampers along the outer perimeter. For the columns, CFT columns (550-N grade steel and Fc-120 and Fc-90 concrete) are applied. Additionally, the tops of about 16 meter high self-standing walls in the east are equipped with 6000-kN oil dampers as described in detail herein below, which serve as damping walls by making use of three-story inter-story drift rate. The hotel floors have a rigid frame structure with seismic resistant braces.

4. Overview of Structural Design

4.1. Design criteria

This building has achieved high seismic performance by employing the Super Damping Structure. Table 1 shows the design criteria that we used. The design of this building is based on the design policy that the design criteria established for normal skyscrapers shall be upgraded for this building by one grade. Specifically, plasticization of the superstructure members is not allowed even under the Level-2 ground motions, where the story ductility factors shall be 1.0 or less, and the story drifts shall be 1/300 or less under the Level-1 ground motions and 1/150 or less under the Level-2 ground motions.

The same concept applies to the foundation. The stresses of members shall be no more than their elastic limit strength, and their bearing capacity shall be no more than their allowable bearing capacity for short-term loading, under the Level-2 ground motions.

We also conducted study on the ground motions beyond the Level 2, which is Level 3. We have not specified any design criteria for that level. However, it was verified that the story drifts were no more than approximately 13 x 10-3 (rad) with the ductility factors not more than about 2.0.

4.2. Sections of main members

Table 2 lists the maximum sections (maximum plate thickness) and types of the steel materials used for this building. Cold-formed square steel tubes (□-1000×1000×50 mm, BCP385) and built-up box-shaped sections (B□-1300×1300×45 (SN550C) and B□- 1100×1100×70 (SN550C)) are used for the columns. In designing this building, the 550-N grade steel was called SN550.

Table 1. Design criteria

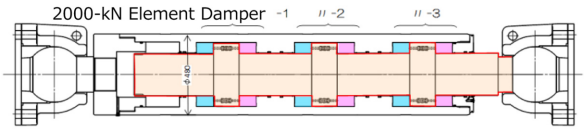
Load Level				Level 1	Level 2
Wind pressure	Force beyond assumption			Return period: 50 years	Return period: 500 years
	Target performance	Superstructure	Member stress	No more than the allowable strength for short-term loading	No more than the elastic limit strength
			Story drift	1/300 or less	1/150 or less
		Truss	Member stress	No more than the allowable strength for short-term loading	No more than the elastic limit strength
		Substructure	Member stress	No more than the allowable strength for short-term loading	No more than the elastic limit strength
			Story drift	1/800 or less	1/400 or less
		Foundation	Member stress	No more than the allowable strength for short-term loading	No more than the elastic limit strength
		Piles	Member stress	No more than the allowable strength for short-term loading	No more than the elastic limit strength
			Bearing capacity	No more than the allowable bearing capacity for short-term loading	No more than the allowable bearing capacity for short-term loading
Seismic force	Assumed external force	Notification Waves		Rare ground motions	Extremely rare ground motions
		Standard observed motions		Maximum ground velocity: 250 mm/s	Maximum ground velocity: 500 mm/s
		Site ground motions		-	Uemachi Fault Earthquake and Nankai/Tonankai Earthquake
	Earthquake scale			Equivalent to moderate scale	Equivalent to large scale
	Target performance	Superstructure	Member stress	No more than the allowable strength for short-term loading	No more than the elastic limit strength
			Story drift	1/300 or less	1/150 or less
		Truss	Member stress	No more than the allowable strength for short-term loading	No more than the elastic limit strength
		Substructure	Member stress	No more than the allowable strength for short-term loading	No more than the elastic limit strength
			Story drift	1/500 or less	1/400 or less
		Foundation	Member stress	No more than the allowable strength for short-term loading	No more than the elastic limit strength
		Piles	Member stress	No more than the allowable strength for short-term loading	No more than the elastic limit strength
			Bearing capacity	No more than the allowable bearing capacity for short-term loading	No more than the allowable bearing capacity for short-term loading

Table 2. Sections of main members

Area	Type of section	Max. section (plate thickness) (mm)	Steel type
Columns	Cold-formed square steel tube	□-1000×1000×50	BCP385
	Built-up box-shaped section	B□-1300×1300×45 B□-1100×1100×70	SN550C
	Round steel tube	B○-700×32	SN490C
	Built-up H-shape	BH-600×500×19×40	SN550B
	Ready-made H-shape (constant outer dimensions)	SH-1000×300×16×28	SN490B
Braces	Built-up H-shape	BH-500×500×25×40	SN550B
Beams	Ready-made H-shape (constant outer dimensions)	SH-1000×400×19×36	SN490B
	Ready-made H-shape	H-900×300×16×28	SN490B
	Built-up H-shape	BH-1200×700×70×80	SN550B
Small beams	Ready-made H-shape (constant outer dimensions)	SH-900×350×19×36	SS400
	Ready-made H-shape	H-912×302×18×24	SS400
	Built-up H-shape	BH-1200×500×19×40	SN400B



Picture of High-damping oil damper



Shared piston rod
Oil chamber: High pressure when the piston moves to the right.
Oil chamber: High pressure when the piston moves to the left.

Stroke +/-80mm type	Stroke +/-160mm type
Weight: Approx. 3.4 tons	Weight: Approx. 4.0 tons
Mounting length: 3130 mm	Mounting length: 3940 mm

Figure 12. High-damping oil damper.

4.3. Overview of super damping system

This building employs "Super Damping Structure" as stated above. This structural system is advantageous in not only ensuring the seismic performance equivalent to that of a seismic isolation structure but also eliminating the need for providing stories which do not serve the building use like an isolation layer by providing the wall framing ("Big Wall Frame") which is stiff enough with several "high-damping oil dampers" while ensuring the stiffness of the stories which are used on a daily basis. The "high-damping oil dampers" and the "Big Wall Frames" which raise the energy absorbing efficiency of the high-damping oil dampers are described below.

4.3.1. High-damping oil dampers

The "high-damping oil dampers (6000-kN oil dampers)" achieve three times the conventional damping force with the sectional area kept small, by applying an unprecedented approach, that is integrating three element dampers in the longitudinal direction. Fig. 12 shows the configuration diagram of a "high-damping oil damper" and a photo showing its appearance. When we tried to ensure the damping force equivalent to that of the "high-damping oil dampers" with the conventional technique, we had to install three 2000-kN oil dampers side by side and ran a risk of interfering with the building's usability. However, use of these "high-damping oil dampers" made it possible to reduce the number of dampers to one-third of the conventional ones, which has enabled the development of a structural system in which the low-rise section absorbs the energy.

The features of the "high-damping oil dampers" are as follows:

1: Can display unconventionally great damping force while maintaining the effect of reducing the sway of buildings during strong winds or frequent small earthquakes and the durability against repeated behavior, both of which are the advantages of oil dampers;

2: The great damping force per piece of the new oil damper and its smaller section area for the greater damping force contribute to a higher flexibility in design through the reduction of the quantity and mounting space of dampers (refer to Fig. 13).

3: Compared with the conventional technique, the structure of new dampers increases their heat capacity and contributes to a great reduction in the oil temperature rise during earthquakes, which consequently leads to their good availability as dampers to prevent the building from swaying for a long time due to long-period ground motions.

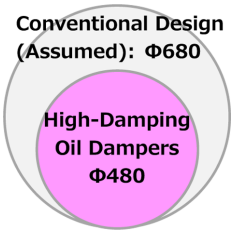


Figure 13. Comparison of sections with conventional product.

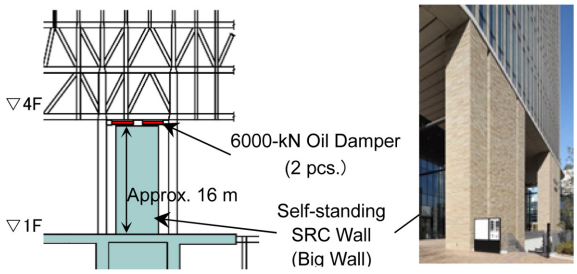


Figure 14. East framing elevation.

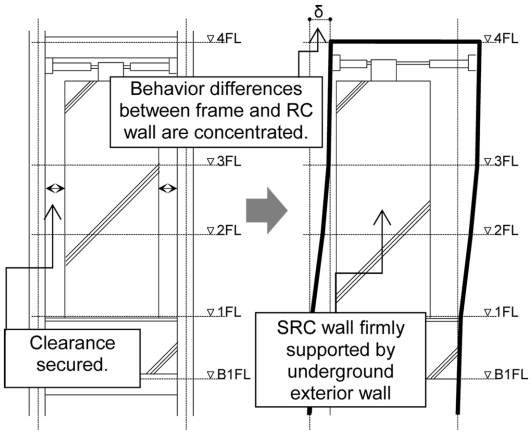


Figure 15. Illustrated concept of Big Wall Frame.

4.3.2. Big Wall Frames

The east side of the low-rise section (the first to 4th floor levels) faces a multi-story open space, where three-story self-standing SRC walls (1300 mm thick) "Big Wall Frames" are installed and have "high-damping oil dampers" on their tops. The Big Wall Frames efficiently concentrate three-story deformation differences for the purpose of energy absorption to enhance the seismic safety. Figs. 14 and 15 show the east framing elevation and the illustrated concept of the Big Wall Frame respectively.

The high-damping dampers installed on the tops of the Big Wall Frames are aimed to absorb the energy more efficiently, which has consequently enabled the reduction of the numbers of high-damping dampers and the fixtures around them to the minimum.

4.4. Study on results of seismic response analyses

4.4.1. Seismic response analysis model

This section discusses our basic policies for seismic response analysis. Fig. 16 shows the illustrated analysis model, the features of which are as follows:

- The relations between the story shear forces and inter-story drifts were defined that matched the results of the static elasto-plastic incremental analysis of a 3D frame model using the story shear force distribution established from the preliminary response analysis results.
- A regular trilinear model was used for the restoring force characteristics of the equivalent shear springs of the superstructure. An origin-oriented trilinear model was used for the restoring force characteristics of the equivalent shear spring of the substructure.
- For the internal viscous damping of the structure, we used a proportional stiffness damping model with 2% for the superstructure and 3% for the substructure. A sway-rocking model was used for the damping characteristics due to the interaction with the ground.

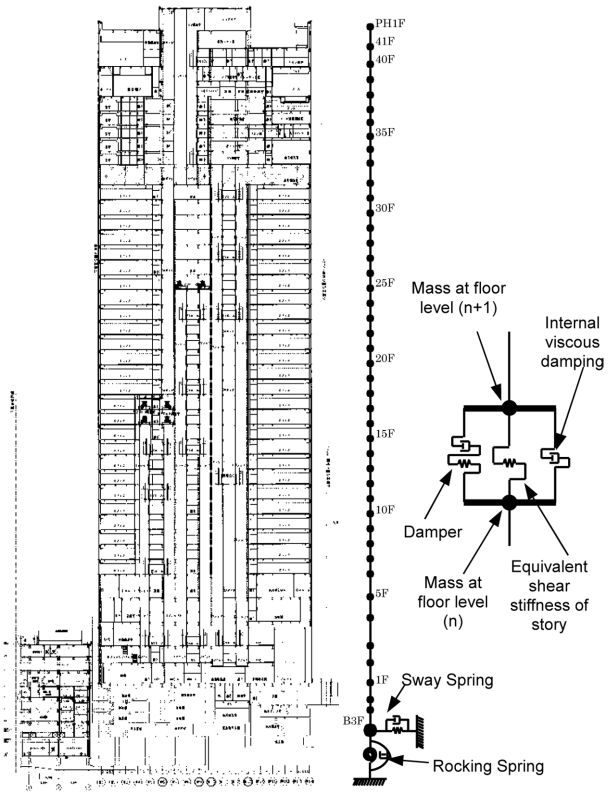


Figure 16. Illustrated analysis model.

4.4.2. Natural period analysis

Table 3 shows the natural periods of a mass system model. The first periods are around 4.5 seconds, and the second periods are around 1.7 seconds, both in the X- and Y- directions.

4.4.3. Input ground motions

Table 4 lists the typical input ground motions: The Extremely Rare Ground Motion Level (Level 2) and the ground motions beyond the Level 2 (Level 3).

For the Notification waves, three types of seismic ground motions were created with different phases, so as to match the spectrum defined at the engineering bedrock specified in the Ministry of Construction Notification #1461 of 2000. Additionally, the three waves, the Elcentro 1940 NS, the TAFT 1952 EW and the Hachinohe 1968 NS, which have been used as standard motions in the previous designs (hereinafter the "Standard Waves") were categorized into the Level-2 Ground Motions on the assumption that the maximum velocity amplitude was 50 cm/s. We also evaluated the ground motions that would be caused by the Nankai and the Tonakai Earthquakes among the megathrust earthquakes at the Nankai Trough the imminent occurrence of which has been pointed out and which are predicted to affect the building seriously. Furthermore, the Osaka City L1 and L2 Waves close to the Project site among the ground motions predicted on the assumption of the activities related to the Uemachi Fault which were announced in 1997 were used as the regional ground motions.

Table 3. Natural periods (in seconds)

	Direction	1st	2nd	3rd	4th	5th
Level-1 ground motion	X	4.529	1.645	1.078	0.806	0.628
	Y	4.578	1.684	1.079	0.806	0.627
Level-2 ground motion	X	4.551	1.652	1.083	0.811	0.634
	Y	4.601	1.689	1.084	0.811	0.634

Table 4. Max. accelerations of Level 2 and 3 input ground motions (mm/s^2) (Representative examples)

Type	Ground motion name	Level 2	Level 3
Standard	EL CENTRO 1940 NS	5,110	—
	TAFT 1952 EW	4,970	—
	HACHINOHE 1968 NS	3,380	—
Notification	Notification Wave A (Random phase)	2,772	—
	Notification Wave B (Hachinohe phase)	2,120	—
	Notification Wave C (Kobe phase)	2,110	—
	L3_Notification Wave A	—	3,736
	L3_Notification Wave B	—	2,772
	L3_Notification Wave C	—	3,386
Regional	Nankai Earthquake	1,454	—
	Tonankai Earthquake	2,867	—
	Osaka City L1	2,190	—
	Osaka City L2	2,591	—
	L3_ Tonankai plus Nankai	—	3,826
	UMTA3_B1EW1	—	6,652
	UMTA3_B1EW2	—	6,782
	UMTA3_B1EW3	—	5,260
	UMTA3_B2EW1	—	3,069
	UMTA3_B2EW2	—	3,097
	UMTA3_B2EW3	—	3,171

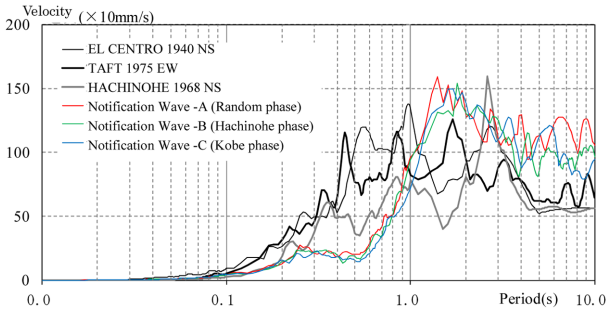


Figure 17. Velocity response spectra (Level 2 and h = 0.05).

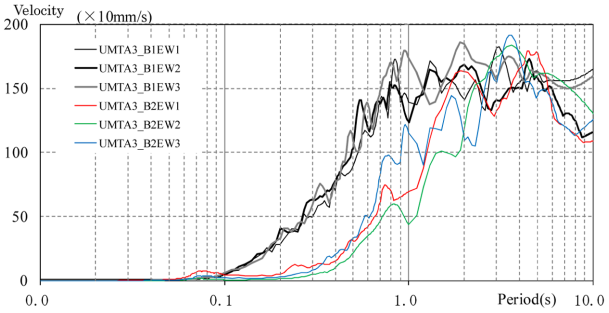


Figure 18. Velocity response spectra (Daishinken Wave 3B (EW direction), h = 0.05).

Moreover, we also created the Level-3 ground motions by increasing the accelerations of the Level-2 Notification motions by 1.5 times. A uniform random phase and the phases of the HACHINOHE 1968 EW and Kobe JMA observatory 1995 NS were used to the above Level-3 motions, like the Level-2 Notification Waves (hereinafter the "L3 Notification Waves A to C"). We simulated the other seismic ground motions in consideration of the regionality on the assumptions of a single occurrence of the Nankai Earthquake and a consolidated occurrence of the Nankai and the Tonankai Earthquakes. In addition, we also used the seismic ground motions described in detail in the "Guidance for Design Earthquake Ground Motion and Seismic Design of Building for Inland Earthquake underneath the Osaka Area: Part 1 - Osaka City Area in Uemachi Fault Earthquake" released by the "Research on Design Earthquake Ground Motion and Design Method of Building for Inland Earthquake underneath the Osaka Area" (hereinafter the "Daishinken"). This Guidance zones the Osaka City area into six, which are categorized into 3 levels of input ground motions for analysis (3A, 3B and 3C).

In the design of this building, we performed analyses for the site area by using the 3A (the average level of the whole predicted ground motion waves during the fault activities) and 3B (the level including about 70% of the whole predicted ground motion waves during the fault activities) (hereinafter respectively the Daishinken Waves 3A and 3B). Figs. 17 and 18 show the velocity response spectra of the Level-2 ground motion and Daishinken Wave 3B respectively.

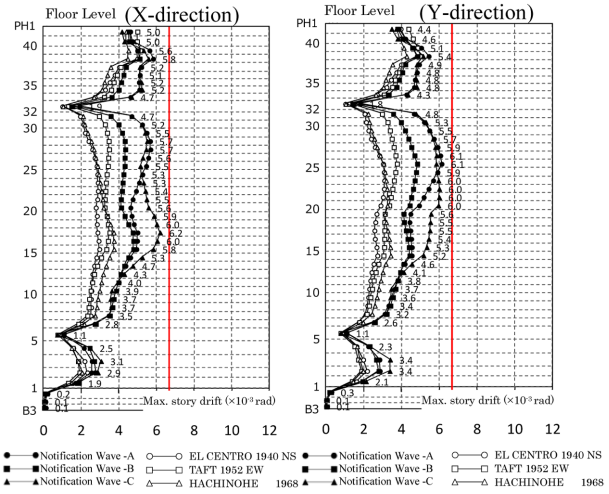


Figure 19. Results of seismic response analysis, Level-2 (max. story drifts).

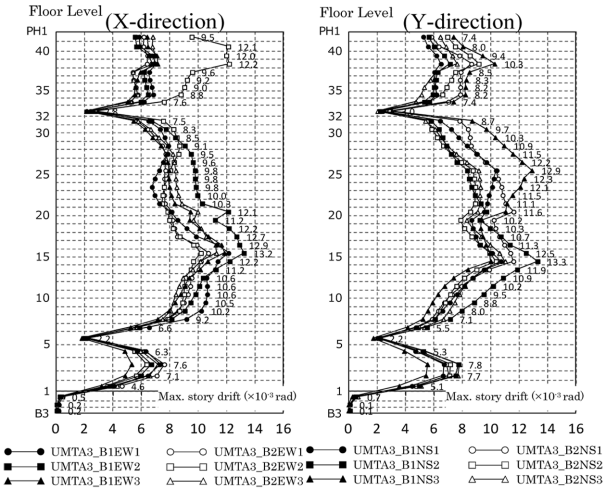


Figure 21. Results of seismic response analysis, Daishinken Wave 3B (max. story drifts).

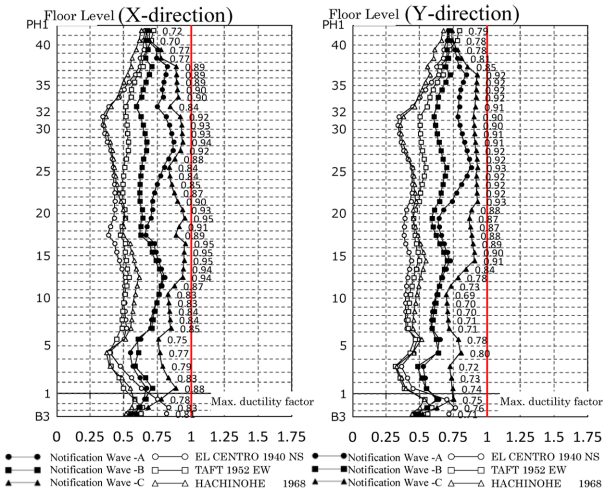


Figure 20. Results of seismic response analysis, Level-2 (max. ductility factors).

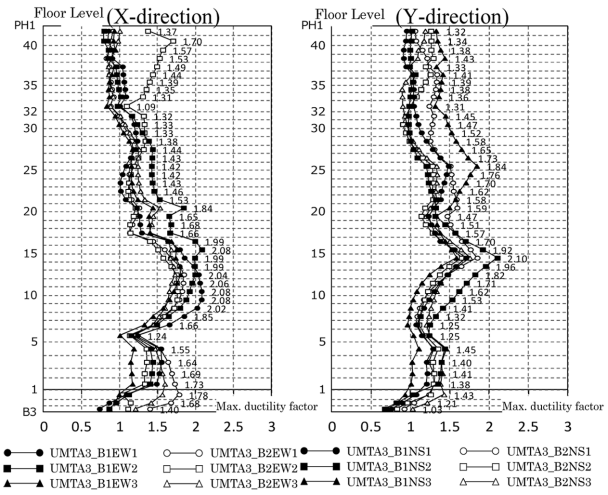


Figure 22. Results of seismic response analysis, Daishinken Wave 3B (max. ductility factors).

4.4.4. Results of seismic response analyses

Figs. 19 and 20 show the results of the dynamic response analysis on the Level-2 Notification Waves and the Standard Waves, both of which indicate that the results meet the above-listed design criteria for the max. story drifts and the max. ductility factors.

Figs. 21 and 22 show the results of the response analysis on the Level-3 Daishinken Wave 3B, where the story drifts are not more than about 13×10^{-3} (rad.), and the ductility factors are not more than about 2.0, from which it has been verified that the seismic safety of the building is ensured.

Fig. 23 shows the comparison between the max. story drift responses with and without oil dampers of the low-rise section (the ground to the 4th floors), which use the Level-2 Notification Wave C as an example. Even without dampers, the drifts did not exceed 1/100, which indicated that the building was fully stiff and strong.

With high-damping dampers installed on the low-rise section, the story drift responses were reduced from those without oil dampers by 20% at the middle- and high- rise sections and by about 50% at the low-rise section, from which we were able to confirm that use of the Super Damping Structure enabled the building to achieve great response reduction effect and consequently high-grade seismic performance.

5. Conclusions

This building was successfully completed at the end of March 2017 after a 33 month period of construction, where the Festival City was born in which 12,000 people

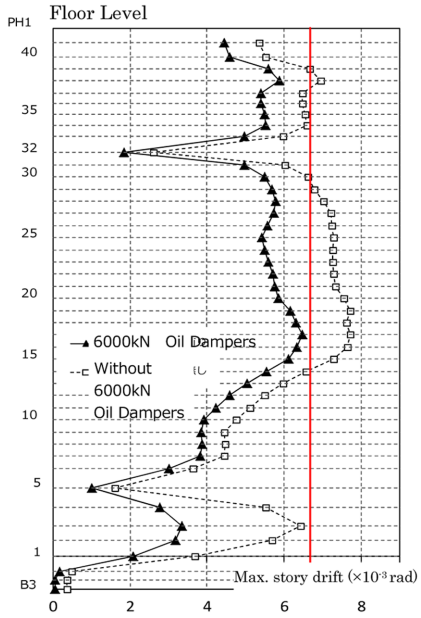


Figure 23. Comparison of max. story drift responses with and without oil dampers of low-rise section (levels 1-4) (Level-2 Notification Wave C, X-direction).

work, appreciate music and arts and enjoy eating the foods of Osaka and staying at the hotel.

Under the constructors' slogan saying, "Let's build Japan's number one twin tower," the related parties with high professional awareness and workmanship focused their efforts on the project. As a result, this new landmark of the water city Osaka has created a lively town.

We were successful in ensuring BCP (Business Continuity Plan) in large earthquakes and achieving secureness and safety by applying a new structural system, Super Damping Structure, to the 200-meter skyscraper, which provides the high-grade seismic performance equivalent to that of a seismic isolation structure.

We would like to express our thanks for this opportunity to take part in designing of this project as structural engineers.