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Structural Design and Construction of High-rise Building to Feature the High-performance Oil Dampers for Vibration Control - Hibiya Mitsui Tower -

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Abstract

This report introduces the structural design of Hibiya Mitsui Tower built in Tokyo Midtown Hibiya. The upper part of this tower is used for offices and the lower portion is for commercial facilities and a cinema complex which need the large open spaces. The 192m-high building has 35 floors above ground and 4 below ground. The structure is a steel frame using CFT columns to feature the high-performance oil dampers and the buckling restrained braces for vibration control. First, an outline of the structural design of this building is presented. Second, we introduce the transfer frame adopted to realize the large open spaces in the lower part, and the long column supporting the corner part of the high-rise building to avoid making a shade on the adjacent Hibiya Park, which are the feature of this building. Finally, we present an outline of the latest highly efficient semi-active oil dampers adopted in this building, and the vibration responses of this tower.

Keywords: Structural design, High-rise building, High-performance oil damper, Transfer frame, Long column

1. Introduction

The central Tokyo district of Hibiya abuts on important business and shopping areas -Otemachi, Marunouchi, Yurakucho, Ginza, Kasumigaseki and Shimbashi- and is adjacent to Hibiya Park, a precious green oasis in the heart of this metropolis. This district also includes a lot of historical buildings, as well as important arts and cultural facilities and hotels, like the Imperial Hotel, Nissay Theatre and Tokyo Takarazuka Theater

"Tokyo Midtown Hibiya" was realized by demolishing two notable buildings, namely, the Hibiya Mitsui Building and Sanshin Building, and reorganizing the local street administrated by Chiyoda City between two blocks. Hibiya Mitsui Tower located in "Tokyo Midtown Hibiya" has office floors on the upper part and commercial facilities and a cinema complex in the lower portion (Figure 1, Figure 2).

2. Outline of the structural design

This building has 35 floors above ground and 4 below ground, with a maximum height of GL+192m, a total floor area of about 189,000m^2 with about 4,200m^2 area at the typical floor. The plan is 98.8m by 105.0m for the lower floor and 56.2m by 77.7m for the upper floors, and the basic column span is 9.0m in the X-direction, 10.8m in the Y-direction, and the typical floor height is 4.45m (Figure 3).

The structure above ground floors is a steel rigid frame



Figure 1. Exterior of the building.

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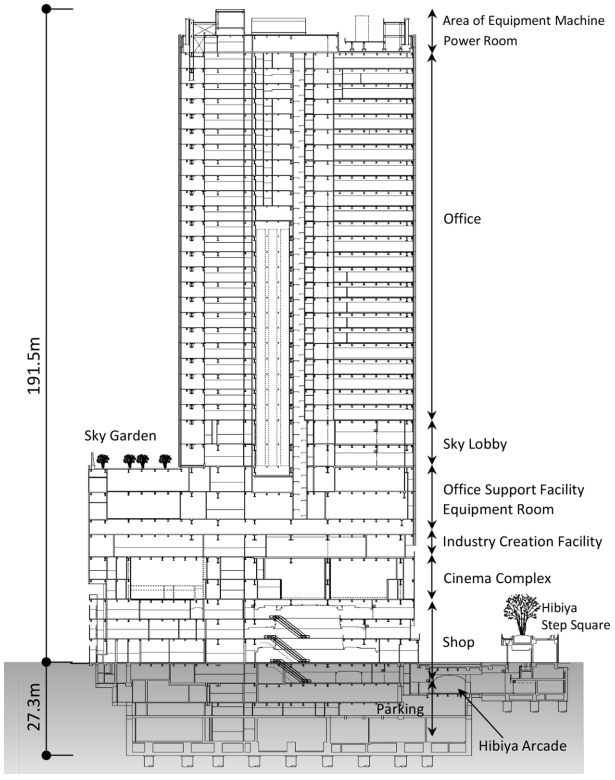


Figure 2. Cross section of the building.

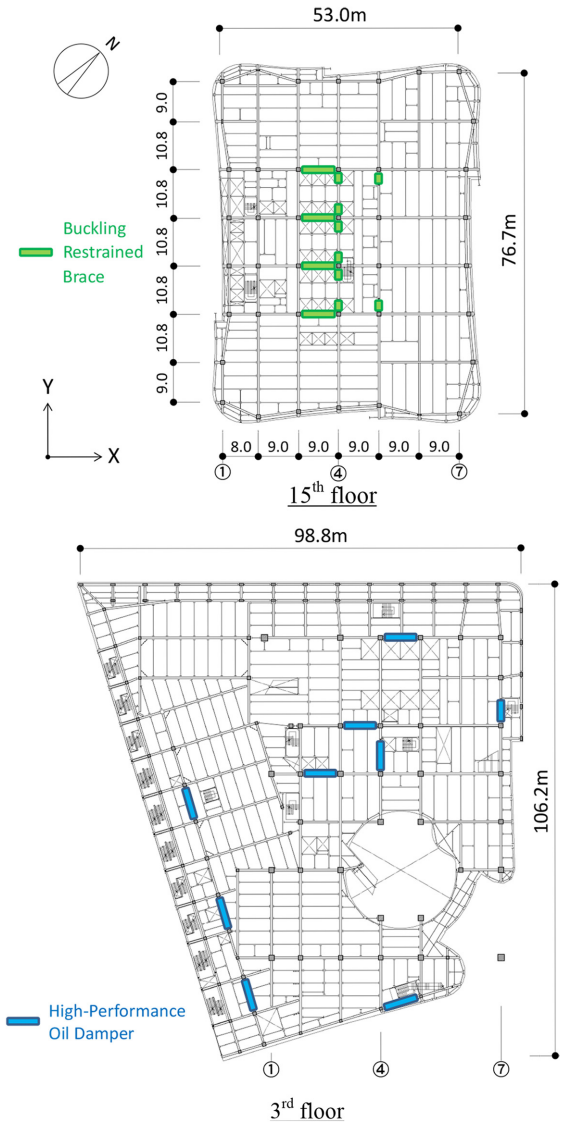


Figure 3. Framing plan.



Figure 4. Precast concrete panel for the perimeter.

using CFT columns, and it is a response controlled structure using high-performance oil dampers and buckling restrained braces. The CFT main columns are comprised of four plates using shop welding along the edge of the plates, the grade of steel material is 490 to 550MPa, and the strength of filled concrete is 60 to 100MPa. The girders are the welded assembled H-shaped steel which grade is 490 to 550MPa. Since the perimeter floor slab of the high-rise part has a complicated shape in accordance with the pleated exterior, the construction was rationalized by using the precast concrete panels that the fasteners for the curtain walls are embedded at the edge (Figure 4).

As the vibration control system, the high-performance oil dampers are arranged intensively on the lower floors from the 1st to the 6th floors to add damping, and the buckling restrained braces are arranged around EV shaft on the upper floors to increase the rigidity and strength of the structure frame (Figure 5).

Bearing walls of the basement are designed to resist all the horizontal force of earthquake. The columns have a transition from a box section to a cross H section encased with reinforced concrete at the 1/3 height of B1th floor. The girders from the ground floor to the second floor of the basement are reinforced concrete and steel structure, and the third floor of the basement has the flat slab structures.

The foundation is a piled raft foundation that combines a concept of the deep (pile) foundation and the shallow (raft) foundation and is supported by a firm sand layer deeper than 20.0m from the ground. The entire construction period was shortened by adopting a reversed placing method in which the above ground and the underground part can be simultaneously constructed using the permanent piles. In the foundation design, the proportion of the load supported by the deep (pile) foundation and the shallow (raft) foundation was calculated by performing non-linear analysis in consideration of the ground-pile-base interaction. The differential settlement of the foundation was controlled

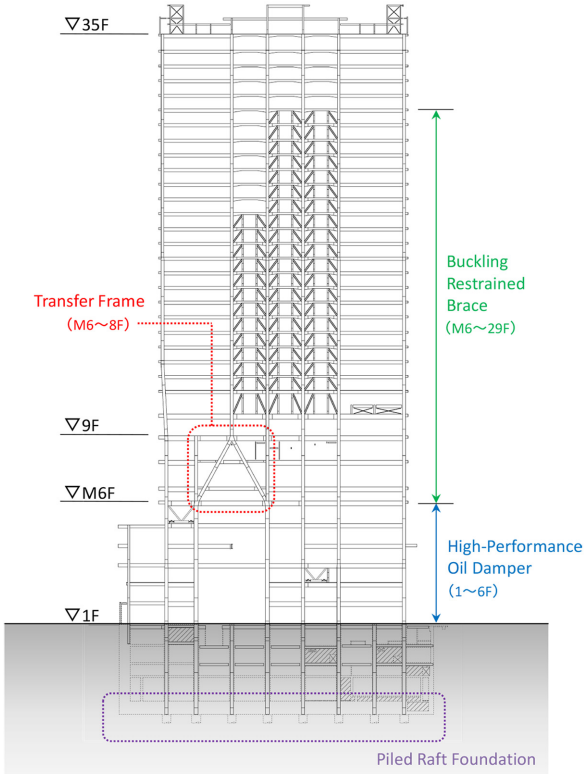


Figure 5. Framing elevation.

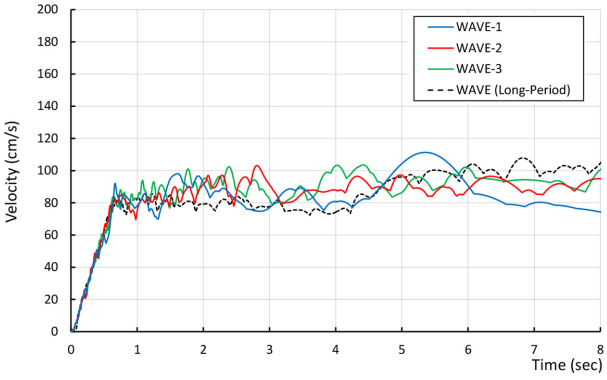


Figure 6. Velocity response spectrum. (Level-2 earthquake motion)

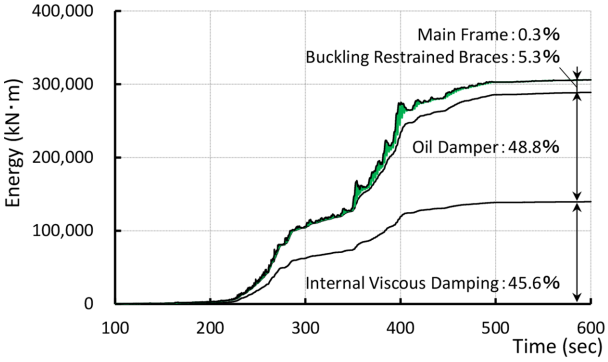


Figure 7. Ratio of energy absorption amount. (Level-2 Long-period ground motion, Y-Direction)

by adjusting the length of the pile according to the calculated axial forces.

For the superstructure, seismic response analysis was conducted using 3-dimensional frame model including each column, girder and vibration control member. According to the eigenvalue analysis result, the primary natural period of the building is 4.67 seconds in the X-direction and 4.37 seconds in the Y-direction. The main frames are designed to remain almost elastic for Level-2 earthquake ground motions which are minimum inputs indicated by Japanese code.

Figure 7 shows the ratio of energy absorption to long-period ground motion of Level-2 (Figure 6). It shows that most of the seismic energy is absorbed by the oil dampers, buckling restrained braces and internal viscous damping, and the main frame is almost elastic.

Moreover to increase even higher seismic safety, this building is designed to keep an inter-layer deformation angle 1/100 or less and a plasticity ratio of members 4.0 or less for Level-3 earthquake motions which are 1.5 times larger than Level-2 earthquake motions (Figure 8, Figure 9).

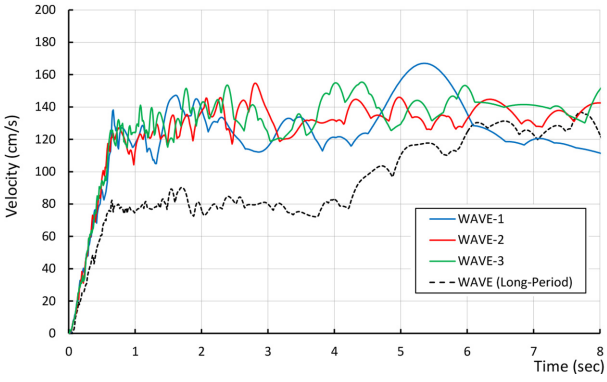


Figure 8. Velocity response spectrum. (Level-3 earthquake motion)

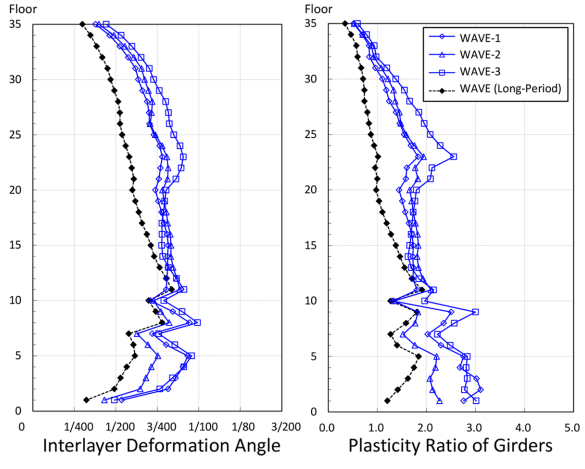


Figure 9. Response analysis result. (Level-3 earthquake motion, X-Direction)

2.1. Transfer frame to realize the large open spaces on lower floors

As the cinema theaters and an atrium for commercial facility floor which are required large spaces are planned on the lower floors, it is necessary to remove the six columns supporting the upper parts at the lower floors. In this project, the column omission in the lower layer parts was realized by transmitting the column axial forces of the upper part to the adjacent columns by the large triangular transfer frame composed of the oblique columns and the connecting beam across three layers from the M6th floor to the 8th floor (Figure 5). Since the transfer frame has much higher horizontal rigidity compared to the rigid frame, the transfer frame was uniformly disposed only in the Y-direction so as to secure rigidity balance of the building plane. The diagonal columns are made of CFT, but in order to balance the horizontal rigidity of the plane, the diagonal columns of the leftmost bay where the transfer frame is two continuous are made of steel (Figure 10). The transfer frame is designed so as not to be plasticized against the stress caused by a huge earthquake due to always bear a large axial force.

In the construction of the steel frame, in order to minimize the displacement of the top of the frame where diagonal columns gather, the construction accuracy was secured by on-site welding at the top of girders of the M6th floor where diagonal columns start (Figure 11).

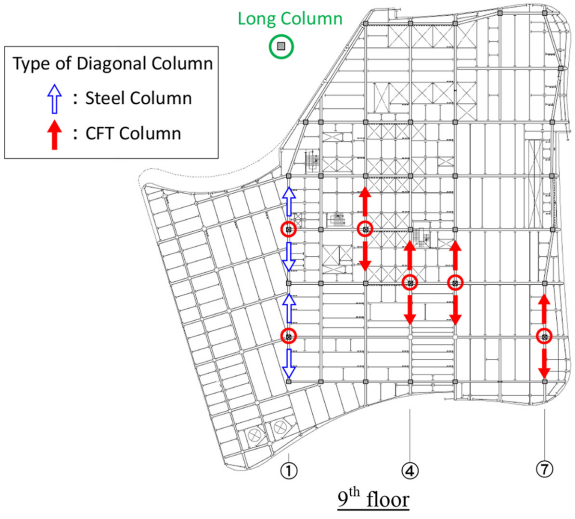


Figure 10. Framing plan. (Top layer of transfer frame)



Figure 11. Construction of transfer frame.

2.2. About 30m long column supporting the corners of a high-rise building

In consideration of the a shade to Hibiya Park adjacent to the northwest side, the shape of the middle layer from the 7th to the 11th floors is partially cut away, and the corner of the high-rise building is supported by a long column of about 30m (Figure 10, Figure 12, Figure 13). This long column is a CFT structure which is a 1,450mm built-up box-shaped cross section comprised of 50mm thick plates, and made of TMCP385C steel material and 80MPa strength concrete. (Column length ratio: Lk / D = 19.5, Diameter thickness ratio: D / t = 29.0).

This long column design was verified by the elastic buckling analysis considering the rigidity of the beam connected to the top and bottom of this column, the horizontal rigidity of the layer, and the initial irregularity and the horizontal displacement at the time of earthquake (Figure 14). The torsional rigidity of the layers supported by this column are increased by arranging some of the braces in the outer frames.

2.3. Application of the high-performance oil dampers to make the building more secure

In this building, oil dampers are arranged intensively on the lower parts from the 1st to the 6th floors where the floor height is high and the inter-layer deformation at the time of earthquake is large so that the energy absorption

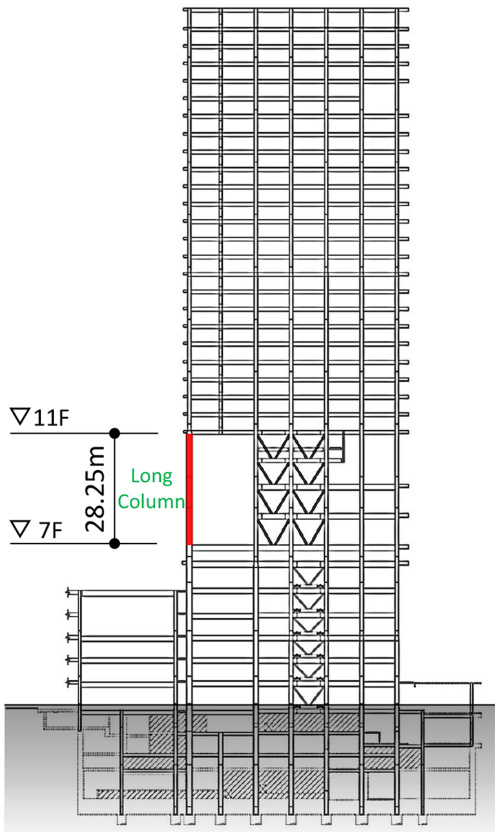


Figure 12. Framing elevation.



Figure 13. Construction of long column.

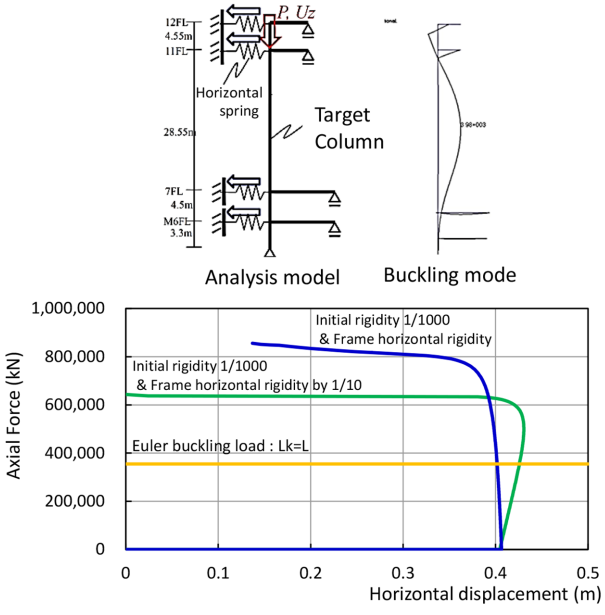


Figure 14. Result of the elastic buckling analysis.

efficiency is more improved. Kajima Corporation has been developing independently an oil damper HiDAX series with higher energy absorption efficiency for many year [1,2]. We developed a highly efficient semi-active oil damper "HiDAX-R (Revolution)" that can break through the limitation of existing oil damper by energy recovery system and applied it to this building for the first time (Figure 15, Figure 16). Conventional oil damper always change vibration energy to heat. However the new device recovers the vibration energy as oil strain energy in the auxiliary tank, and reuses it at an optimum timing to enlarge the damper stroke or to improve the control efficiency. The energy absorption efficiency can actually reach 4 times that of a conventional oil damper (Figure 17).

Because HiDAX-R has a large energy absorption Even in low amplitude areas, at the time of earthquake of seismic intensity 4-5 classes with high frequency of occurrence and the long-period ground motion, it is possible to reduce the shaking width during the earthquakes and the convergence time of shaking after the earthquake. Therefore, not only the seismic safety of the building but also the safety performance can be greatly improved.

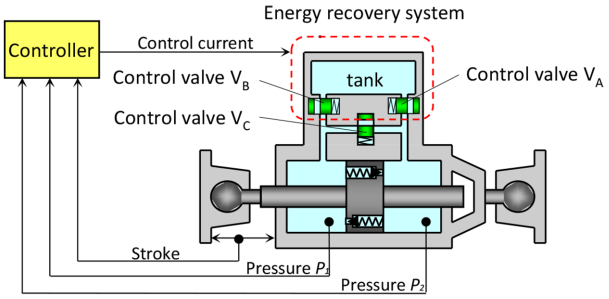


Figure 15. Basic configuration of a semi-active oil damper with energy recovery system.

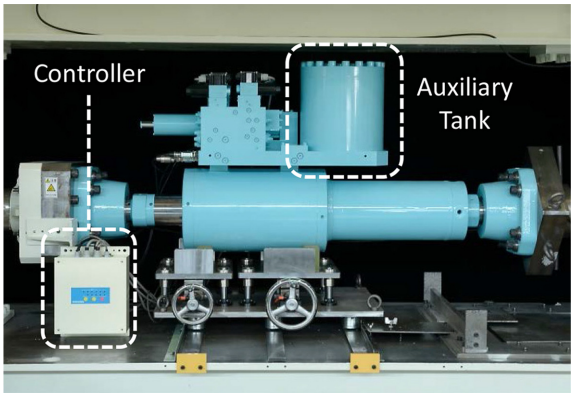


Figure 16. External view of HiDAX-R.

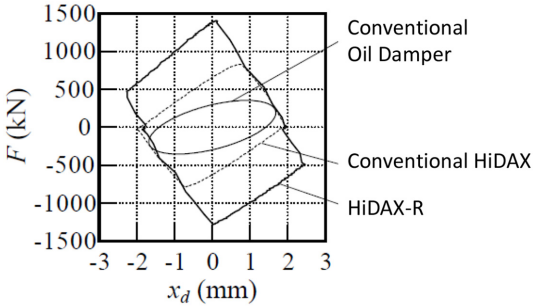


Figure 17. Energy absorption amount.

As verification for the long-period ground motion, response analysis was conducted by inputting the seismic motion observed in Otemachi during The 2011 off the Pacific coast of Tohoku Earthquake to the analytical model of this building. Compared with the response analysis results of the case that only the steel dampers were used as the vibration control device, the swing width was reduced by about half and the convergence time of the shaking after earthquake was reduced to 1/9. Therefore it is thought that this building is more secure (Figure 18).

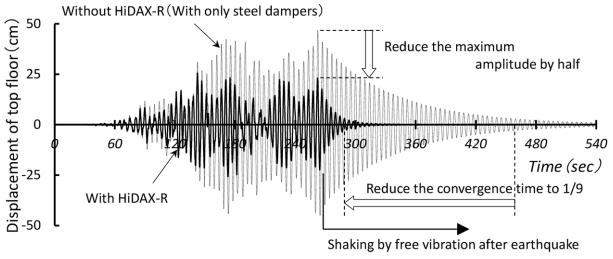


Figure 18. Response displacement time history.

3. Conclusions

This paper introduced the structural design and the construction of Hibiya Mitsui Tower. The feature of this building is summarized as follows:

(1) The large open spaces in the lower part of this high-rise building were economically realized by the transfer frames.

(2) The cutaway shape of the middle layer to reduce a shade to the adjacent Hibiya Park was realized by supporting the corner of building with a long column.

(3) High seismic performance is achieved by adopting the newly developed highly efficient semi-active oil dampers.

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