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Performance-based Design of 300 m Vertical City "ABENO HARUKAS"

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Abstract

In designing a 300 meter high skyscraper expected to be the tallest building in Japan, an earthquake-ridden country, we launched on the full-scale performance based design to ensure redundancy and establish new specifications using below new techniques. The following new techniques are applied because the existing techniques/materials are not enough to meet the established design criteria for the large-scale, irregularly-shaped building, and earth-conscious material saving and construction streamlining for reconstructing a station building are also required:
• High strength materials: Concrete filled steel tube ("CFT") columns made of high-strength concrete and steels;
• New joint system: Combination of outer diaphragm and aluminium spray jointing;
• Various dampers including corrugated steel-plate walls, rotational friction dampers, oil dampers, and inverted-pendulum adaptive tuned mass damper (ATMD): Installed as appropriate; and
• Foundation system: Piled raft foundation, soil cement earth-retaining wall construction, and beer bottle shaped high-strength CFT piles.

Keywords: Vertical city, Linked void structure, High-grade vibration-damped building

1. Overview

ABENO HARUKAS is Japan's tallest skyscraper, standing at 300 meters, which was completed in March 2014 (Fig. 1).

The project site is situated in Abeno, Osaka which is a city representative of Western Japan and the world's 7th largest metropolitan area. Abeno is one of the major areas of Osaka, and this area has been growing fast and drawn the most attention in recent years.

ABENO HARUKAS is a building located immediately above the Abenobashi Station owned and operated by the private railway company Kintetsu Corporation. This building is a superhigh-rise vertical city with the gross floor area of approx. 212,000 square meters. Rising 60 stories above the ground and 5 underground stories, this tower incorporates diverse functions: a terminal station, a department store, an art museum, offices, a hotel, an observatory, parking spaces and more. No other building of this scale has been built above a station in any place of the world.

2. Special Features of ABENO HARUKAS

ABENO HARUKAS (hereinafter "HARUKAS") stands out from other general skyscrapers because of the following three noteworthy features:

(1) This is a vertical city type skyscraper beyond the bounds of a mixed-use complex;

Figure 1. Northwest view.

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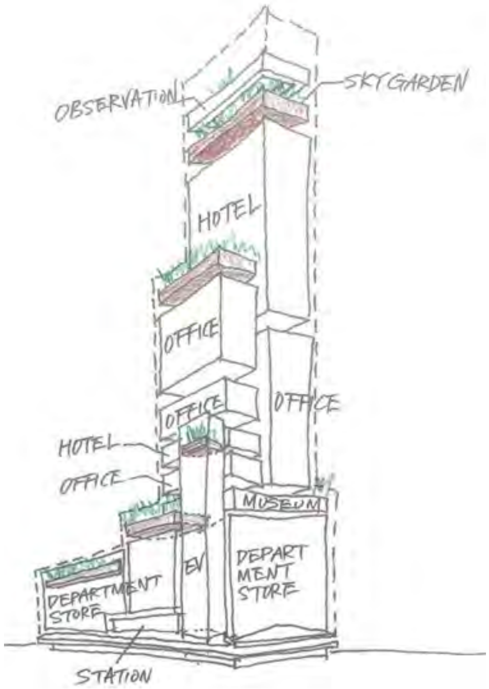

Figure 2. Diagram of ABENO HARUKAS.

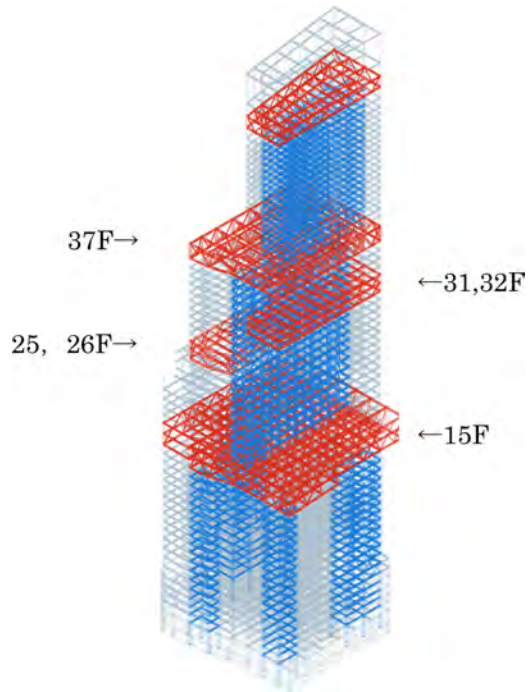

Figure 4. Void structure.

(2) The existing building was reconstructed into this skyscraper; and

(3) A high-grade vibration-damped building was constructed in Japan, the world's most earthquake-ridden and typhoon-ridden country.

2.1. Vertical city type skyscraper beyond bounds of mixed-use complex

Many of mixed-use skyscrapers have diverse uses and functions laid out in a homogenous volume consisting of repeated planes relatively approximated to one another. On the other hand, HARUKAS was so designed as to maximize the performances of a terminal station and many other uses and functions, which are shifted with different footprints and stacked (Fig. 2).

This Japan's tallest HARUKAS building incorporating functions in such a sophisticated manner not only will contribute to the convenience of the station and to the local revitalization but also is expected to serve as a gateway to Osaka from the Kansai International Airport and become a worldwide recognizable signature building of Japan.

Furthermore, HARUKAS is outstanding not only in that the activities of the functions in the city are vigorous and attractive but also in that the infrastructure through which they achieve their objectives are regarded as important, and all its factors are functionally, environmentally and structurally linked to one another (Fig. 3).

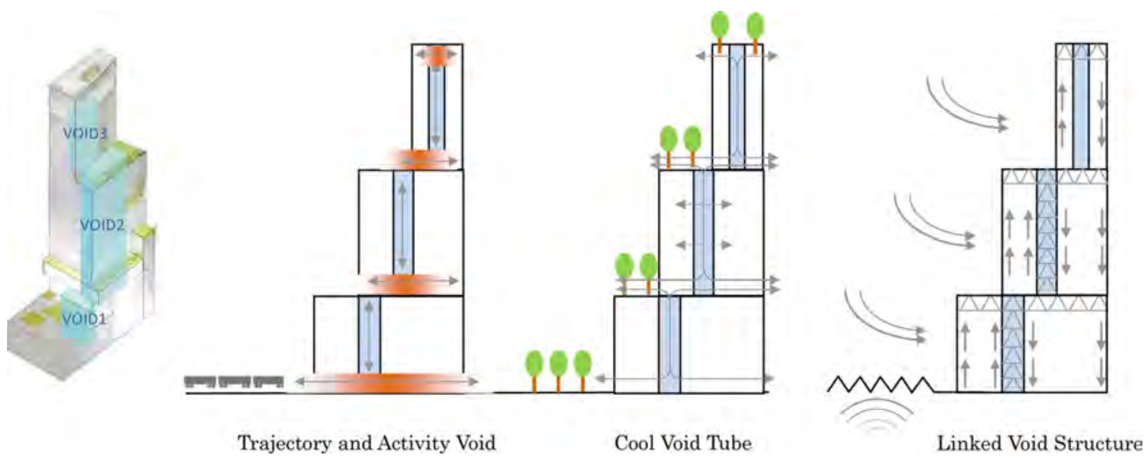

Figure 3. Infrastructure of ABENO HARUKAS.

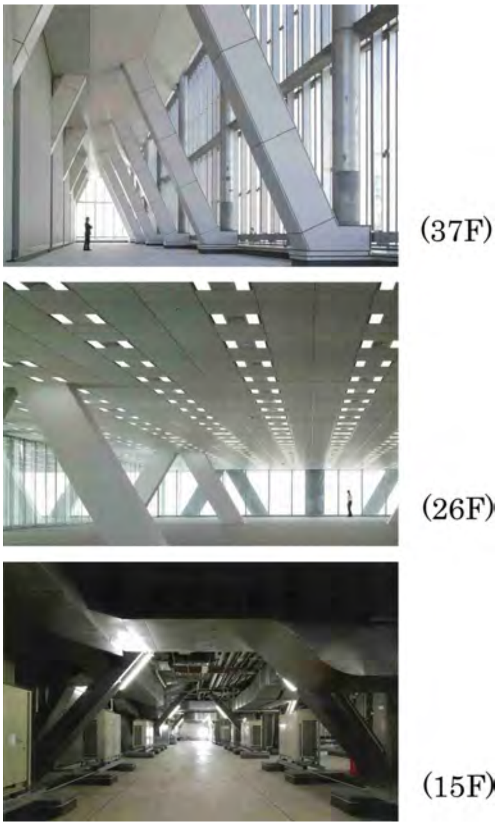

Figure 5. Outrigger floors.

Environmentally, the voids in the building are utilized for such purposes as daylighting, ventilation and heat exchange.

Structurally, the vertically located voids are interlinked to the horizontal outriggers, which forms a Linked Void Structure (Figs. 4 and 5).

For the low-rise floors, vibration dampers are concentrated to absorb the energy according to the large shear deformation components, where the stairwells in the back-of-house area of the department store are laid out at the four corners of planes and used as a vertical void (Fig. 6).

On the mid-rise floors, a core located at the center of office spaces serves as a void. Many skyscrapers have closed concrete voids located at their centers as structural voids. However, HARUKAS does not use the void only as a lateral force resistance element; it is also functioning as a transition space between different uses of this vertical city, where a steel truss void is employed so that you may feel comfortable as if you were riding on a train passing through an overpass with sunshine filtering through foliage (Fig. 7).

This mid-rise floor void has outriggers on the 15th and 37th floors and two 2-story braced outriggers located between them; one on the 25th floor and the other on the 31st floor. These outriggers suppress the deformations equivalent to the antinodes in higher vibration modes of and work effectively to reduce the responses throughout the whole building (Fig. 8).

Environmentally, we aim at causing the cooled-down air moving through this mid-rise floor void to ooze into the corridors and office spaces adjoining the void. The 37th-floor outrigger has another function serving as a cool-air intake for the high-rise floor void ventilation.

The high-rise floor void serves as a climbing passage for the cool air taken in from the 37th-floor outrigger and has a role of expanding the stance of high-rise in the lateral direction. This void also provides a space for installing core truss dampers which are effective to restrain the hotel deformation as shown in Fig. 9. This type of dampers consist of a combination of shafts, arranged in a similar way to the central pillars used in the Japanese old

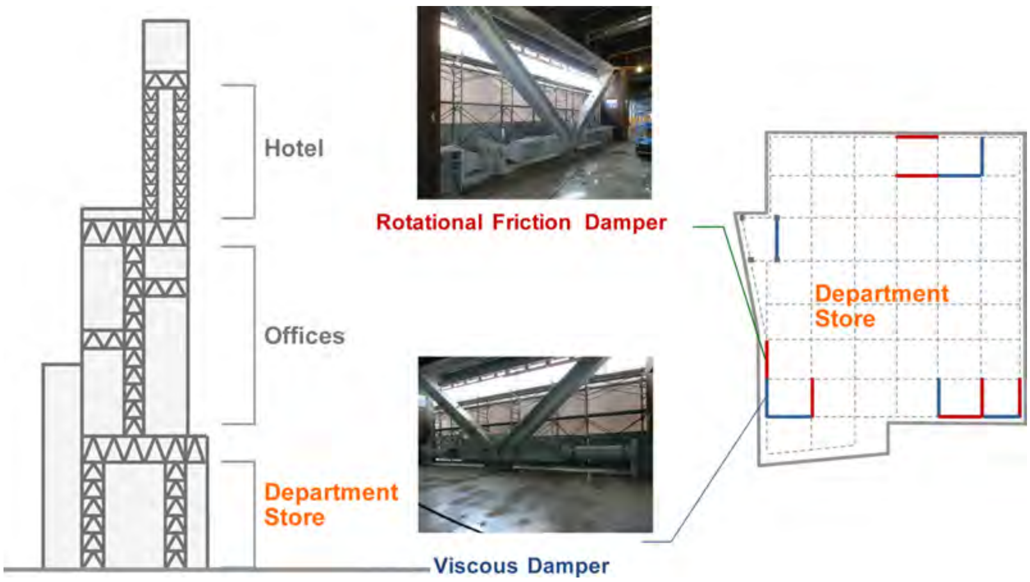

Figure 6. Stairwell void of low-rise floors.

Figure 7. Image of truss bridge (left) and mid-rise floor void (right).

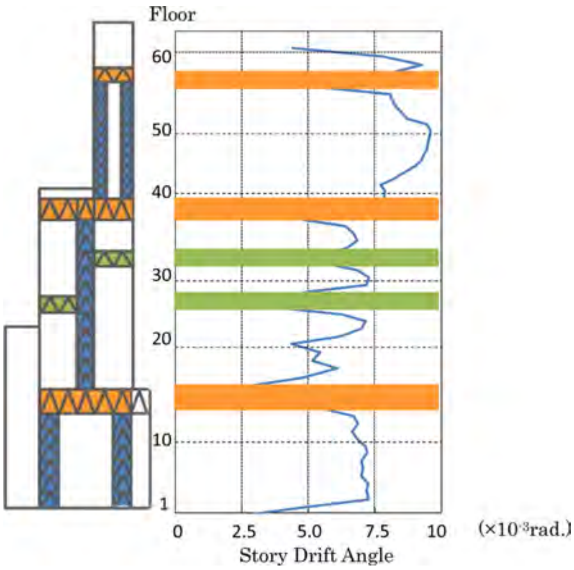

Figure 8. Maximum story drift angles.

five-story pagodas and other buildings, and oil dampers mounted in the space along the surrounding hotel frame.

Thus, the low-rise, mid-rise and high-rise floor voids integrates the vertical city while providing multiple functions as functional, environmental and structural infrastructure and effectively realizes a mixed-use building constructed on a limited space site in the center of a city.

2.2. Existing building reconstructed into skyscraper

HARUKAS is a reconstructed skyscraper above the terminal station used by Osaka's third largest number of passengers. This building is adjacent in the east to the existing high-rise department store which has been in business, which is connected to the low-rise department store of HARUKAS through a large void space. The space created between these two buildings as shown in Fig. 10 produces a visual continuity of the two department store spaces, new and old, and also creates a 3-dimensional vertical space configuration.

For environmental consideration, this void space is used

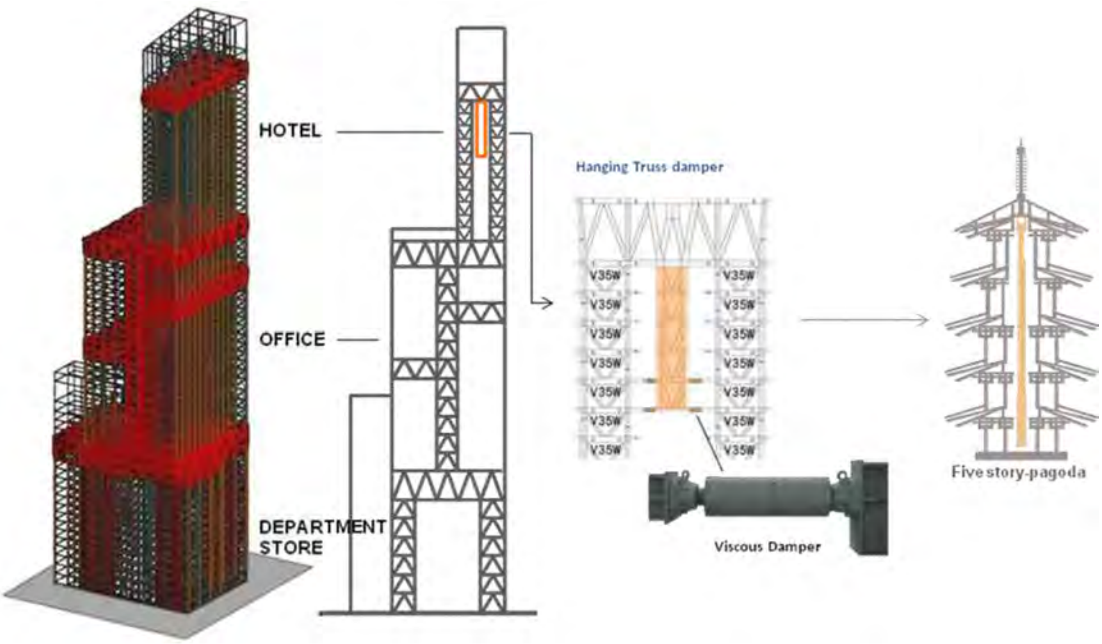

Figure 9. Illustration overview of hanging truss damper.

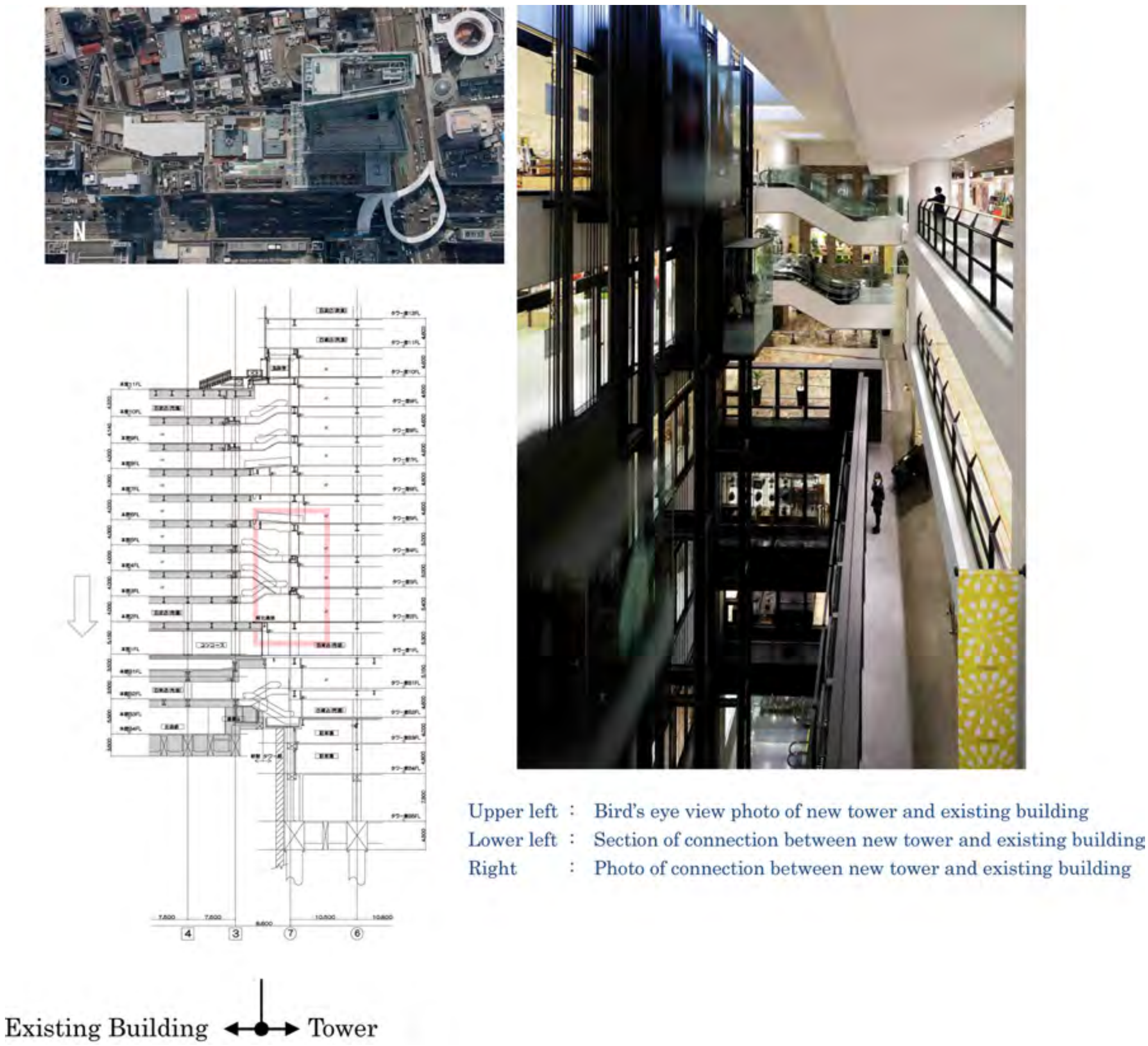

Figure 10. Low-rise connection void.

for the following multistage ventilation: The floors are cooled down by the exhaust heat from the department store selling space and the nighttime exhaust heat from the inside of the ceiling, and these exhausted airs rise upwards to cool down the machine room on the 15th-level truss floor.

Structurally, this void space serves as an expansion joint that will allow the two buildings to move differently in case of earthquake. The floors and movable escalators that connect the buildings allow the motions from those of the Level-2 earthquake up to 1.5 times more to prevent the buildings from colliding with each other during an earthquake.

2.3. High-grade vibration-damped building constructed in Japan, the world’s most earthquake and typhoon ridden country

Japan belongs to the region where both the seismic and wind design loads are the largest as shown in Fig. 11, and it would be no exaggeration to say that Japan is number one in the world in terms of the severeness of disturbance.

According to the world map of natural hazards in Fig. 11, the seismic intensity of Japan is at least the highest level IX on Modified Mercalli intensity scale (MMI), and approx. 475 gal., the highest seismic acceleration with recurrence interval of about 500 years, is used for the seismic design load.

For the wind design load in Japan, the reference value of the velocity pressure ($0.6*V^{0.2}$) calculated from the design reference wind velocity with recurrence interval of 50 years is approx. 700N/m^2, which is larger than the data of any other typical region of the world.

Under the above conditions of external forces, the design criteria of HARUKAS is established so that the design criteria of normal skyscrapers may be upgraded by one grade for this building, by allowing no member of this building to be plastically deformed against any Level-2 external force. Therefore, the seismic and wind safety of this vibration-damped building is extremely high.

We also considered the safety of the building against

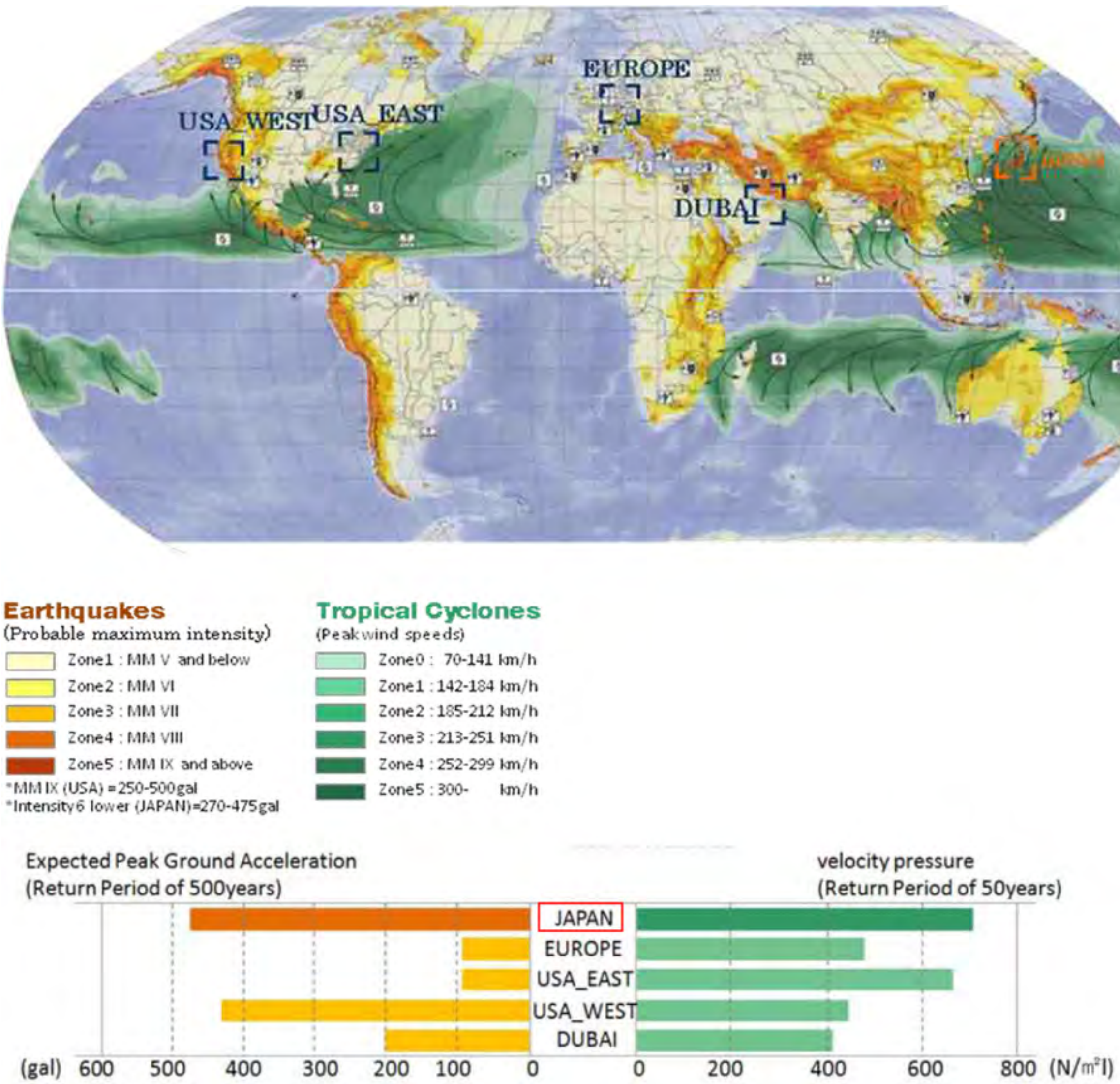

Figure 11. World map of natural hazards.
[Left] The expected peak ground acceleration (maximum intensity of earthquake). with recurrence interval of about 500 years is about 475 gal.
[Right] Velocity pressure based on basic wind
http://econintersect.com/images/2012/12/46531184naturalhazardsworldmapnathan.JPG

Table 1. Design criteria

	Level 1	Level 2	Seismic Safety Margin Analysis Level	Examples of building uses
	- Rare. - Recurrence interval: Approx. 50 years	- Very rare. - Recurrence interval: Approx. 500 years	- 1.5 times stronger than the Notification Level-2.	
ABENO HARUKAS	No damage	Minor damage	Small-scale damage	Disaster prevention and other especially important facilities
General skyscrapers	No damage	Small-scale damage	Not foreseen (More than medium-scale damage)	Hospitals, evacuation, HQ. and other important facilities
General buildings (Building Standards Law level)	Minor damage	Medium-scale damage	Not foreseen (More than medium-scale damage)	General buildings

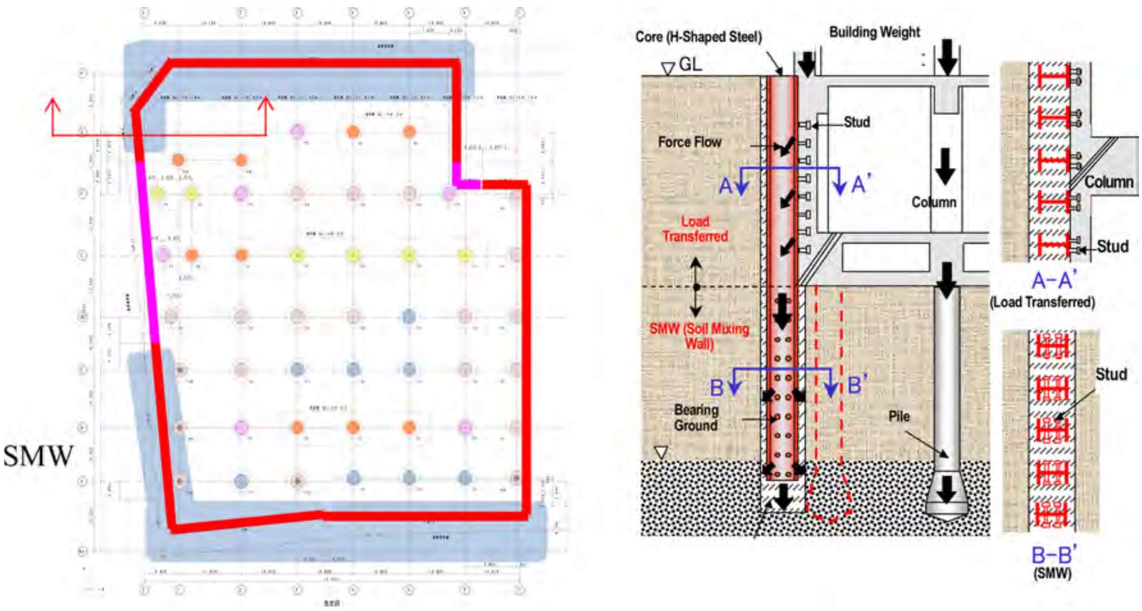

Figure 12. Pile plan (left) and sectional view of SMW (right).

mega earthquakes 1.5 times stronger than the Level-2 earthquakes and against ocean and strong local earthquakes in consideration of regionality. As this is a high-grade vibration-damped building, columns are not allowed to be plastically deformed in such a mega earthquake, except for some exceptions. (Table 1)

Specifically, refer to the 2012 September issue of IJHRB for the PBSD (Performance Based Seismic Design) and the 2013 September issue of IJHRB for the PBWRD (Performance Based Wind Resistant Design).

3. Techniques to Achieve Design Concepts

3.1. High-capacity piled raft foundation with soil-cement continuous wall construction

Since HARUKAS is a reconstructed building above the terminal station at the heart of the city, the building covers almost the whole site as shown in Fig. 12. In the circumstances, the foundation structure is under many restrictions and requires high efficiency. Therefore, a piled raft foundation consisting of piles and bottom plate both of which bear the building load is used for this building, where an inverted placing method is applied, using basement columns. Therefore, the superstructure is constructed up to about the 50th floor level prior to the bottom plate installation. Accordingly, the piles bear as much as about 90% of the column axial forces, and the bottom plate bears the remaining forces (only about 10%). One pile is located per column as shown by the pile plan in Fig. 12, but the existing building frame is buried in the circumference, which makes it difficult to drive piles. Consequently, the SMW (soil mixing wall) construction method is used. As shown in Fig. 12, the column axial forces are transferred to the core steel of the soil cement retaining walls through the headed studs from the exterior wall of the basement, and finally transferred to the ground. The SMW method is environmentally friendly because about 40% of the soil can be reused.

The shape of the piles under the columns that produce high axial forces is beer bottle shaped as shown in Fig. 13 to maximize the frictional forces of the piles. High-strength concrete (Fc60) is used to make the piles the strongest in Japan.

3.2. High-strength CFT columns

Since HARUKAS was constructed in the limited space on the site as stated above in 3.1., it was absolutely necessary to minimize the column sections as much as possible. Therefore, concrete filled steel tube ("CFT") columns made of high-strength concrete Fc150 and high-strength steels equivalent to the yield strength 440 N/mm^2 and tensile strength 590 N/mm^2 are used in this building in order

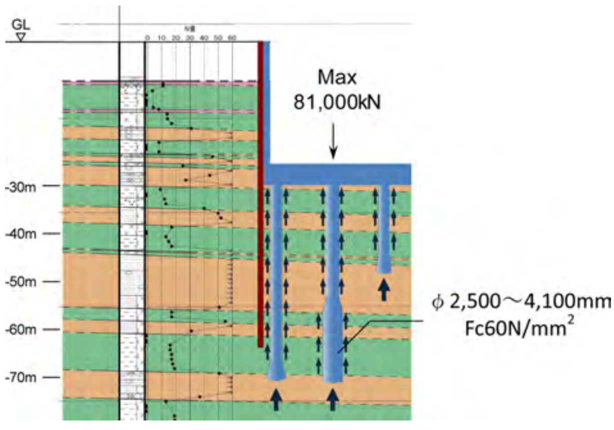

Figure 13. Elevation of piles.

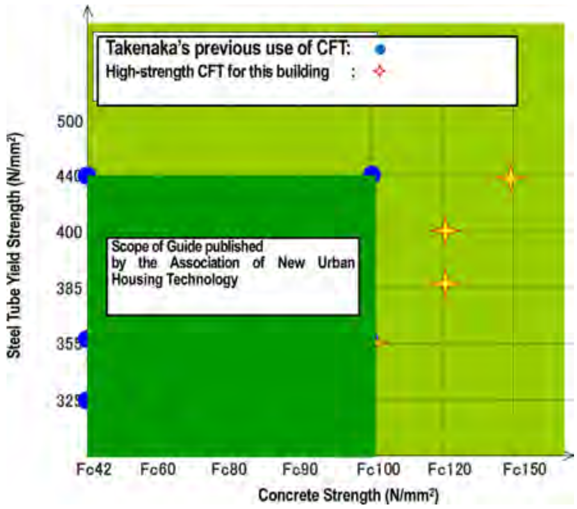

Figure 14. Scope of Guide.

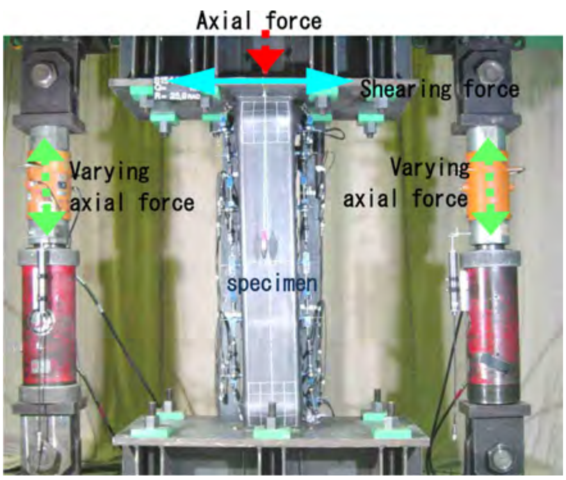

Figure 15. View of loading test.

to ensure the safety of the columns that bear high axial forces. They are out of the applicable scope of the Japanese guideline as shown in Fig. 14. Accordingly, the calculation equations for deformation capacity in the guide cannot be applied, and other various performances are not grasped. Therefore, the specification has been established by such means as the tests.

In the loading test (Fig. 15) performed prior to the design, we increased the axial force from 0.70 cNu (cNu: compressive axial load capacity) to 0.5 Nt (Nt: tensile axial load capacity) in proportion to shearing forces. Consequently, the deformation capacity equivalent to the value at the member's angle around 10/1000 rad. was identified as shown in Fig. 16.

The experimental value can be evaluated if the concrete strength is multiplied by the strength reduction factor (cru = 0.70) as shown in Fig. 17 because the shape of the concrete stress block assumed in the accumulative strength equation with fully-plastic moment is not square.

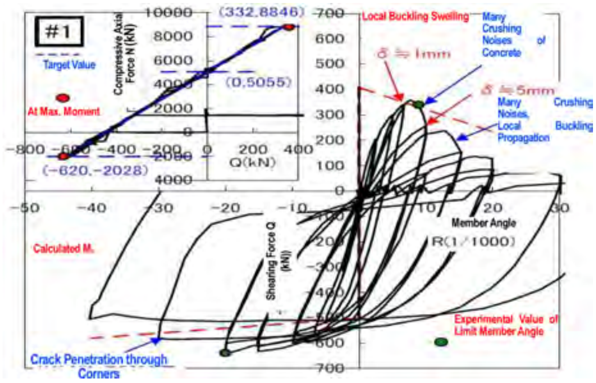

Figure 16. Load-deformation relations.

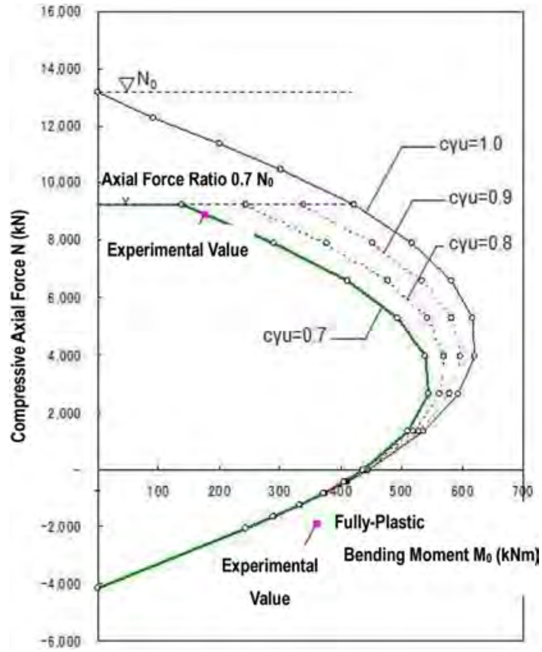

Figure 17. M-N correlations.

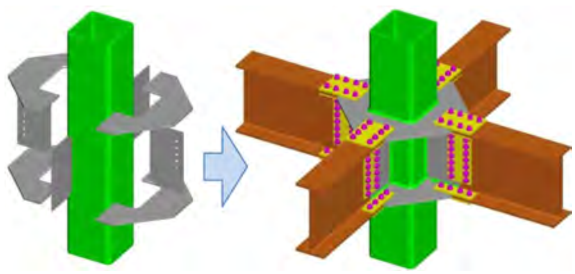

Figure 18. Split outer diaphragm.

3.3. New joint system

This building uses a new joint system consisted of outer diaphragm and aluminum spray jointing, to realize the self-filling property of high-strength concrete as stated in 3.2. and high-grade seismic resistance as described in the

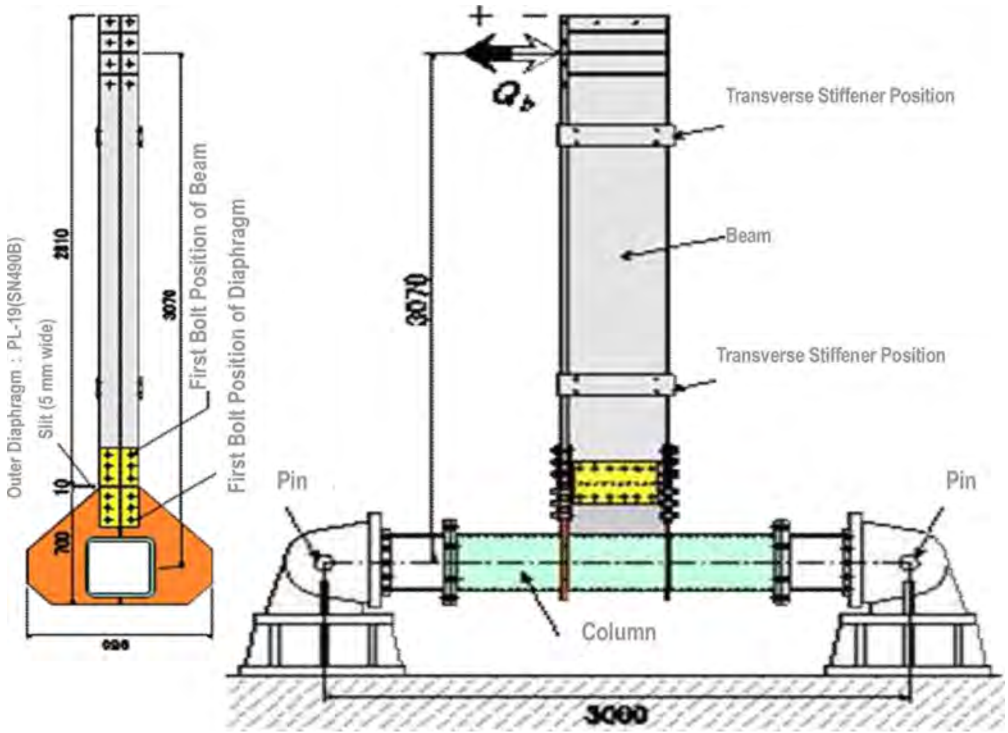

Figure 19. Test article - outer diaphragm.

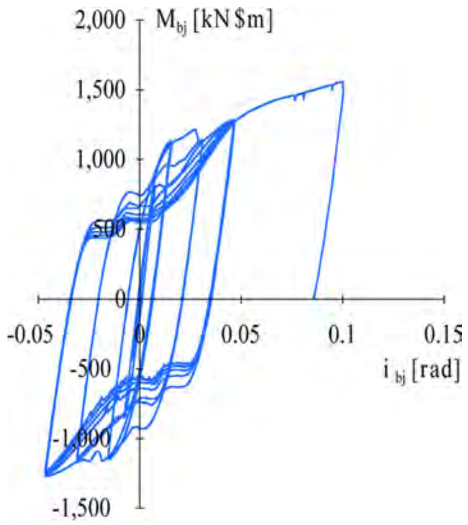

Figure 20. Load-deformation relations.

chapter 2. and reduce the construction period because it is located above the station.

The outer diaphragm employed in this building is a split type as shown in Fig. 18 and oblique-fillet welded with a column. A horizontal force application test was performed on a partial frame jointed with a beam by aluminum spray jointing, and as the result, it yielded at the bolts, by which it was verified that it has a sufficient deformation capacity equivalent to about $4\theta p$ (Figs. 19 and 20).

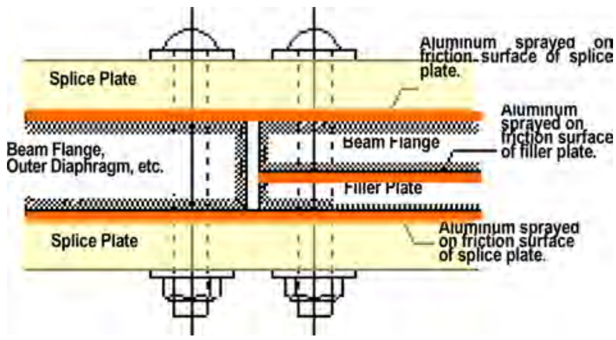

Figure 21. Aluminum spray jointing.

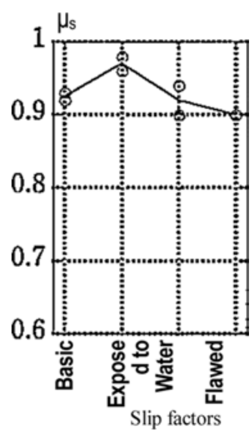

Figure 22. Relations between construction troubles and slip factors.

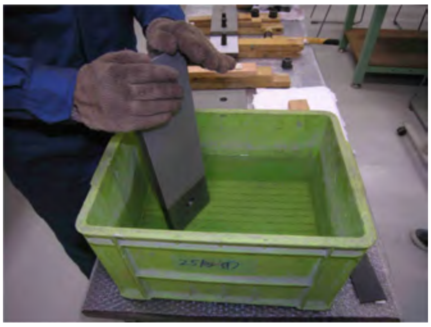

Figure 23. Base material soaked in water.

Figure 24. Flawed test articles: Direction orthogonal to force application.

Aluminum was sprayed on the surface of the splice plate at each beam flange bolt joint that is in contact with the base material as shown in Fig. 21. The jointing method with the slip factor improved to 0.70 is used to reduce the quantity of bolts and the size of splice plates. The following conditions were established to keep the slip factor 0.70.

(1) Spraying method: arc
(2) Sprayed coating thickness: 300 μm or more
(3) Splice plate thickness: 12 mm or more
(4) Friction treatment surface: blasting
(5) Splice plate base treatment: blasting to remove black scale
(6) Allowable lap gaps: 1.0 mm or less

Figure 25. Oil-stained test: Oil-stained leather glove.

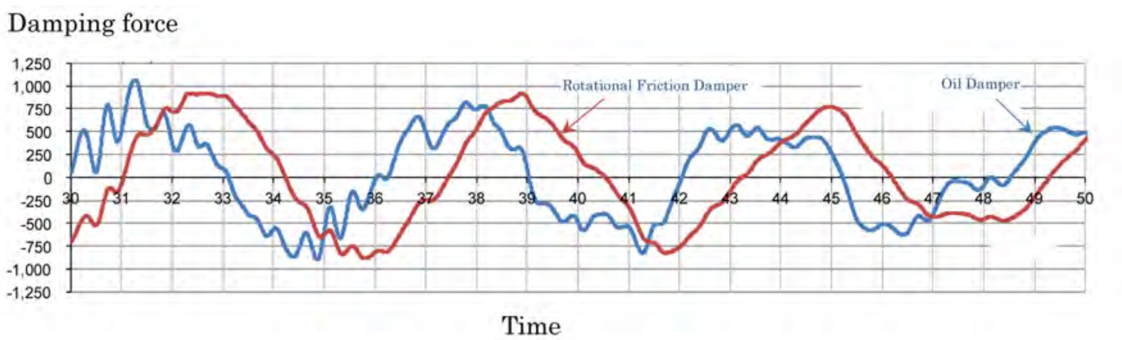

Figure 26. Two types of dampers working with lag between their most effective time.

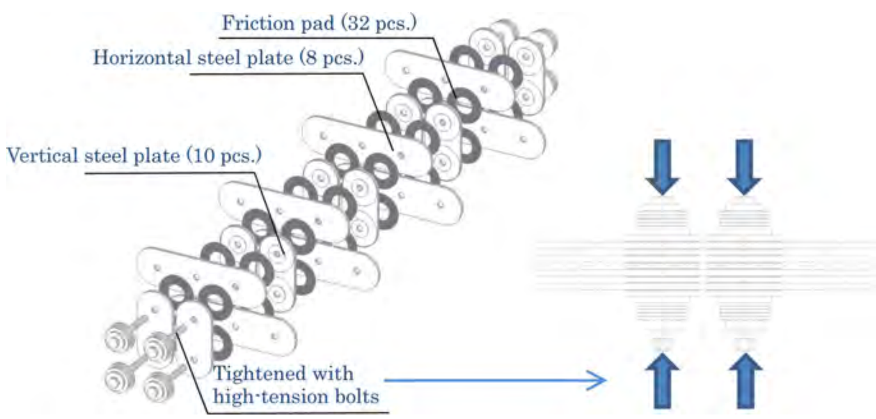

Figure 27. Mechanism of rotational friction damper.

Figure 28. Appearance of rotational friction damper.

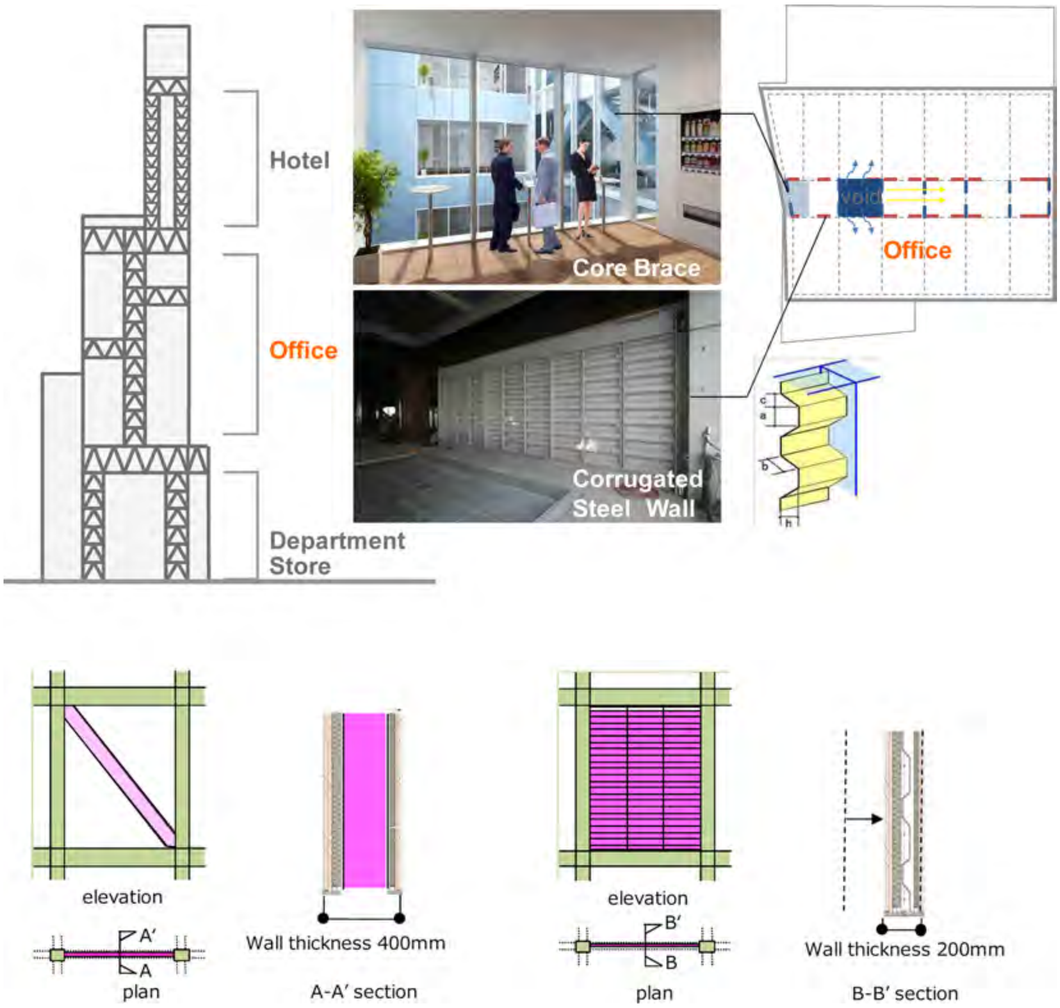

Figure 29. corrugated steel wall.

We also provided construction troubles on purpose and grasped their effects on the slip factors (Figs. 22 to 25) (Architectural Institute of Japan [5]).

3.4. Rotational friction dampers

Rotational friction dampers as well as oil dampers are installed in the low-rise department store void as described in the chapter 2. to absorb the seismic energy that

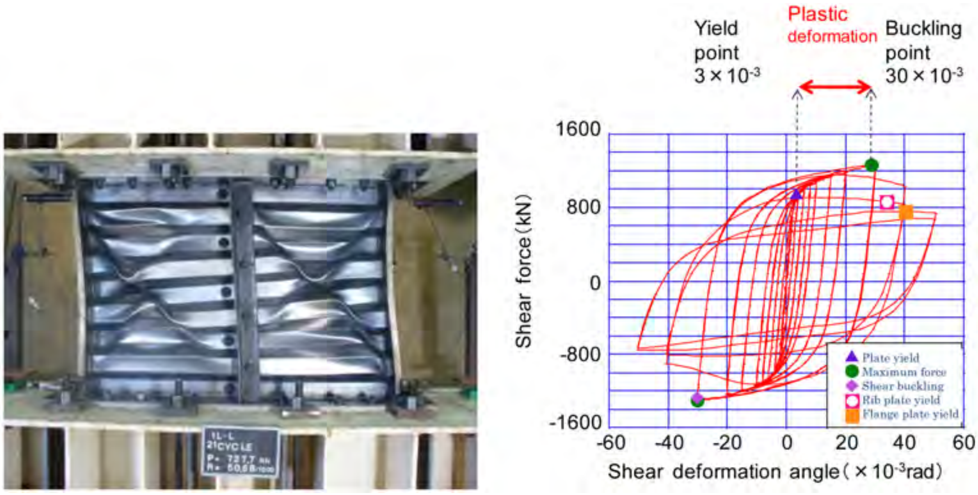

Figure 30. Photo of corrugated steel plate wall (left) and chart of load-deformation relations with excellent energy absorptions (right).

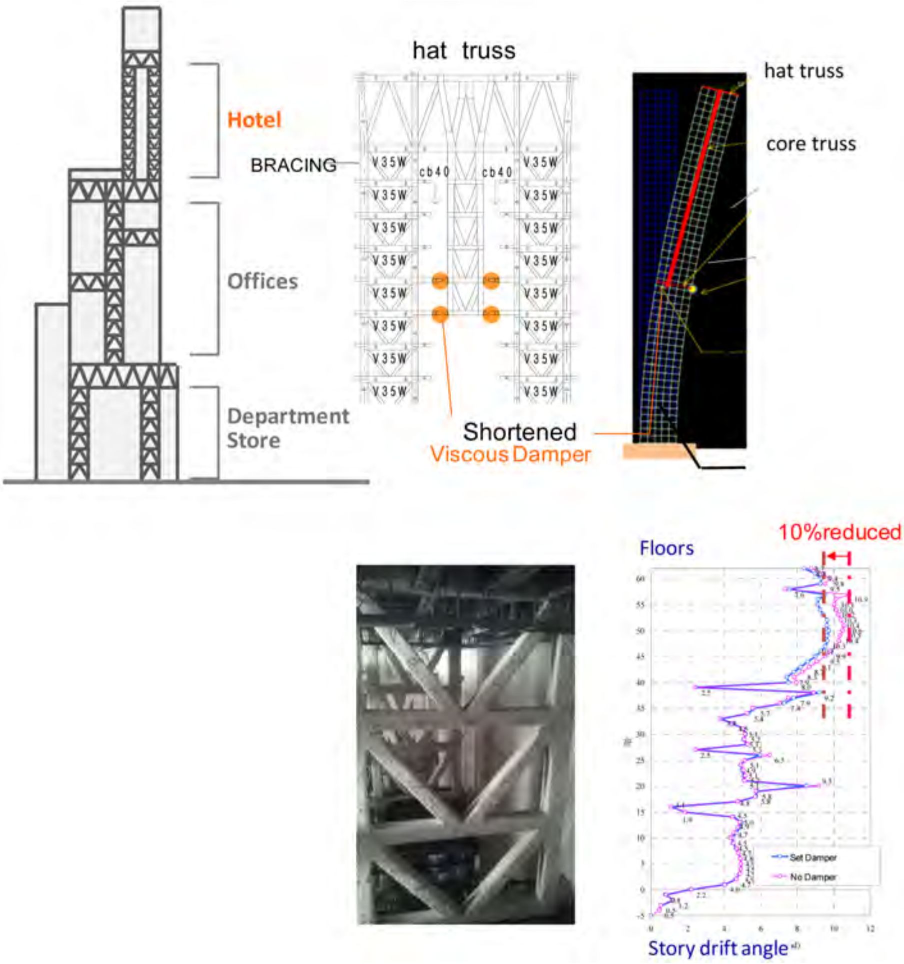

Figure 31. Mechanism of Core Truss Damper.

will be input in the building and help reduce the seismic responses. The oil dampers are very velocity-dependent, while the rotational friction dampers are very deformation- dependent. Therefore, the two types of dampers are working with a lag between the times when they are the most effective, as shown in Fig. 26. Thus both of them

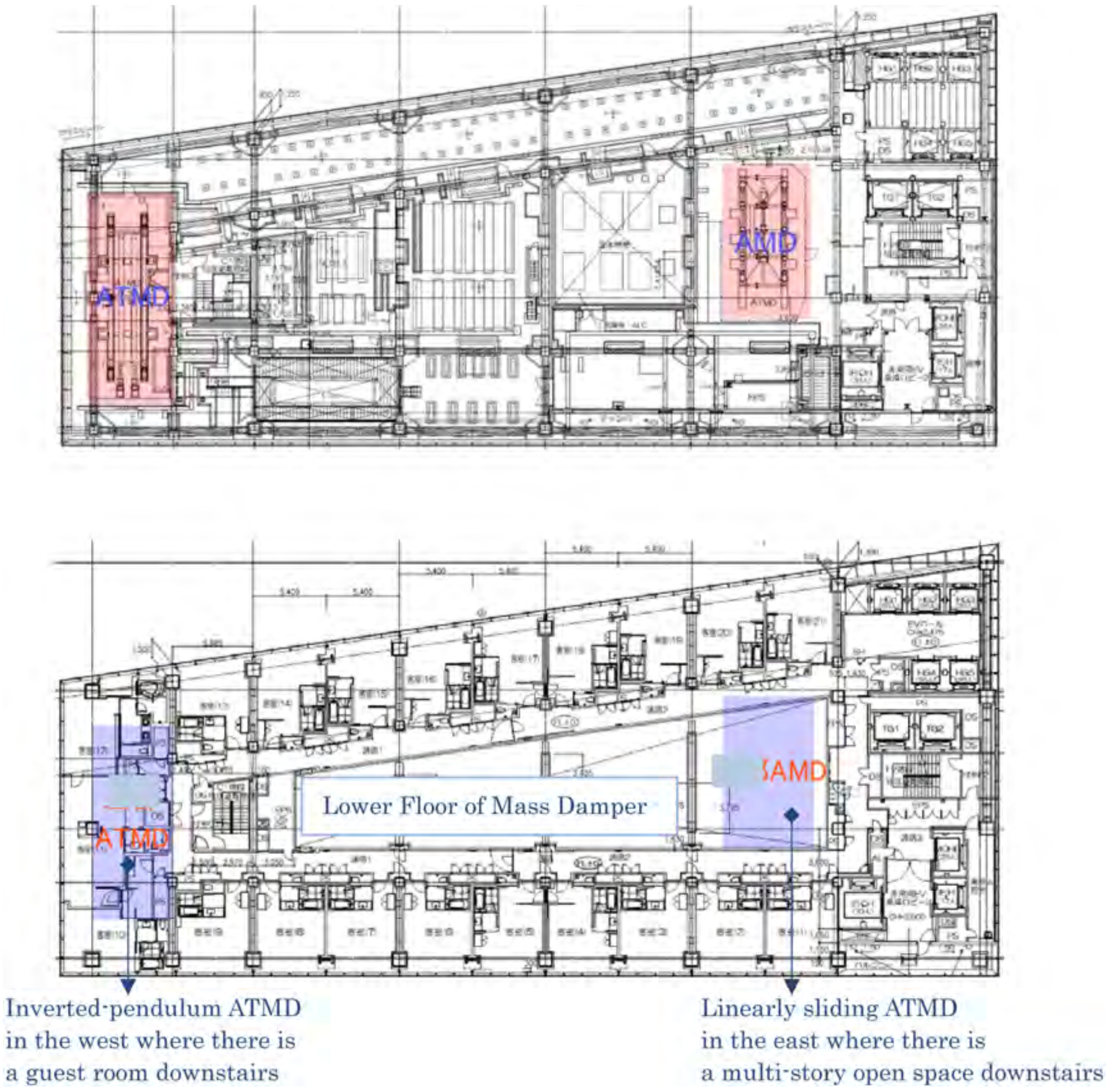

Figure 32. ATMD layout.

help increase the redundancy of HARUKAS as a vibration-damped building.

A rotational friction damper generates a given frictional force via the friction pads each sandwiched in between horizontal and vertical steel plates, which are bolted together, as shown in (Figs. 27 and 28)

3.5. Corrugated steel plate walls

Corrugated steel plate walls are installed in the longitudinal direction of the building, in the central void of the office space as described in the chapter 2. The longitudinal void is located on the boundary between the elevator shaft and pipe space, which requires a larger effective area for the pipe space rather than transparency required in the lateral direction. A corrugated steel plate wall is an earthquake-resisting member consisting of a steel plate corrugated in the direction of the height and the surrounding flanged steel plates that are integrated with their frame (Fig. 29).

The angles arranged with a given spacing restrain buckling as stiffened ribbed plates and reach shear yield at R = 3/1000 ad. as shown in Fig. 30. They display high plastic deformation performance until they are buckled at R = 30/1000 rad., and absorb seismic energy. We also calculated the marginal scale factor of cumulative plastic deformation from the fragility curves shown in Fig. 30 that were based on the fatigue test results. Then it was confirmed that it exceeded the scale factors of cumulative plastic deformation of the walls that we calculated from the earthquakes experienced during the in-service period of this building.

3.6. Core truss dampers

As stated in the chapter 2., the core truss dampers as shown by the sectional view in Fig. 31 are installed in the central void of the hotel so as not to interfere with ventilation, for the purpose of reducing the deformation of the high-rise component. Vertical rod-shaped trusses are han-

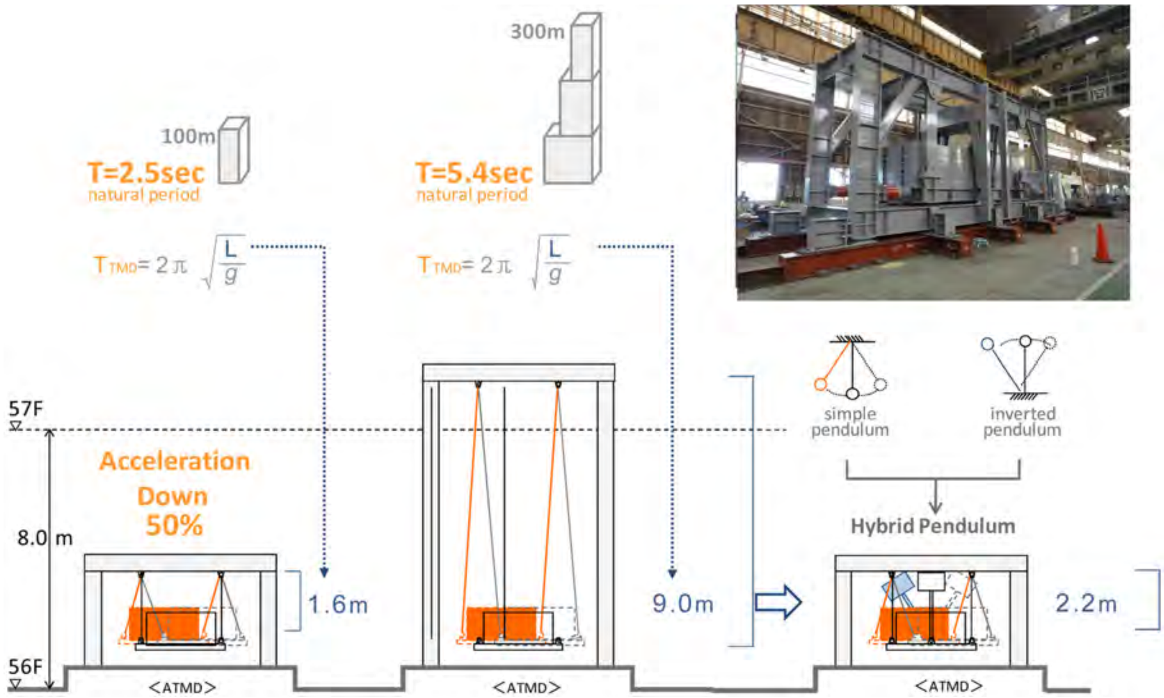

Figure 33. Illustration overview of hybrid pendulum ATMD.

ging down from the hat trusses into the multi-story open space. Oil dampers mounted between the core trusses and surrounding frames reduce the story drift of the high-rise component by up to about 10% through the mechanism shown in Fig. 31.

3.7. ATMD

The hat truss floor is equipped with mass dampers that operate only in the north-south (narrow side) direction, one each at the west and east ends of the building as shown in Fig. 32 for the purpose of improving the habitability of the hotel in strong winds. They are both active dampers, but the one at the west end which has a guest room downstairs is pendular to minimize the noise for the guests downstairs. Dampers work only when their period is synchronized with the natural period of the building which is as long as about 6 seconds. The length of the conventional suspended pendulum has to be extremely long for that purpose but can be minimized by combining it with an inverted pendulum (photo in Fig. 33). Those damper effects keep the accelerations, even in strong winds at a recurrence interval of one year, as low as the level (approx. 3 gal) corresponding to the Class H-30 (about 30% of habitants feel the quakes) specified in the Habitability Evaluation Guidelines.

4. Conclusion

All the uses of a vertical city ABENO HARUKAS are dynamically linked to one another where environmentally continuous vertical ventilation works, and structurally a Linked Void Structure that consists of voids and multiple outriggers linking voids is built to achieve the unprecedented top-level seismic and wind performance. This Linked Void Structure enabled us to realize ABENO HARUKAS that meets the architectural, environmental and structural requirements from the different approach from those for the previous skyscrapers and thus to create a worldwide recognizable signature building of Japan.

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