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Structual Design of a Building with High Damping Provided by Deformation Amplification Mechanisms and Tuned Viscous Mass Damper

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Abstract This paper presents the structural design and response control system of the JR MEGURO MARC building, a 70 meters high office building with steel structure located in Tokyo (Figure 1). In order to achieve high earthquake resistance and useable office space, this building integrates a centralized response control system with deformation amplification mechanisms and tuned viscous mass dampers on the lower floor. Moreover, buckling-restrained braces (BRB) are installed on the upper floors to increase the effectiveness of centralized response control system and to reduce damage of the main frames in the event of a major earthquake. It features an efficient centralized response control system by amplifying the deformation of the dampers without creating a soft story.

Keywords Structural design, Centralized vibration control system, Deformation amplification mechanism, Tuned viscous mass damper (TVMD), Robust design

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1. Introduction

To increase the efficiency of the response control structure, it is important to ensure a large deformation of the dampers. For high-rise buildings, a typical response control system with dampers placed on each floor may cause dysfunction of the dampers due to the overall bending deformation, thereby reducing the response control performance of the building. Therefore, in this building, the dampers are concentrated on the lower floor and by amplifying the deformation of the dampers, a highly efficient centralized response control structure is realized. As a result, high damping can be ensured with a few dampers and spacious office and entrance hall are realized at the same time.

Following this introduction, the second chapter presents the building outline and the architectural scheme. The third chapter presents the structural scheme. The fourth chapter presents the response control scheme. Finally, the fifth chapter summarizes the conclusions of this paper.

2. Building Outline and Architectural Scheme

2.1. Site conditions and the design of exterior

The site is located between residential and office areas. The JR line is to the north and the Meguro River terrace with an elevation change of 10m to the south, with high-rise office buildings and residential buildings in proximity (Figure 2).

The fin-shaped exterior PC panels that characterize the building avoid the line of sight from neighboring offices and residences and guide it toward the direction of the open view. It also shields against solar radiation and reduces light pollution (Figure 3). The diagonal shape changes the appearance of the building in relation to the surrounding view, creating an eye-stopping effect. The deeply sculpted exterior casts impressive shadows and, combined with the lush greenery, creates a new symbolic presence (Figure 4).

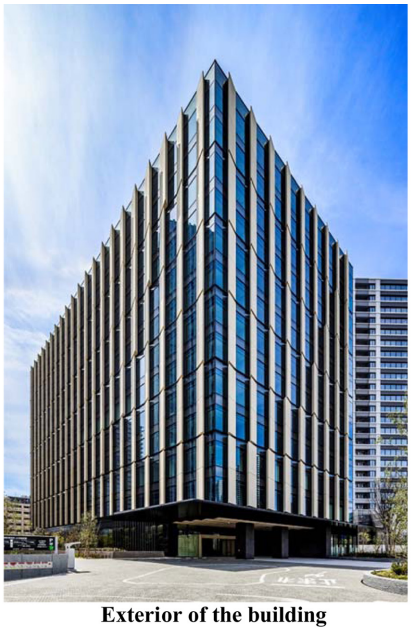
2.2. Architectural scheme of the tenant office

By concentrating dampers on the lower floor, it is possible to make effective use of the typical floor. As a result, the rental ratio of the tenant's office building is improved, and a usable, spacious column-free office with a ceiling height of 2.8 m, a floor height of 4.25m and a depth of approximately 20m is realized (Figure 5). In addition, on the first floor, the support structures for the dampers are designed as column type, so that the area under the dampers can be effectively used as a passageway or equipment machine area (Figure 5).

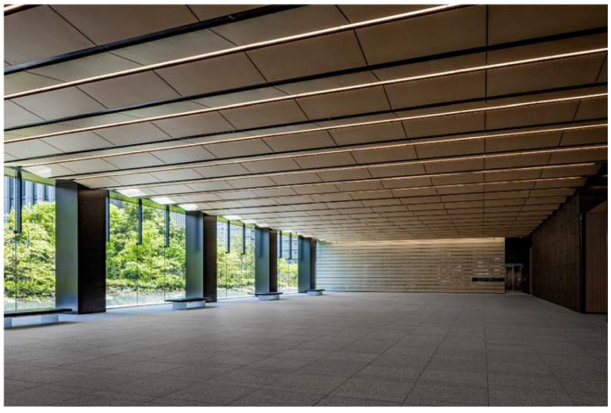
3. Structural Scheme and Response cOntrol Scheme

3.1. Outline of the structural design

This building has 13 floors above ground and 1 below



Exterior of the building



Entrance Hall

Figure 1. JR MEGURO MARC building. (Photo by Kouji Horiuchi)

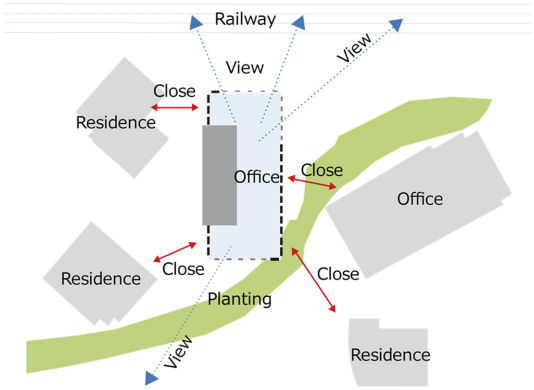


Figure 2. Site conditions.

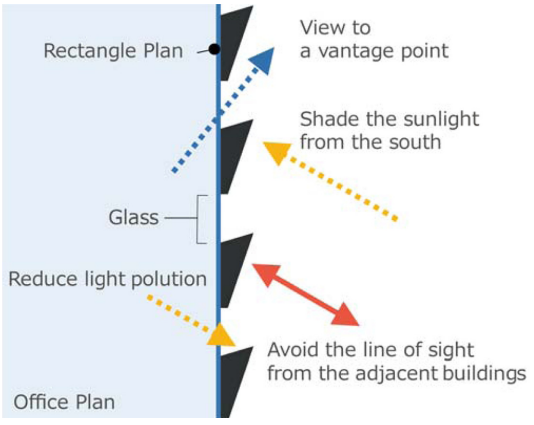


Figure 3. Function of the fin-shaped exterior PC panels.

ground, with a maximum height of GL+70 m, a total floor area of approximately 38,700 m^2, and approximately 2,500 m^2 at the typical floor. The plan of the typical floor is 33.7 m by 74.4 m, and basic column span is 11 m and 22.9 m in the X-direction, 7.2 m in the Y-direction.



Northeast face South face Fin-shaped PC panels

Figure 4. Exterior of the building. (Photo by Kouji Horiuchi)

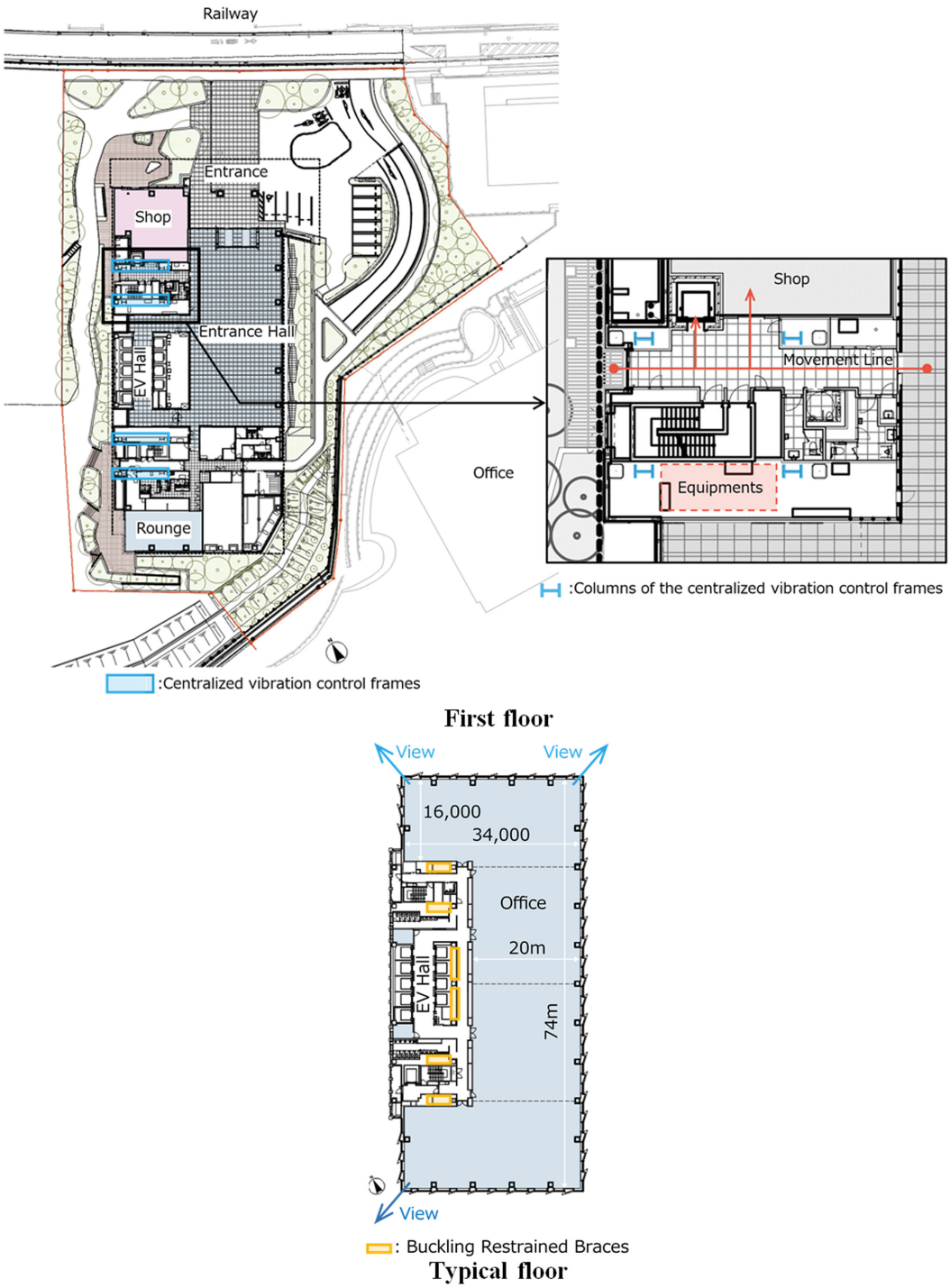


Figure 5. Floor plan

The structure above ground floors is a steel rigid frame using CFT columns, and it is a response-controlled structure. The Basement floors is a steel reinforced concrete structure with bearing RC walls. The foundation consists of reinforced concrete piles which are supported by firm gravel layer deeper than 15m from the ground (Figure 7).

3.2. Design of the response control system

In high-rise buildings, the higher the floors, the greater the overall bending deformation during an earthquake. In the case of typical distributed response control structures, where dampers are placed on each floor, the dampers on the upper floors may not work effectively, resulting in reducing damping performance. Therefore, in this building, dampers are placed on the lower floor where the overall bending deformation is small. In addition, by amplifying the deformation of the damper, the efficiency of the dampers in absorbing seismic energy are improved

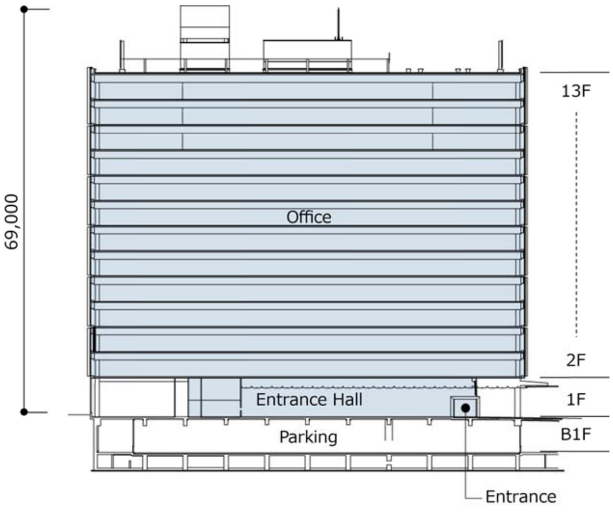


Figure 6. Cross section.

(Figure 8). To amplify the deformation of the dampers, a combination of two methods is utilized. One is the geometric deformation amplification mechanisms, which utilize the rotation of pin connections. The other is a tuned viscous mass dampers (TVMD), which can amplify the deformation of the dampers by resonating with the vibration of the building. On the upper floors, buckling restrained braces (BRB) are installed to increase the stiffness of the upper floors and enhance the effect of the centralized response control. Meanwhile, in the event of a major earthquake, the BRBs are also designed to yield before the girders to reduce damage to the main frames (Figure 9, Figure 10).

4. Design of High-performance Centralized Response Control System

4.1. Details of the deformation amplification mechanisms

Figure 11 shows the deformation amplification mechanism. The TVMDs are placed under the second-floor girder and supported by a rigid frame on the first floor and T-shaped column from the third floor, which penetrates an opening in the center of the girder on the second floor. The girder on the second floor also functions as a seismic resistant member during earthquakes. For the girder on the third floor, two pin connections are

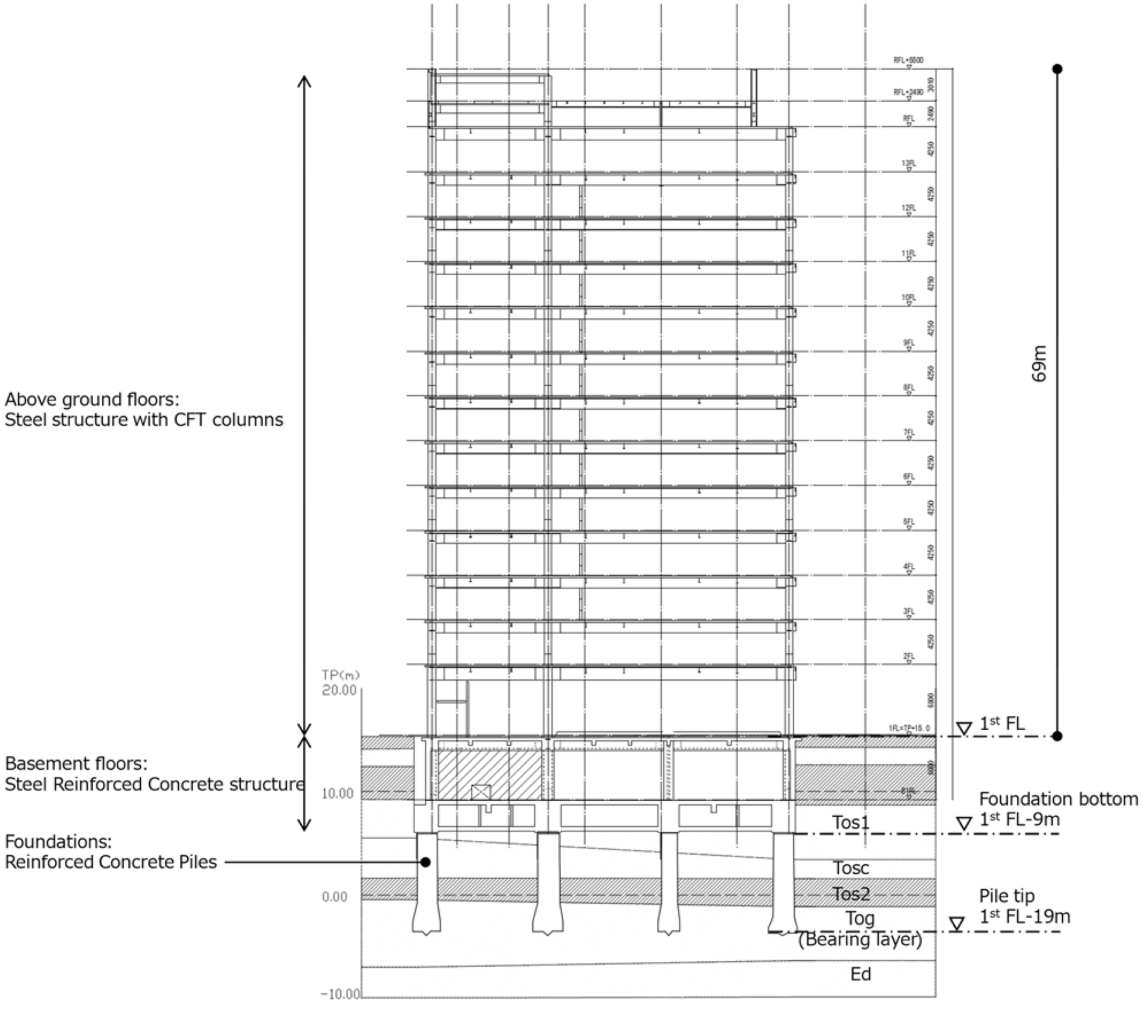


Figure 7. Structural framing elevation.

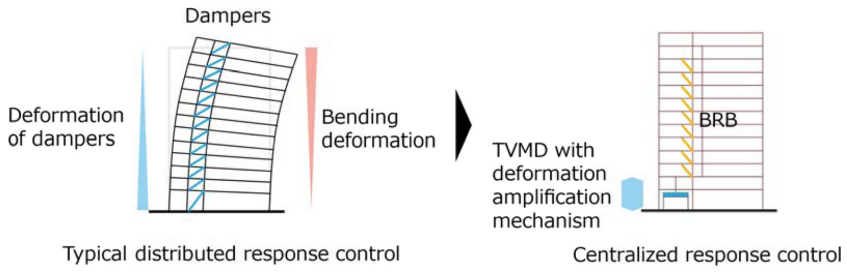


Figure 8. Concept of the centralized response control.

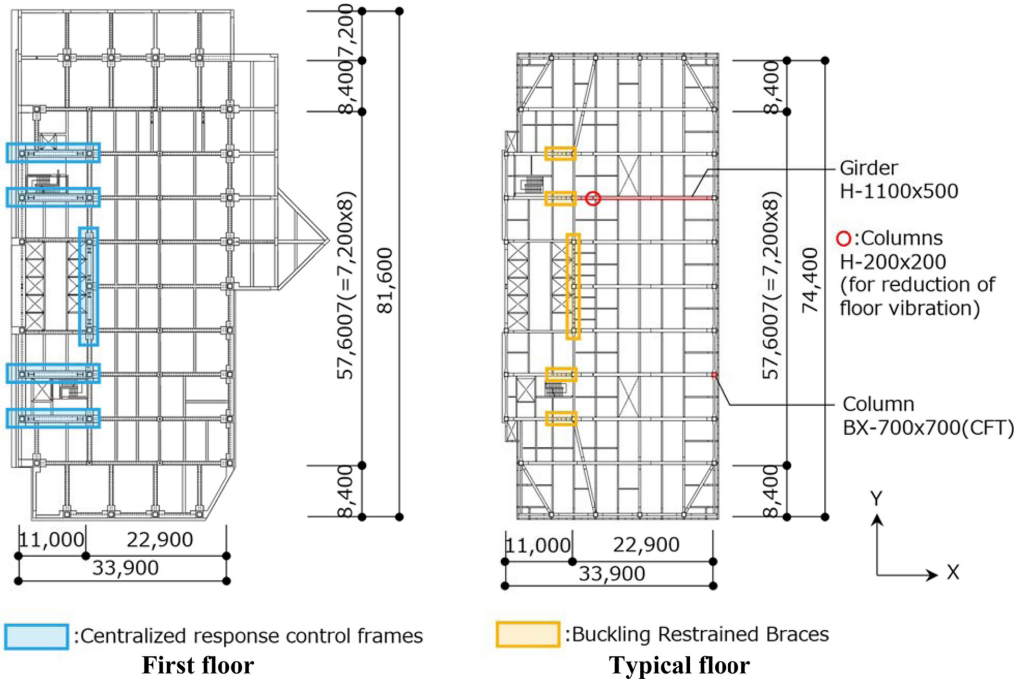


Figure 9. Structural framing plan.

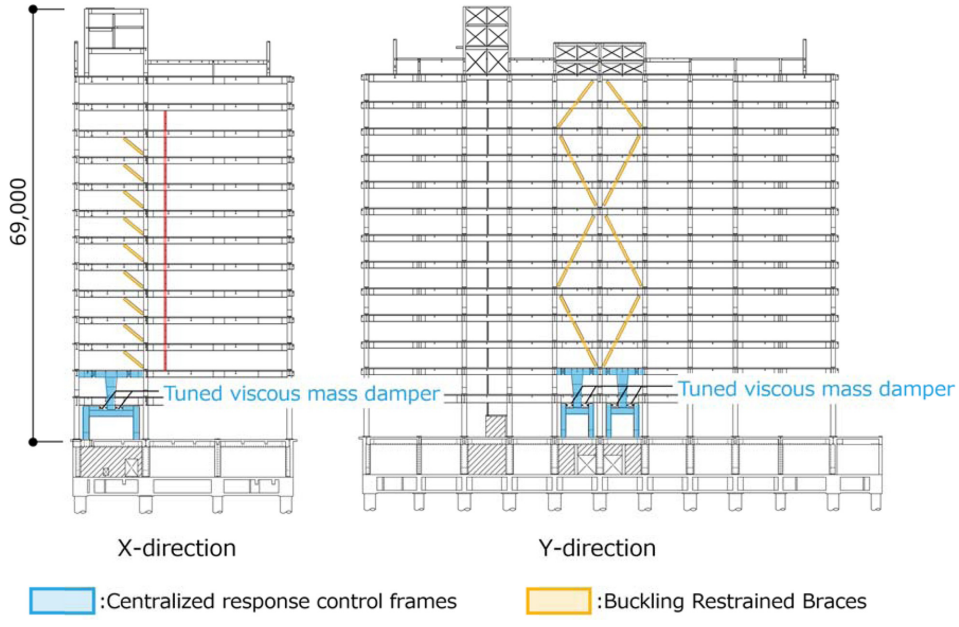


Figure 10. Structural framing elevation with vibration control elements.

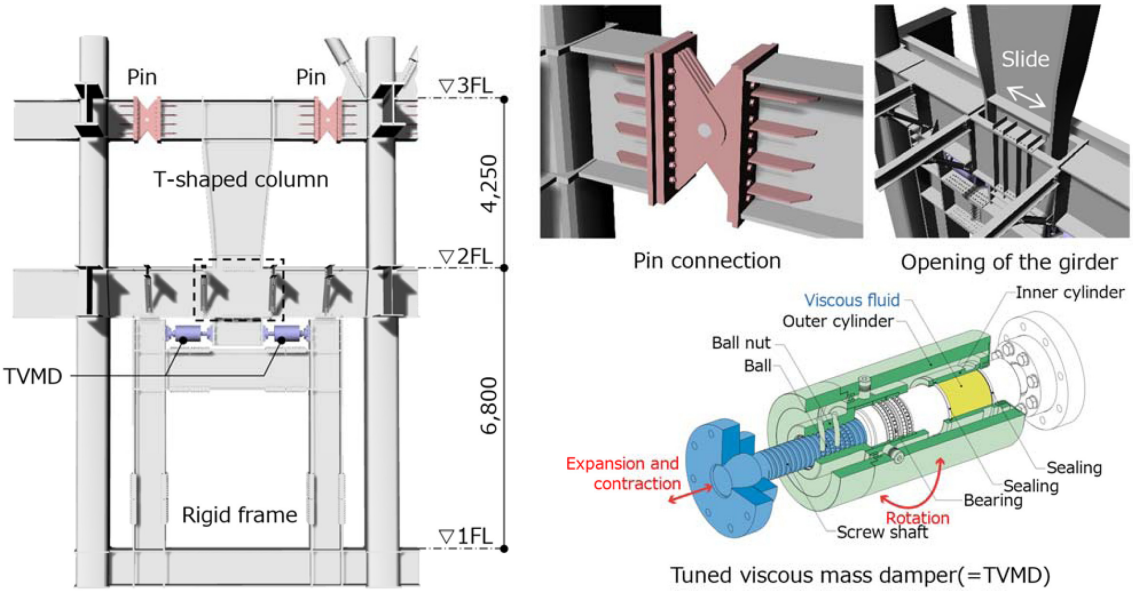


Figure 11. Details of the deformation amplification mechanism and TVMD.

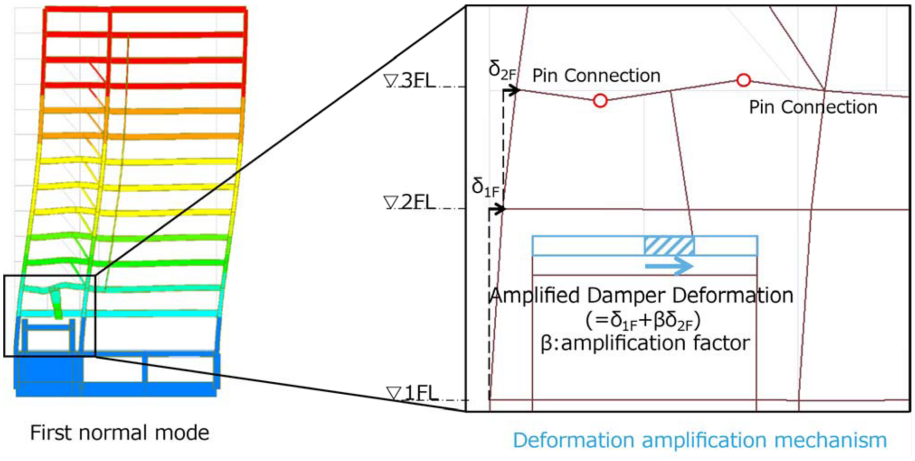


Figure 12. First mode shape in the X-Direction.

installed. As the building deforms, the deformation of the dampers is amplified by rotating the T-shaped column between the two pin connections. The important feature of the deformation amplification mechanism is that the closer the two pin connections are to the center, the greater the amplification factor, but the lower the stiffness of the support structure.

4.2. Design of the TVMD properties with enhanced robustness

The TVMD can provide significant vibration control by dynamically amplifying the deformation of the damper by tuning it to the natural period of the building. In this building, the period consisting of the stiffness of the support frame and the inertia mass of the TVMD is tuned to the first natural period of the building. This section presents the design of the TVMD properties with enhanced robustness.

In the X-direction, four vibration-controlled frames are installed and a total of eight TVMDs with an inertia mass of 1,000 tons per device are installed. The ratio of equivalent additional mass is approximately 5% of the equivalent mass of the first mode. By amplifying the deformation of the TVMD, a large mass ratio can be achieved with a small number of dampers.

The optimal TVMD properties can be calculated from the displacement response optimal conditions based on the fixed-point theory (Table 1). In this case, the TVMD period is set to be approximately 10% shorter than the optimal period (Table 2). This considers the effects of variations in the natural period of the building and the stiffness of the TVMD support frame. Figure 14 shows response magnification of the TVMD deformation to the building deformation of equivalent SDOF system. As

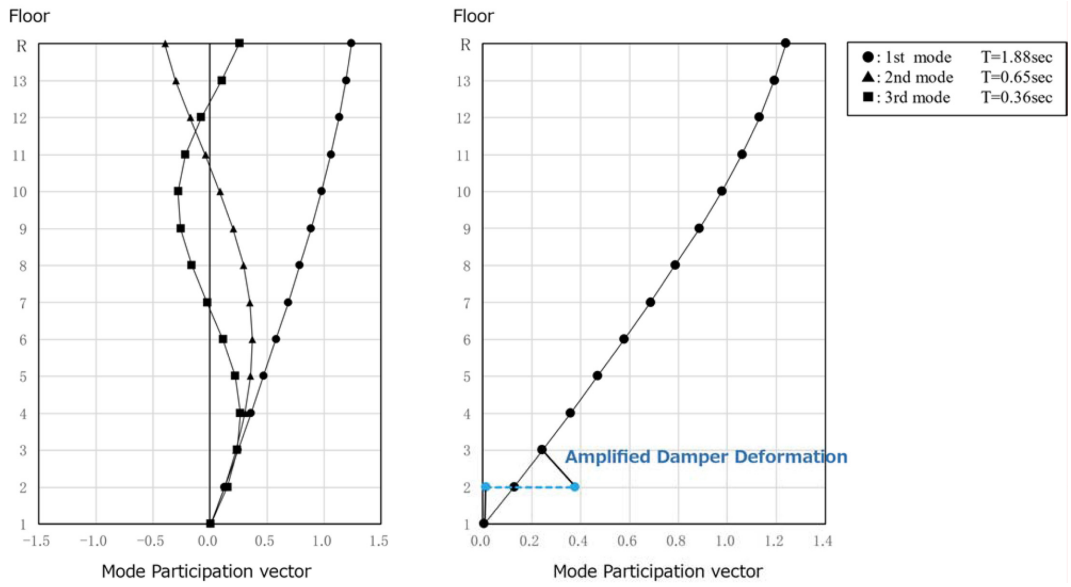
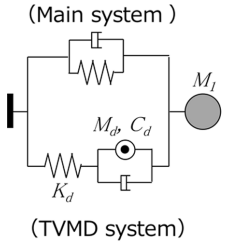


Figure 13. Natural mode shapes of the building in the X-direction.

Table 1. Optimal TVMD properties for equivalent SDOF system of first mode

Item	Symbol	Unit	Value
Total mass of building	M	ton	29,892
Equivalent mass of the first mode	M_1	ton	20,844
Equivalent mass ratio	M_1/M	-	0.697
Period of the main system	T_1	sec	1.88
Equivalent mass of TVMD	M_d	ton	1,060
Ratio of additional TVMD mass	$\mu(=M_d/M_1)$	-	0.051
Magnification ratio of optimal additional tuning vibration	γ_{opt}	-	1.06
Optimal period of TVMD system	T_{opt}	Sec	1.78
Optimal additional stiffness (per frame)	K_{opt}	kN/m	99,864 (24,966)
Optimal additional damping constant	h_{opt}	-	0.142
Optimal additional damping coefficient (per device)	C_{opt}	kN/(m/s)	8,024 (1,003)



shown in Figure 14, if the period of the TVMD is shorter than the period of the building, the deformation of the TVMD is not less than the deformation of building. On the other hand, if the period of the TVMD is longer than the period of the building, the deformation of the TVMD converges to zero. It was also confirmed that for random seismic motion, stiffer tuning can increase the energy absorption efficiency of TVMD.

4.3. Response analysis result

Figure 15 shows the response analysis result of major earthquake with and without centralized vibration control. As shown in Figure 15, the share force and the story drift were reduced by approximately 20% with centralized vibration control. Figure 16 shows the hysteresis loop of the TVMD force and displacement. Figure 17 shows the time history of the story drift and the deformation of the TVMD. As shown in Figure 16, Figure 17, the deformation

Table 2. TVMD Properties (per device)

Item	Symbol	Unit	Value	
Additional mass	m_d	ton	1,000	
Stiffness of the supporting frame	k_d	kN/m	28,224	(= Optimal value × 1.13)
Period of the TVMD system	t_d	sec	1.67	(= Optimal value × 1.07)
Additional damping coefficient	c_d	kN/(m/s)	1,100	(= Optimal value × 1.10)
Axial force limit	f_y	kN	1,000	

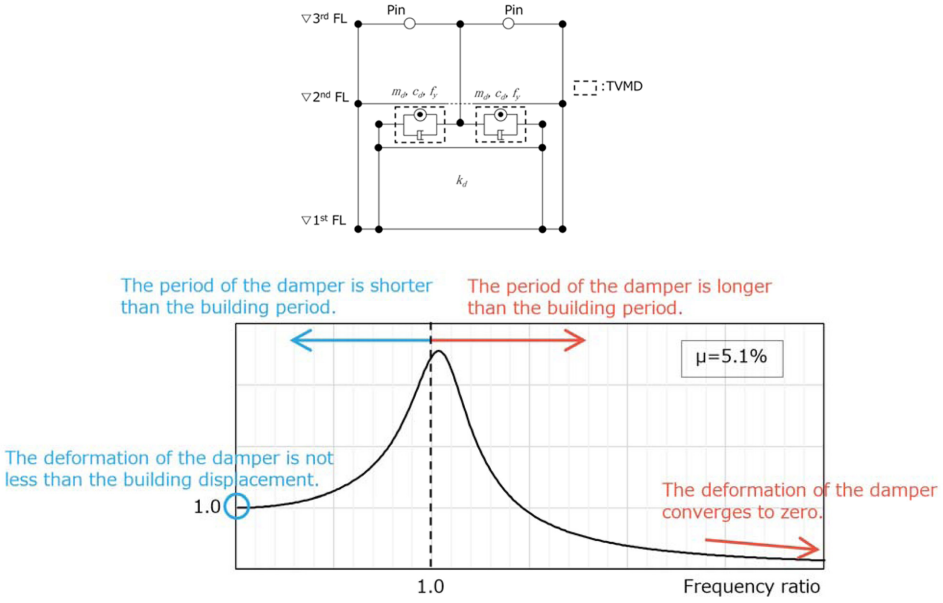


Figure 14. Response magnification of the TVMD deformation to the building deformation.

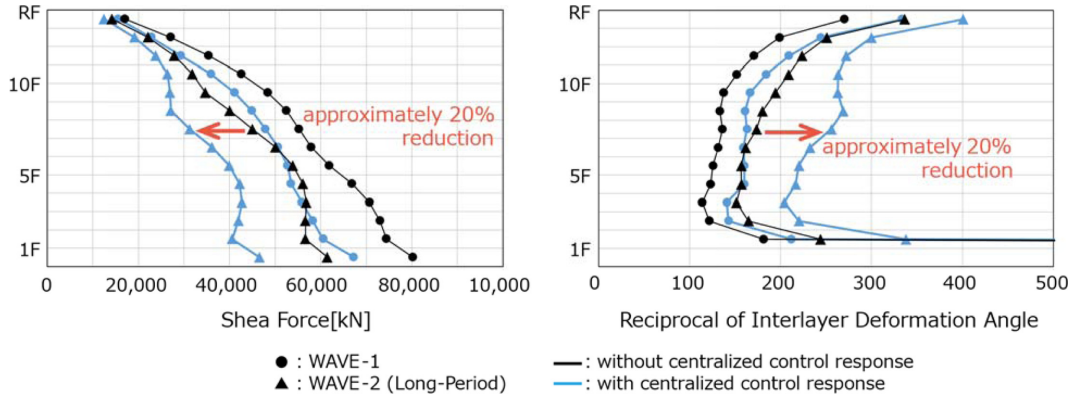


Figure 15. Response analysis result. (major earthquake motion, in the X-direction)

of the TVMD was amplified approximately 2.4 times the story drift, resulting in high energy absorption. Figure 18 shows the ratio of the energy absorption amount. The energy absorption ratio of the TVMD was approximately 50% and can provided about 2% attenuation. As a result, the maximum plasticity ratio of the story was approximately 1.1, and the damage control of the main frames was adequately achieved in the event of the major earthquake. In addition, it can reduce vibrations not only during major earthquakes, but also during small and medium earthquakes and typhoons.

4.4. Details of deformation amplification mechanism

The deformation amplification mechanisms supporting the TVMD, which are the key to realizing the centralized vibration control, have been consistently designed during the design, manufacturing and construction phases. The pins were confirmed to achieve smooth movement as the manufacturing accuracy by machining finish. As for the T-shaped columns penetrating the girder on the second floor, clearance was secured to allow for the difference in deformation between the building and the TVMD support frame. Once the support frame was erected on site, an oil

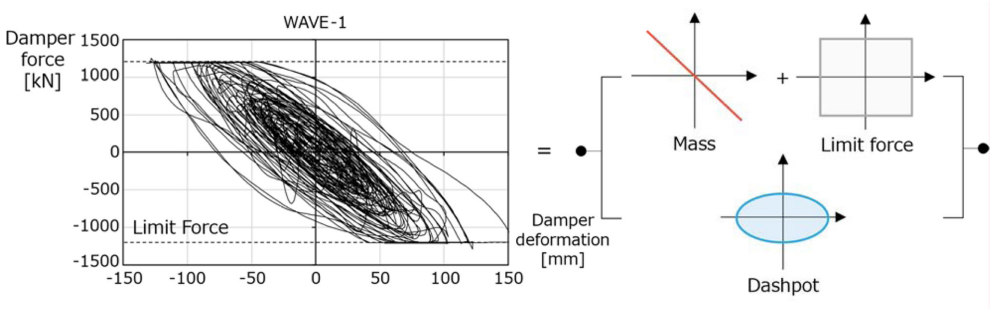


Figure 16. Hysteresis loop of the TVMD force and deformation.

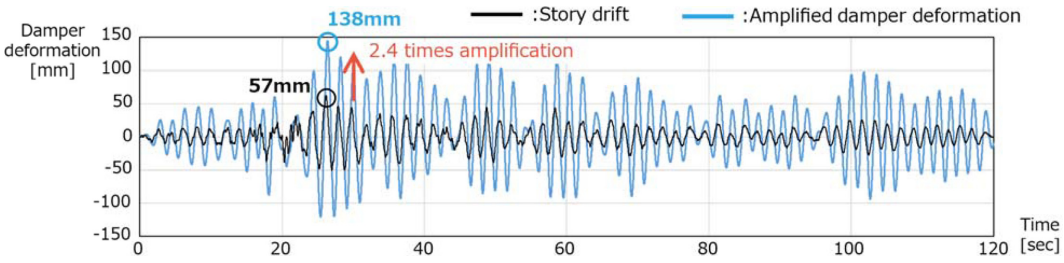


Figure 17. Time history of the story drift and the deformation of the TVMD.

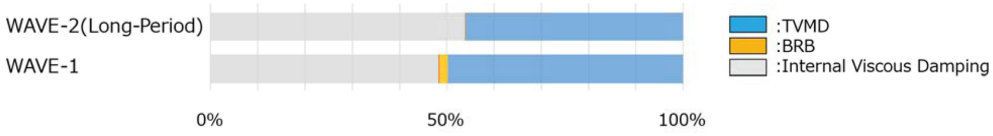


Figure 18. Ratio of energy absorption amount.



Figure 19. Constructions of the deformation amplification mechanism and TVMD.

jack was installed at the damper location and force was applied to confirm that the movement and stiffness of the support structures were as expected. Figure 19 shows construction photos of the deformation amplification mechanism.

Conclusions

This paper introduced the structural design and vibration control design of JR MEGURO MARK building. This building realized high seismic performance and spacious office space by adopting the centralized vibration control with deformation amplification mechanisms and TVMD on the lower floors. The feature of the vibration control system is summarized as follows:

(1) The deformation of the TVMD can be geometrically amplified approximately 1.5 times the story drift by the deformation amplification mechanisms.

(2) The TVMD are tuned to the first natural mode of the building, and the period of the TVMD is tuned to be approximately 10% shorter than the optimal period to enhance the robustness.

(3) An additional 2% damping is achieved by the centralized vibration in the event of a major earthquake.

Acknowledgments

In Mach 2022, this building was completed and has started operation. Here, I would like to express my sincere gratitude for the great cooperation and understanding of the building owner, constructor and all other parties involved.

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