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Structural Design of Vibration Controlled Tall Building with Overhang Structure

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Abstract

This paper describes the structural design of a 212 m tall building currently under construction in the Tokiwabashi District Redevelopment Project facing Tokyo Station. In this project there was a requirement to rationally solve many issues arising from the conditions of the redevelopment project. In particular, the following two points were considered to be important from the point of view of structural design. 1) To provide an overhang frame with the perimeter columns on the lower stories inclined, in order to enable a typical floor area that greatly exceeded the limitations of the underground structure shape. 2) To provide high grade seismic performance for the office buildings to be constructed on prime city center land. LSCVCS (Lower Stories Concentrated Vibration Control System) was proposed as the method of rationally designing the overhang frame, which is an extremely disadvantageous element in the structural scheme of the tall building with a large slenderness ratio. LSCVCS is a system to provide effective damping by arranging vibration control devices in a concentrated manner in a lower story with large story height, that produces large deformation in an earthquake. Also, the vibration control devices arranged in the lower story are limited to viscous devices, to take into consideration the residual deformation of the overhang frame after an earthquake. The results of investigations into the specific effects of the system for the seismic design are reported, including Performance-based seismic design.

Keywords: Tall buildings, Overhang, Performance-based seismic design, Damping devices, Energy absorption, Dynamic Torsional Deformation

1. Introduction

1.1. Tokiwabashi Project in front of Tokyo Station

This project is part of the redevelopment of the Tokiwabashi district facing of Tokyo Station. (Figs. 1 and 2). The site area is approx. 3.1 hectares, and the total floor area is scheduled to be about 686,000 m^2. The plan includes development of four buildings in the area including two tall buildings (Tower-A with a height of 212 m, and Tower-B with a height of about 390 m), and a large scale open space. Additionally, the project area includes public infrastructure facilities such as an electric substation, sewage facilities, the Metropolitan Expressway, etc., and the development is proceeding in stages with the continued use of these facilities as a pre-condition. Construction Phase commenced in FY 2016, and at present Tower-A and two other buildings are under construction. Construction of Tower-B and the large scale open space are scheduled to commence in FY 2023, and completion of the building construction of the overall area is scheduled for FY 2027.

This paper presents an overview of Tower-A of this project, and mainly introduces the vibration control system and Performance-based seismic design.

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1.2. Overview of Tower-A

As shown in Fig. 3, Tower-A is a tall office building

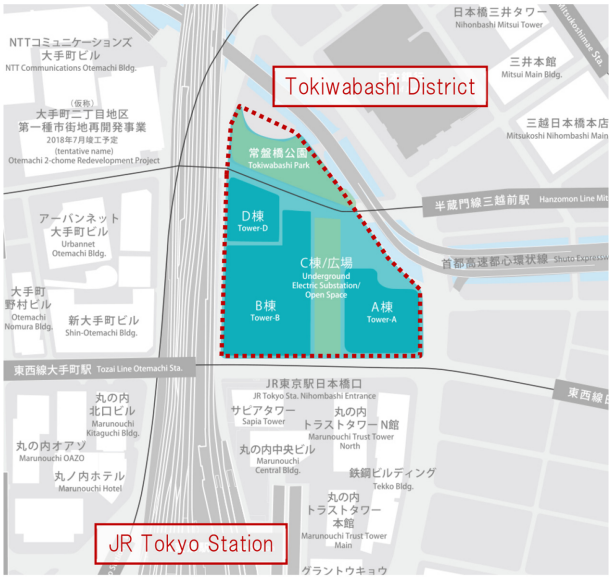


Figure 1. Sitemap of Tokiwabashi District.

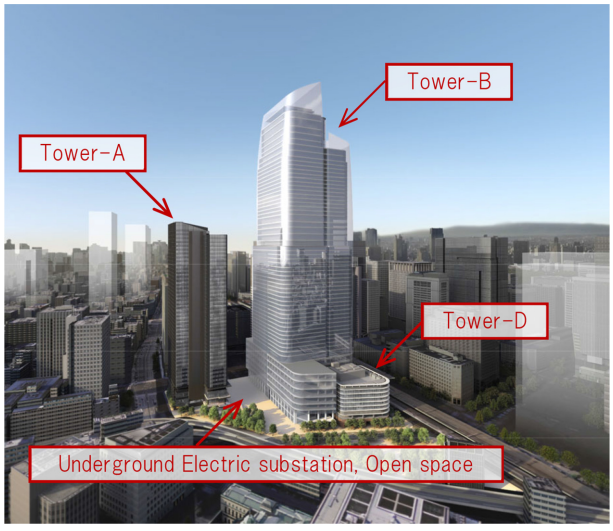
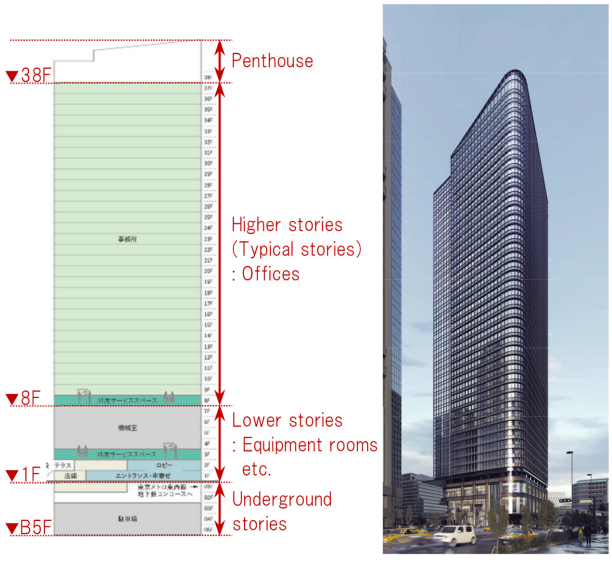


Figure 2. Rendering of Tokiwabashi project.



Project Name:	Tokyo Tokiwabashi Tower-A
Address:	1-Chome Otemachi, Chiyoda-ku,Tokyo 1-Chome Yaesu, Chuo-ku, Tokyo
Design and Supervision:	Mitsubishi Jisho Sekkei Inc.
Contractors:	Toda Corporation
Main Use:	Offices, stores and parking areas
Number of stories:	5 floors below ground / 38 floors above ground*1
Maximum Height:	Approx. 212m
Total Floor Area:	Approx. 146,000m^2

＊1: 40 floors above ground in accordance with Building Standards Act of Japan

Figure 3. Overview of Tower-A.

that includes 5 stories underground, 40 stories above ground, 3 penthouse levels, and has a maximum height of 212 m. The typical office stories are arranged from the 8th story upwards, and the lower stories (1 to 7th story) include retail shops, office entrances, and equipment rooms. The building

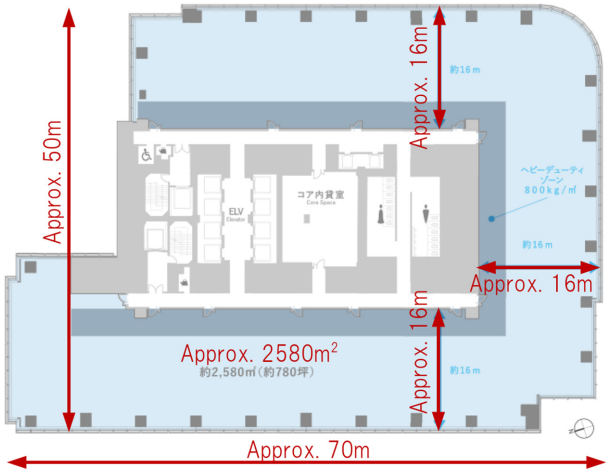


Figure 4. Typical floor plan.

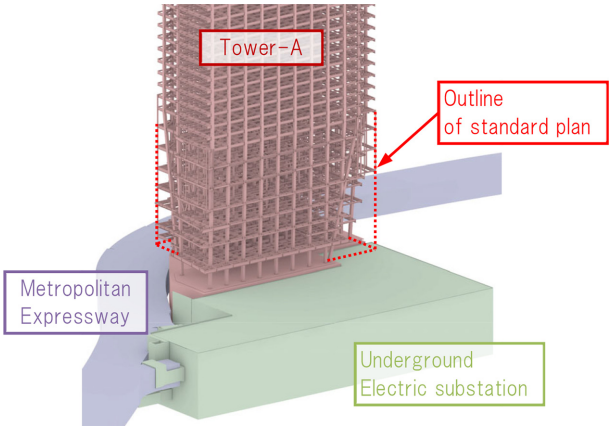


Figure 5. Relationship between Tower-A, Metropolitan Expressway and Underground substation.

shape in plan is about 50 m × 70 m with a center core, the typical stories having spans of about 16 m to provide large spaces with no columns (Fig. 4). The story height is about 4.3 m on the typical stories, and on the lower stories the height varies between 6.2 m and 8.6 m in accordance with the use of each story.

Also, as stated previously, public infrastructure facilities exist within the planned site, and as a result the footprint of Tower-A is restricted by the Metropolitan Expressway on the northeast side of the site and the underground substation on the southwest side (Fig. 5). Under these restricting conditions it was a requirement to provide a regular large space with no columns on the typical stories, and dealing with these restrictions rationally contributed greatly to the structural plan of Tower-A.

2. Structural Plan

2.1. Design Concept

The conditions in terms of the structural plan of the building were as follows.

1) High seismic performance
To provide high seismic performance as a high-grade office building in the center of Tokyo.
2) Adoption of an overhang frame
In order to achieve both the maximum regular typical story and to deal with the restrictions on the footprint, an overhang frame was adopted using inclined columns on the lower stories.

The following structural plan was adopted to deal with the above conditions.

1) Concentrated vibration control system in the lower stories
A highly effective vibration control system was adopted utilizing the difference in the structural properties between the lower stories and the higher stories, while incorporating consideration for the overhang frame into the seismic design.
2) Performance-based seismic design taking into consideration control of damage to the overall building
The building was divided into the higher stories part and the lower stories part taking into consideration the difference in structural properties between the parts with the higher stories (typical stories part) which accounts for most of the building, and the lower stories part characterized by the overhang frame and the greater story height. Performance-based seismic design was adopted in which design criteria were determined in accordance with the load levels for the damage to each type of member (main frame members and buckling restrained braces) in each part (higher stories and lower stories).

2.2. Overview of the structural plan

Fig. 6 shows flame elevation of the building. The major features are the regular typical stories from the 8F and higher, and the adoption of inclined columns around the periphery and an overhang frame in the lower stories part, resulting from the conditions of the structural plan as described previously. Also, because of their use there was a requirement for greater story height in the lower stories part.

Fig. 7 shows the framing plan for a typical story, a lower story, and the 1st story. As can be seen from the framing plan of the typical story, the standard span of the building is 7.2 m and the maximum span is 20.1 m. Compared with the 1st story where the footprint was restricted by the infrastructure facilities, the typical story was able to provide an additional about 21% floor area. Blue Area shows the 1st floor framing plan with the typical story shape superimposed on it, and the part shown in red columns shows the inclined columns that support the overhang frame.

In this way, because the lower stories part of the building has an unsymmetrical overhang frame, the following two points were taken into consideration in the design.

1) Long-term story shear is generated as a result of the unsymmetrically-arranged inclined columns, so there was concern over residual deformation after an earthquake. For this reason, plasticity of the members used in the lower stories part during an earthquake was reduced as much as possible.
2) There is eccentricity in the lower stories part due to the unsymmetrical overhang frames.
Therefore, an effective vibration control system was designed to deal with the torsional vibrations generated in the whole building as a result of this eccentricity.

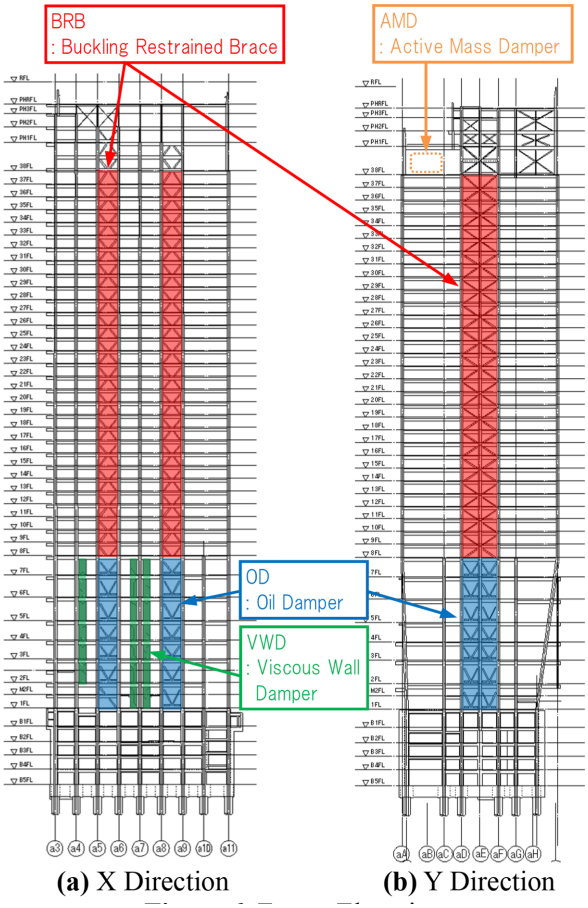
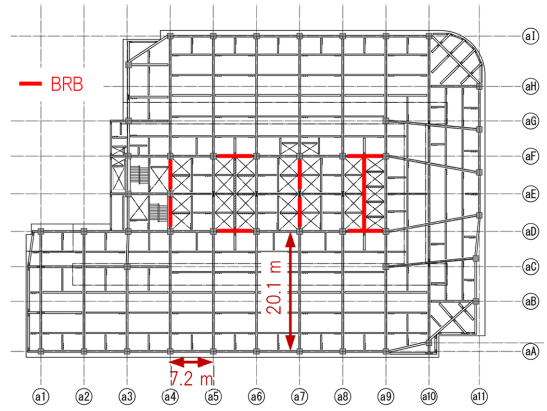


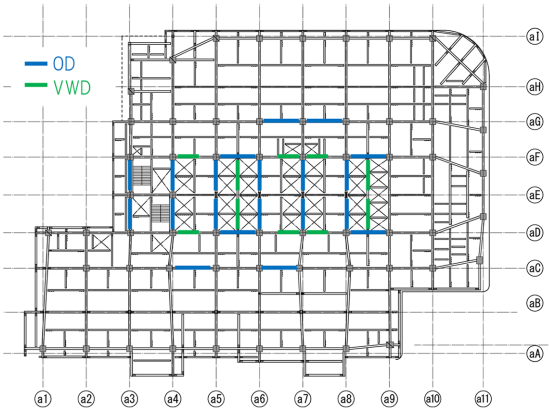
Figure 6. Frame Elevation.

Based on the above, LSCVCS in which viscous dampers were concentrated in the lower stories was adopted as a rational structural plan for the structural properties of the building. This provides a structural plan in which energy can be efficiently absorbed during an earthquake. The specific arrangement of the vibration control devices is shown in Figs. 6 and 7. On the typical stories hysteretic dampers (buckling restrained braces) are provided, and in the lower stories viscous dampers (oil dampers and viscous wall dampers) are concentrated. It is considered that this system has the following advantages.

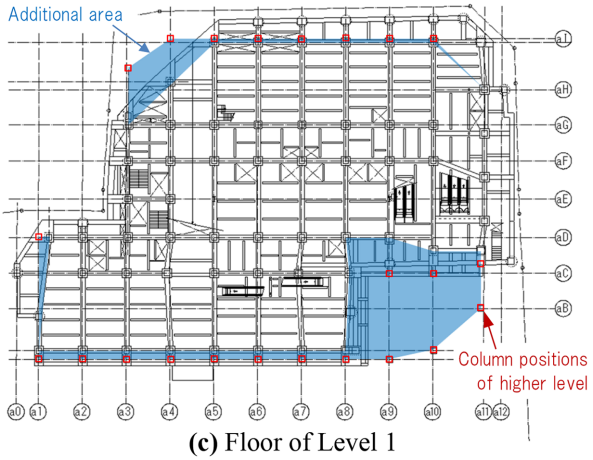
1) During a major earthquake the lower stories remain in the elastic range, so accumulation of residual deformation in the lower stories causing horizontal deformation as a result of the story shear forces from the inclined columns can be prevented.



(a) Floor of higher level

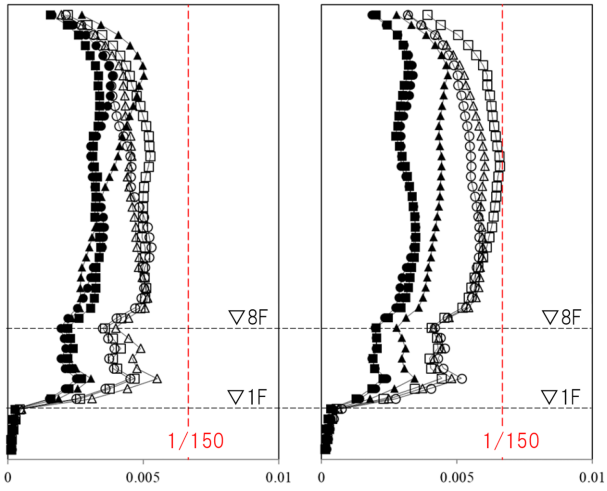


(b) Floor of lower level



(c) Floor of Level 1

Figure 7. Floor Plan.



(a) X Direction (b) Y Direction

Figure 8. Maximum response story drift angle.

2) Concentrating the viscous dampers in the lower stories where the deformation is large due to the large story height provides efficient damping.
3) Amplification of dynamic torsional deformation is reduced by providing viscous dampers within the core frame of the lower stories to maintain a planar stance.

In addition, two active mass dampers (AMD) with mass 300t are installed on the rooftop, to improve the dwelling comfort under wind loading, reduce the response values during an earthquake, and rapidly reduce the oscillations after the earthquake.

The following are the seismic design targets (Table 1) and the response results during a level 2 earthquake (Fig. 8).

3. Lower Stories Concentrated Vibration Control System (LSCVCS)

In this section, the results of LSCVCS adopted in this building are described from the following two viewpoints.

1) A comparison of the vibration control results of the system and the normal arrangement is provided using vibration analysis results (ratios of maximum response values and energy absorption).
2) Evaluation of the effect of the system in reducing

Table 1. Target performance of the seismic design

Earthquake level		Level 1	Level 2	1.5 times to Level 2
		Rare Earthquake	Extremely Rare Earthquake	1.5 × ERE
Estimated seismic intensity		5 upper	6 upper to 7	above7
Target for seismic performance	Tower-A	Graze Story drift ≦ 1/200H Continuous use	Minor damage Story drift ≦ 1/150H Continuous use	Middle damage Story drift ≦ 1/100H Maintenance and repair
	Ordinary buildings (based on building code in Japan)	Graze Story drift ≦ 1/200H Continuous use	Middle damage Story drift ≦ 1/100H Maintenance and repair	

large torsional response using 3-dimensional vibration analysis of a model of the members. Also, a comparison with dynamic analysis was carried out using static analysis as the basis.

3.1. Comparison with a vibration control building with a normal arrangement of dampers

Fig. 9 shows two types of analysis model having different damper arrangements. Model_a had viscous dampers in the lower stories only (in the comparative study, all are oil dampers), and hysteretic dampers in the typical stories only, the same as in the building.

Model_b was a vibration control building with a normal arrangement of dampers, with viscous dampers and hysteretic dampers arranged in a balanced manner on each story. At this time the individual parameters of the dampers that were placed were adjusted so that the total value of the damping capacity for the viscous and hysteretic dampers was the same as for Model_a. Three-dimensional models were used for the vibration analysis models, and two types of seismic wave were used in the study as shown in Table 2, the KA1 and the Notification Kobe (level 2) waves.

Fig. 10 shows the maximum response story drift, and Table 3 shows the energy absorption percentages, obtained from the vibration analysis. The difference between the two models was in the damper arrangement only, but for both seismic waves the maximum story drift was smaller and the energy absorption percentage of the viscous system was larger for Model_a. In particular when the response properties were close to those of the primary mode, as in the case of KA1, the vibration control effect of this system was more pronounced. By arranging the viscous dampers concentrated in the lower stories where the bending deformation ratio is small, effective energy absorption is enabled, regardless of the load level.

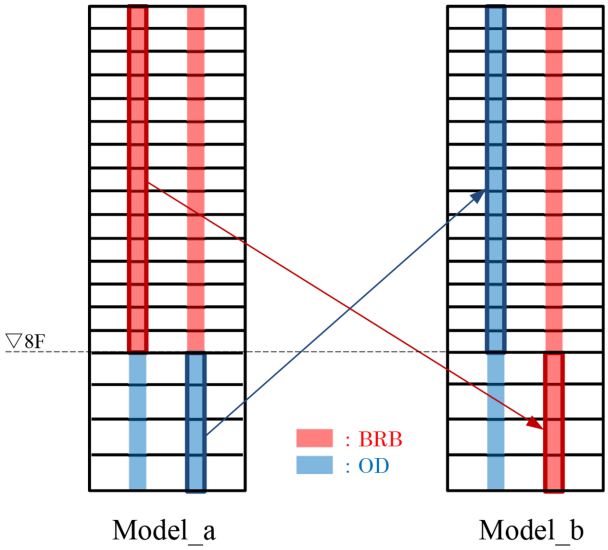


Figure 9. Damper arrangement comparison model.

Table 2. Examination seismic wave

Input seismic wave	Maximum acceleration (cm/s^2)	Maximum velocity (cm/s)	Duration (s)	Notes
KA1	45.5	21.6	655	Long period seismic motion
K-Kobe (Level 2)	374.7	51.9	60	Notification wave (inland earthquake)
K-Random (Level 2)	403.9	46	120	Notification wave (random)

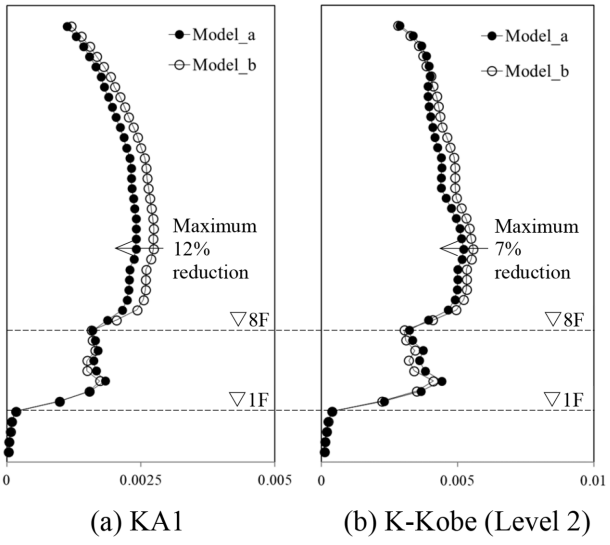


Figure 10. Maximum response story drift angle. (X-direction)

Table 3. Energy Absorption Rate

	KA1		K-Kobe (Level 2)	
	Model_a	Model_b	Model_a	Model_b
Viscous damping	36.8%	43.2%	51.5%	55.0%
OD	63.3%	56.9%	44.1%	39.4%
BRB	0.0%	0.0%	4.0%	5.2%
Main frame	0.0%	0.1%	0.3%	0.5%
Input (kN·m)	62573	55553	92542	91811

3.2 Effect of reduction in torsion

The verification for torsion was carried out focusing on 1) dynamic amplification (comparison with dynamic analysis), and 2) the effect of the vibration control devices in reducing torsion, as described below. Fig. 11 shows the centroid position of a typical story and the position of a corner node that were investigated. Fig. 12 shows deformation

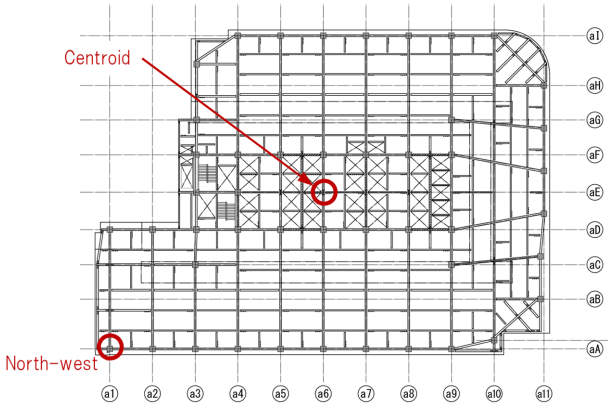


Figure 11. Centroid position of a typical story and the position of a corner node.

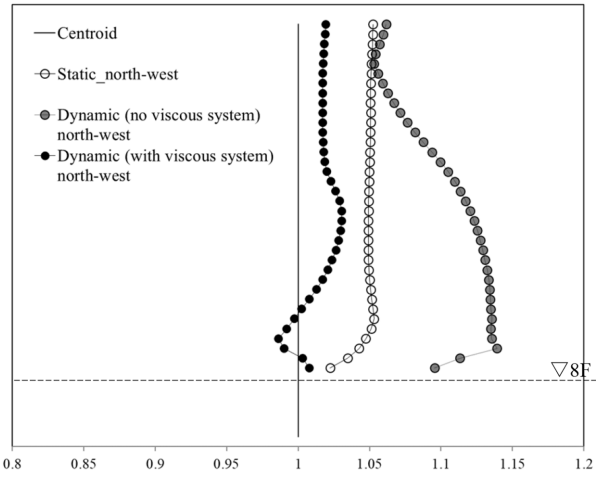


Figure 12. Deformation magnification factor of corner node with respect to the centroid position. (K-Random, Level 2, Y-direction)

magnification ratio for the maximum response displacement of each story as the displacement of the corner node normalized with respect to the displacement of the centroid position.

1) The static analysis plot was calculated from load incre-mental analysis results, torsional deformation occurs in the lower stories, with amplification increasing continuously up to about 5% at the level of the typical stories. In the dynamic analysis (no viscous system), the torsional deformation is greater than in the static analysis, and the dynamic torsional deformation is amplified by a maximum of about 15%.
2) In the dynamic analysis with viscous dampers provided in the lower stories, it was possible to reduce the torsional deformation magnification to about 3%, so it was confirmed that LSCVCS is capable of effectively controlling the response of the building overall, including the torsional response.

4. Overview of the Seismic Design (Performance-based Seismic Design Including Investigation of the Margin Level)

In this section, an overview of the seismic design is presented including an investigation of the margin level, using the vibration analysis results obtained using seismic waves with the load level increased in stages (damage to the building and the damper energy absorption percentages at each load level).

This building has an overhang structure in the lower stories with strong characteristics, so performance-based seismic design was carried out taking into consideration control of damage in the building as a whole, which was classified into the lower stories and the typical stories. Specifically, from the initial stages of the design, design criteria were defined for the damage in each part of the building (higher stories and lower stories), for each type of member (main structure and buckling restrained braces) for each load level, and the design proceeded on this basis.

Table 4. Overview of performance-based seismic design including the margin investigation level

			Rare Earthquake	Extremely Rare Earthquake	1.5 × ERE	2.0 × ERE
Earthquake level Sv			Level 1 16 kine	Level 2 80 kine	1.5 times Level 2 120 kine	2.0 times Level 2 160 kine
Plasticity state	Higher stories	BRB	elastic	yielding	yielding	yielding
		Main frame	elastic	$\mu \leqq$ Approx. 1.5	$\mu \leqq$ Approx. 2.0	$\mu \leqq$ Approx. 4.0
	Lower stories	Main frame	elastic	elastic *($\mu \leqq 1.0$)*	$\mu \leqq$ Approx. 1.2	$\mu \leqq$ Approx. 1.5
Energy absorption percentage		Viscous damping	65.7%	62.2%	56.9%	50.8%
		OD+VWD	34.3%	33.9%	30.2%	26.2%
		BRB	0.0%	3.8%	8.4%	10.2%
		Main frame	0.0%	0.0%	4.6%	13.0%

Sv : Peak velocity of pseudo Velocity Spectrum assuming 5% damping ratio
μ : ductility factor

Table 4 shows an overview of the performance-based seismic design including the investigation of the margin level. Also, the energy absorption percentages at each load level are shown for reference. The energy absorption percentages were obtained from vibration analysis using seismic waves multiplied by coefficients corresponding to each load level.

Under the Level 1 seismic load, energy was absorbed only by viscous damping and the viscous dampers in the lower stories. At this time the buckling restrained braces in the typical stories maintained their elastic stiffness, and this played the role of concentrating the deformation in the lower stories.

On the other hand, under the external load levels of the Level 2 seismic load and higher, yielding occurred in the buckling restrained braces of the typical stories prior to yielding of the main structure, so the seismic energy was absorbed and damage to the main structure was reduced. In other words, the typical stories behaved as a vibration control building provided with hysteretic dampers. The behavior of the main structure of the lower stories was also within the range of the elastic limit ($\mu \leqq 1.0$, μ: ductility factor) under the Level 2 seismic loads.

Under seismic loads 1.5 times that of Level 2, which was the maximum load envisaged in the design, plasticity occurred in the main structure of the typical stories before the lower stories, and the damage to the lower stories was reduced as much as possible. This was the same for a margin investigation level with a seismic load double that of Level 2, the damage level of the lower stories main structure was about $\mu \leqq 1.5$, so it maintained a sufficient margin of seismic performance, and the damage level of the typical stories was reduced to about the same as the design criteria with respect to the Level 2 seismic load of a normal tall building ($\mu \leqq 4.0$).

5. Conclusions

This paper introduced the Tokiwabashi Project in front of Tokyo Station, and presented an overview of the structural plan of Tower-A which is currently under construction.

LSCVCS that was adopted taking into consideration the overhang structure in the lower stories that is a characteristic of the building contributes to efficient damping regardless of the level of seismic motion, and it has been shown that this system is capable of effectively reducing the response of the building as a whole.

Also, extremely high seismic performance was achieved by utilizing the efficient energy absorption of the system and carrying out seismic design taking into consideration damage control in the building as a whole, thereby greatly reducing damage to the main structure when subject to seismic forces at the level for investigation of the margins.

References

Katsuhito Yoshizawa, Yoji Ishibashi, Kenji Nagayama, Hatsuka Oki, Ichiro Ogawa, Masatoshi Tamari : A high rise building with efficient energy dissipation induced by viscous dampers of lower stories, Summaries of Technical Papers of Annual Meeting 2018, pp.877~878, Architectural Institute of Japan.