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Structural Design of Mid-Story Isolated High-Rise Building - Roppongi Grand Tower

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Abstract

Since the response reduction effect on over 200-meter-tall resulting from the seismic isolation system is smaller in general than low-rise and mid-rise buildings, mid-story isolated buildings are considered to reduce the response in the upper part above the isolation story, however, in many cases, the acceleration response just below the isolation story is likely to be the largest. This paper presents the structural design schemes, the design of the main structural frames, and the constructions of a 230-meter-tall super high-rise building with mid-story isolation mechanism integrated in Roppongi, Tokyo. Moreover, this paper shows how the architectural and structural design for integrating a mid-story isolation system in a super high-rise building has been conducted and what solutions have been derived in this project. The realization of this building indicates new possibilities for mid-story isolation design for super high-rise buildings.

Keywords: Structural design, Super high-rise building, Mid-story isolation, Concrete filled tube, Transfer steel wall

1. Introduction

Compared to other major big cities in the world, there still remain many small residential houses and buildings in Tokyo. Such building situation in Tokyo, however, has been gradually changing these days. Recently, many new large-scale building projects have been planned and completed.

The Roppongi 3-Chome East Side Project is among these newly completed building projects. This building project consists of two high-rise building; one is an office tower building and the other a residence tower building. The former is larger building in this project.

As a seismic-isolated building, the office tower measuring about 230m in height is categorized as a very tall building (Fig. 1). With regards to this building project, this paper shows what solutions of the architectural and structural design work have been derived with the design philosophy of isolating a high-rise building at the mid-story.

Following this introduction, the second chapter presents the building outline and architectural scheme. The third chapter presents structural schemes including comparison of the aseismic system, the design scheme and details of the isolation story, the examination of the building vibration characteristics, and the settings of the clearance in each part. The fourth chapter details the design outline of the CFT column and the steel walls. Finally, the fifth chapter summarizes the conclusions of this paper.

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Figure 1. Roppongi Grand Tower (Photo by SS Tokyo).

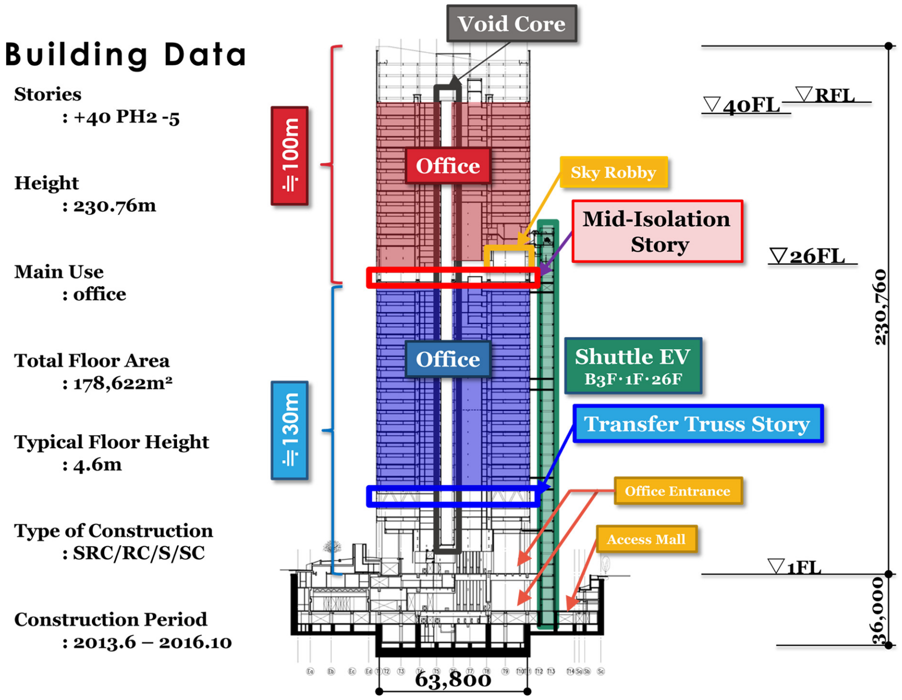


Figure 2. Building Outline and Architectural Scheme.

2. Building Outline and Architectural Scheme

As shown in Fig. 2, the height of the building is 230 meter. The dimensions of the floorplan of the building is about 65m × 65m. The longest beam span is about 17 m. The main use of the building is office, as shown in red and blue in the illustration. The mid-isolation story is installed between the red and blue colored office floors. The shuttle elevator from the third underground floor connected to the subway station via the ground floor is placed at a position off the square plate, going straight to the sky lobby located on the 26th floor just above the isolation story. The local elevators are completely divided between the upper and lower parts of the isolation story, with only the emergency elevator passing through the isolation story.

Due to the existence of an atrium space in the lower part of the building, a transfer truss beam is installed into the 7th floor so as to increase the rigidity of the lower structure below the isolation story. This transfer truss also plays the role of smoothly transmitting the vertical load from the columns of the typical floor to the columns with large sections such as those of a diameter of 1800mm.

As shown in Fig. 3, aseismic braces and dampers of the viscous material shear walls are installed around the center core. The latter is used for reducing the response acceleration just below the isolation story.

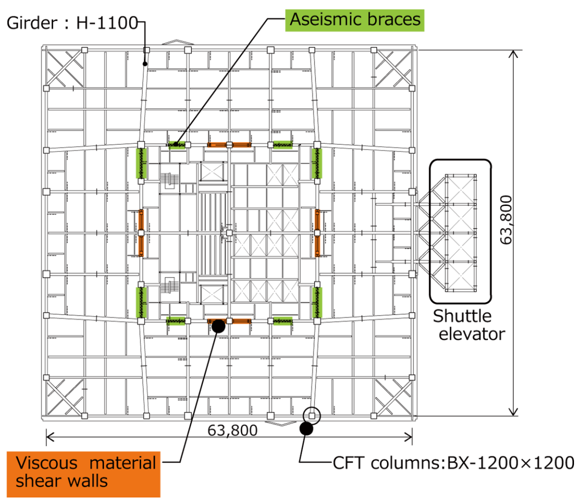


Figure 3. Typical Floor Structural Plan.

3. Structural Scheme of Super High-Rise Mid-Story-Isolated Structure

3.1. Comparison of the Aseismic System

The building at the early design stage had been planned to be a vibration-controlled structure. However, after the 2011 off the Pacific coast of Tohoku Earthquake, social demands for high performance and habitability during an earthquake was grown and isolated structures were increased rapidly. Therefore, conducting the isolation system to this building was considered.

In the case of a super high-rise building, the response reduction effect resulting from the seismic isolation is less significant relative to its increase in height. This paper focuses on a new possibility with regards to the mid-story isolation applied to a super high-rise building.

In general, comparison of aseismic systems is required in the early stages of a project. Fig. 4 shows the response acceleration in the cases where the building is an aseismic structure (OPT.-1), seismic isolation structure (OPT.-2), and seismic isolation + vibration control structure (OPT.-3). The input earthquake motion is a simulated ground motion (its shape is nearly bi-linear and its pseud response velocity on the long period side is 1.0 m/s), and it is an extremely rare earthquake motion. In the three cases, only the applied OPT.-3 achieves roughly 2.0 m/s^2 or less in the floor response acceleration at the all office floors. In general, the acceleration response just below the isolation story is likely to be the largest. Therefore, the lower part below the isolation story has dampers of viscous material shear walls.

3.2. Design Scheme of the Isolation Story

In the following section, it will be presented how the determination of the isolation layer position has been processed. The following four design factors were considered:

1. Maximization of the number of the floor above the isolation story.
2. Securing pull-out resistance of the isolator against horizontal force during earthquakes or storms.
3. Securing vertical support strength of the isolation story.
4. Maintaining consistency with the architectural scheme.

The first factor means that the number of floors with the benefit from the effect of isolation should be increased, i.e., more floors above the isolation story allow for adding value to the building.

Regarding the second factor, the pull-out resistance of the isolation story needed to be so that the tensile stress of the isolators during earthquakes and wind loads is less than allowable tensile stress. Due to this factor, it was necessary to set the isolation story to higher than 20th floor.

The third factor is the vertical support capacity of an isolator. It is reasonable from the viewpoints of cost and space that one column is supported by one isolator. Considering the area supported by one column of this building, one isolator can support the vertical column axial force of about 30 story at most. The limit position of the isolation story because of this factor was about at the 20th floor similarly to the second factor.

For the last factor, for reasonable architectural planning, it is required that the scheme of elevator transportation about the same distance in the upper and lower parts of the isolation story. Adding to this, the large atrium space would have been planned on the 26th floor and connected to the ground level by the direct elevator.

Considering the above factors, the position of seismic isolation story was set just below the atrium space which is the top landing floor of the shuttle elevator. Between the upper structure of this building above the isolation story and the frame of the shuttle elevator, an EXP.J was set up on the 26th floor and the elevator frame was designed as a self-standing cantilevered frame only for the upper four stories.

3.3. Parametric Study Regarding Vibration Characteristics

One of the essential points of this building's structural design is the design of horizontal rigidity in the upper struc-

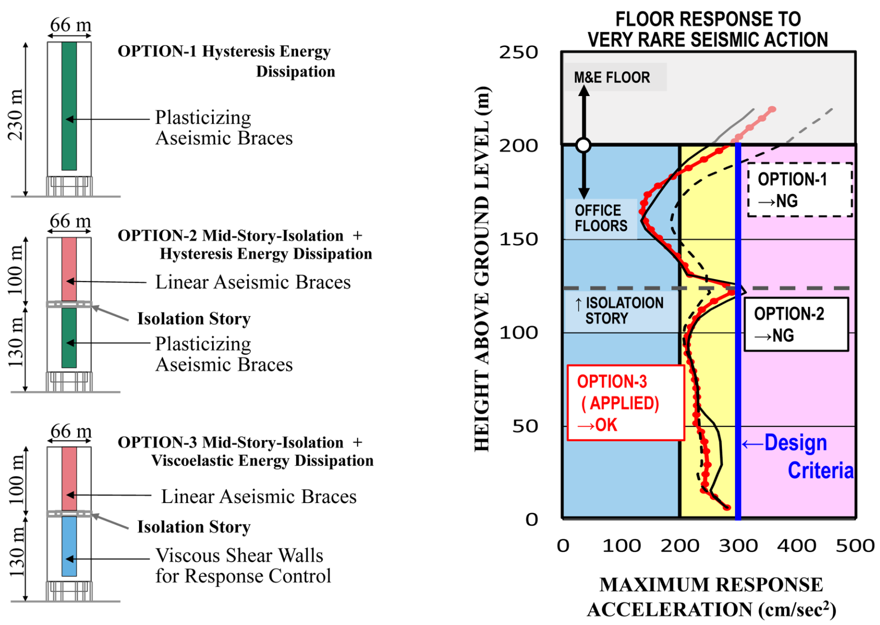


Figure 4. Comparison of Structural System.

Table 1. The Ratio of the Rigidity of each Model

Model	Ratio of the Rigidity		Legends
	Upper Structure	Lower Structure	
No.1	1.0	1.0	
No.2	1.0	0.7	
No.3	1.5	1.5	
No.4	1.5	0.7	

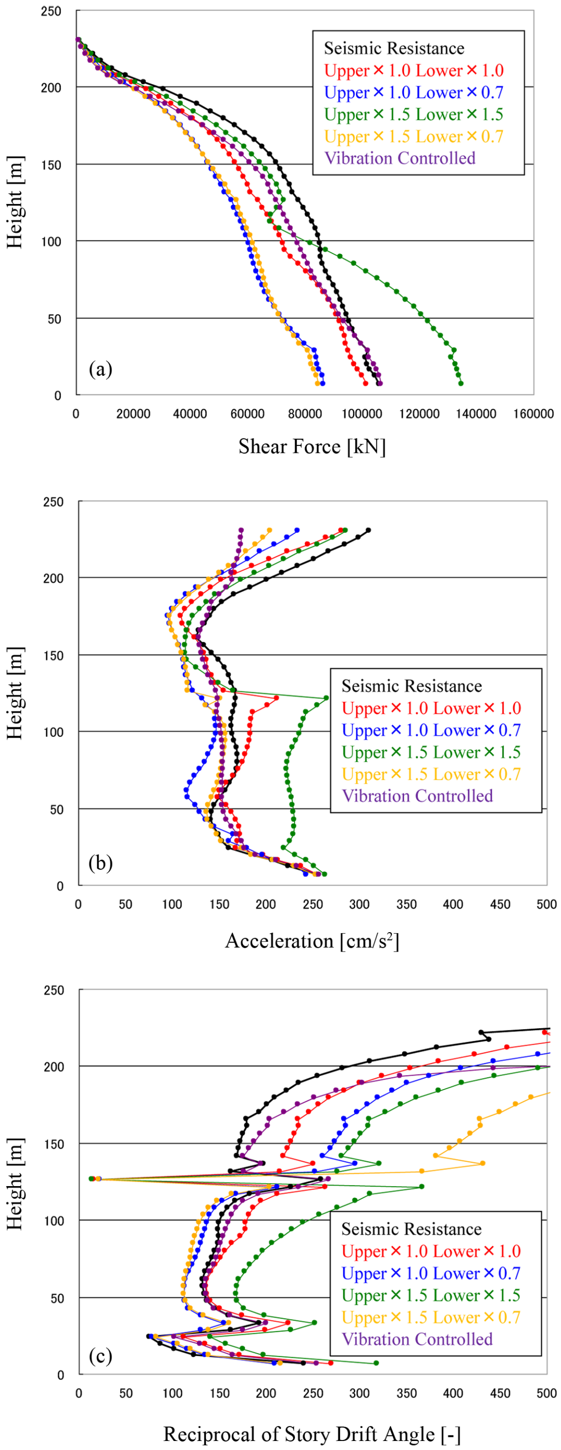


Figure 5. Results of Time-History Analysis.

ture above the isolation story and the lower below the isolation story. To find the proper rigidity of the building, this section explains the verifications of the vibration characteristics using time-history analyses with multi-mass system model of this building. The analysis model is a multi-mass system with one-mass for each story. The input earthquake motion is the same as 3.1 section.

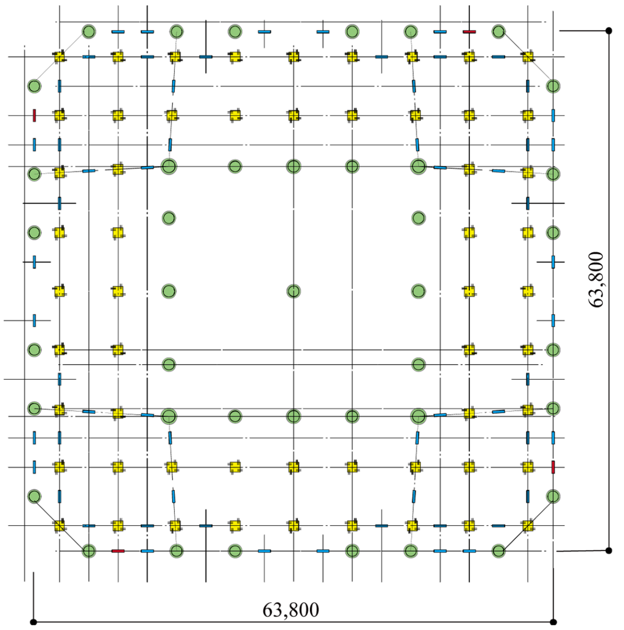
Table 1 shows that the models varied parametrically in the rigidity ratio of upper and lower structure to the isolation story. The standard model is shown as the No.1 circled red line. The other models were varied in the rigidity ratio of the upper and lower structure of the isolation story by 0.7 to 1.5 times from the standard model. Figs. 5(a)-(c) are the results of the time-history analysis in each model. These figures include the results of the model of seismic resistance structures and vibration-controlled structures without isolation system. According to Figs. 5(a) and (b), in the model No.3 circled green line, shear force and acceleration is larger than the other models. Therefore, the higher this building rigidity is, the less effect of the isolation system. The models No.2 and No.4 is better performance than the others. Moreover, the models of No.2 and No.4 has almost the same performance in Figs. 5(a) and (b). The model of No.4 has the best deformation capacity in Fig. 5(c). However, the rigidity ratio of 1.5 times to the standard model causes the high cost regarding to the steel amount. In result, the scheme of the model No.2 those lower structure is low rigidity to some extent is adopted to this building.

3.4. Design of the Isolation Story

Utilizing the square plan as shown in Fig. 3, the seismic isolation devices are arranged point-symmetrically in consideration with no torsion as shown in Fig. 7.

The steel dampers in the isolation story yield against the design wind load, on the other hand, those are designed not to yield against only the variation component of the design wind load. The resistance force against wind load is set as the total value of strength of 56 steel dam-

Figure 6. The Isolation Story (Photo by: SS Tokyo).



Legends

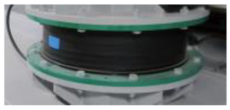
Mark	Type	Number	Photo
Laminated rubber isolator	1300φ	33 units	
	1400φ	4 units	
	1500φ	4 units	
Steel damper	NSUD55×8	56 units	
Oil damper	1000kN Stroke : ± 600 mm	60 units	
Oil damper (With rock mechanism)	1000kN Stroke : ±600 mm	4 units	

Figure 7. Isolation Story Plot Plan.

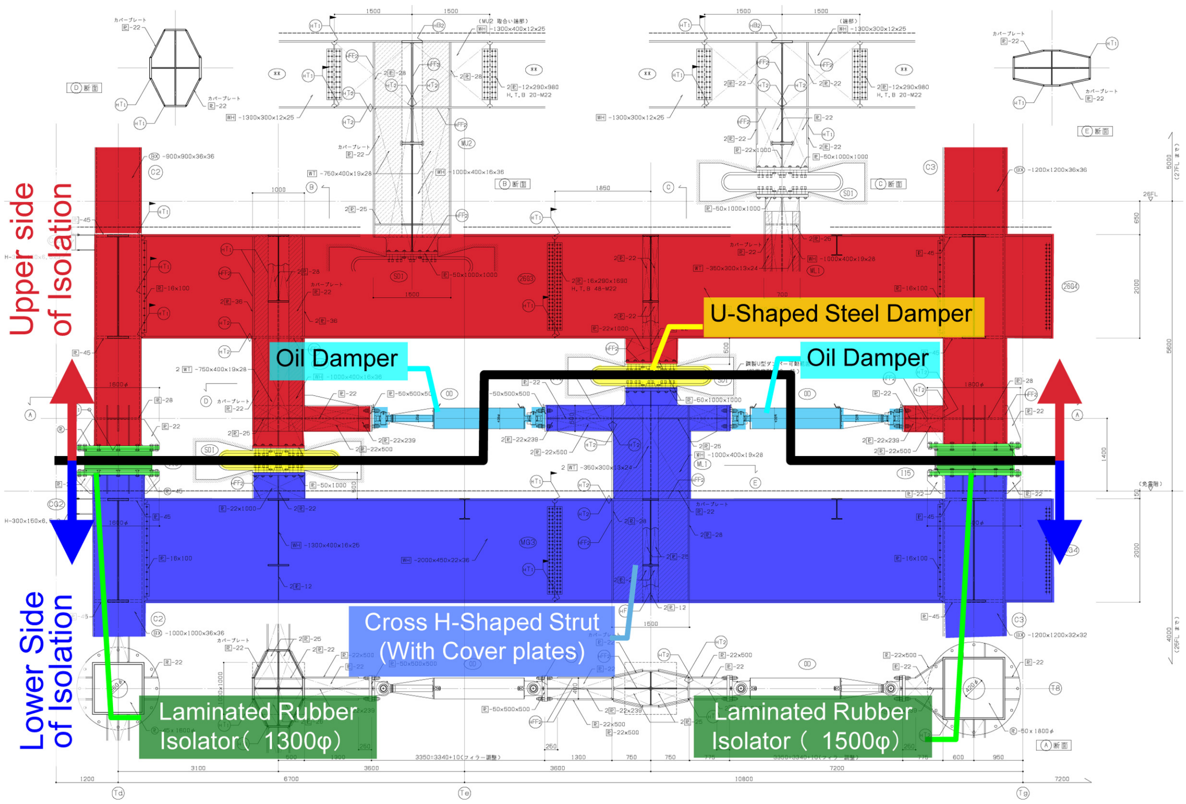


Figure 8. Details of the Isolation Story.

pers and the lock strength of 4 oil dampers with locking mechanism (for two units acting in X and Y directions in each). The maximum deformation of the isolation story at the case of extremely rare earthquakes is set to 40 cm, and the required damper amount is planned by response analysis.

Due to the relationship between columns and the facades position, the isolator integrating with U-shaped damper could not be used, and a separate type was adopted. Because setting up struts for each damper causes to increase the amount of steel, a staggered damper arrangement in which steel dampers were installed at the upper and lower part of the struts supporting one oil damper as shown in Fig. 8.

As shown in Fig. 8, red color indicates the upper side of the isolation story while blue color the lower side. The red color strut-A is hanging from the upper side, the other blue color strut-B is standing up from the lower side. U-shaped steel dampers are set above the strut-B or below the strut-A. In the case of a large earthquake, oil dampers installed between the two struts generate resistance proportional to the story velocity and steel dampers operate to the story deformation of the isolation story. It is designed as a cross H-shaped strut considering the forces operating from the two directions of parallel or orthogonal to paper surface in Fig. 8.

In addition, because the axial force of the oil damper is eccentric to the strut core when the isolation story is deformed to the orthogonal direction of paper surface, the strut is reinforced by the cover plate for the purpose of transmitting this eccentric moment.

The laminated rubber isolators of sizes of 1300 mm to 1500 mm in diameter with sufficient vertical support capacity was adopted, such as one isolator supports one column.

3.5. Setting of Clearance in each Part

This project is made up of several buildings, including the residence tower which is isolated at the top column of the first underground floor.

The office tower and the residence tower are connected by a bridge at a height of about 20 m above the ground as shown in Fig. 9. The shuttle elevator (which is integrated to the lower structure of the isolation story) directly connected to the atrium space on the 26th floor (which is a part of the upper part of the isolation story) is installed in the office tower, and the elevator following a deformation of the isolation story contains only the emergency elevators. Therefore, because structures with different deformations in earthquake are architecturally linked, it was necessary to appropriately set the clearance between the structures and the deformation followability of the non-structural components such as the hardware and equipment. The story deformation angle of each structure in the case of a large earthquake is shown in Fig. 9. Also, the horizontal displacement of the isolation story in the large earthquake for the office tower and residence tower is 400 mm and 430 mm. Hardware with the risk of falling (e.g.: exp-

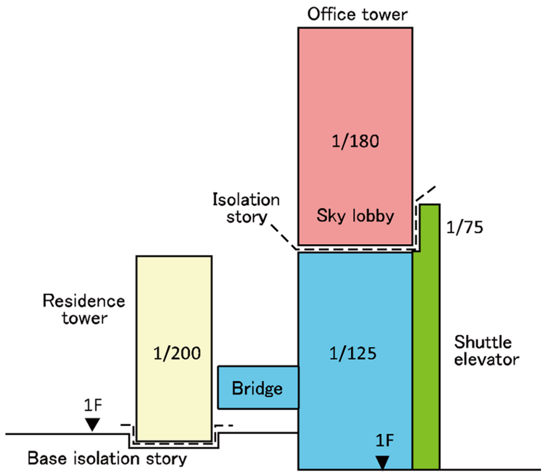


Figure 9. Story Drift Angle of each Part in this Project.

Table 2. Clearance set in each Part

	Building	Number of floor	Position	Clearance [mm]
Structural Clearance	Office tower	29F	Between office tower and shuttle elevator on their exterior grasses	1100
		26F	Just above the isolation story	900
		Isolation story	Around the mid-story isolated elevator	650
	Office Residence	Bridge	Between Bridge and residence tower	1000
	Residence tower	B1F	Between all adjacent part	700
Hardware Cearance	Office tower	26F	The cover of EXP.J (exterior floors, walls, roofs and interior floors)	850
			The cover of EXP.J (interior walls, ceilings)	650
	Office Residence	Bridge	The cover of EXP.J (exterior floors, walls, roofs and interior floors)	950
			The cover of EXP.J (interior walls, ceilings)	730
	Residence tower	Underground including 1F	The cover of EXP.J (floors)	650
			The cover of EXP.J (walls and ceilings)	430
Equipment				Office:400 Residence:430

ansion joints) were designed so as not to collide or fall even when deformed by 1.5 times this horizontal displacement.

4. Design of the Structural Frame

Considering the structural scheme above mentioned as mid-story isolation system, the structural frames in each part were designed. Fig. 10 is the structural framing elevation including important structural elements in each part of the building.

This chapter presents only two structural elements of whole structures of this building. The first one is the Concrete Filled Tube (=CFT) columns, the other one is the transfer steel walls.

4.1. CFT Column

CFT long columns of 1,800 mm diameter is installed in the lower atrium spaces as shown in Fig. 11. Those steel material is TMCP385C (ultimate strength is 550 N/mm^2)

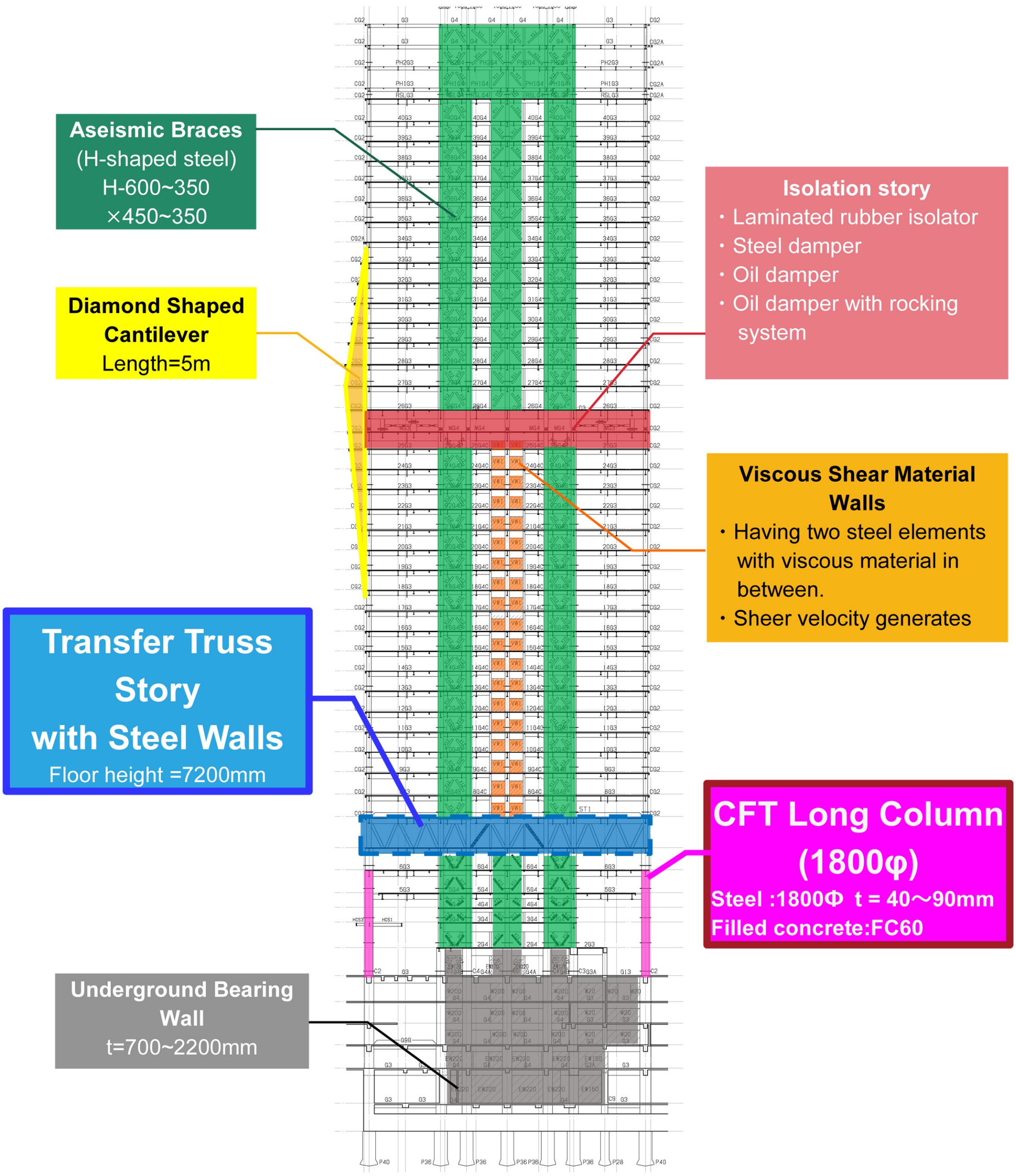


Figure 10. Structural Framing Elevation with each Structural Elements.

Figure 11. Perspective of Lower Structural Frame.

Figure 12. Construction of CFT Long Columns.

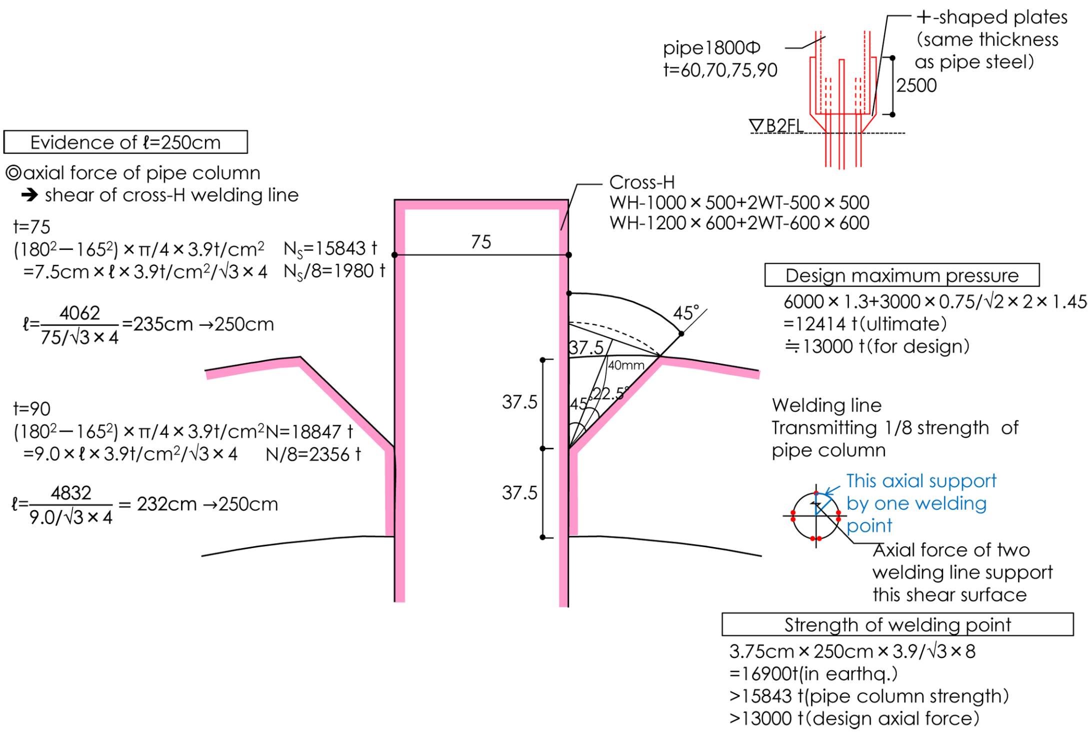


Figure 13. Examination of a Welding Groove.

and those filled concrete strength is Fc 60 N/mm^2. These CFT columns are one of the largest columns in Japan as the CFT column of building, and carried out sufficient construction planning and accurate construction of the concrete.

As shown in Fig. 12, the CFT long column in the underground floor has a special part that connects the different column shape. This part must be transferred to the vertical load smoothly. Fig. 15 shows a detail of the special part of underground CFT long column. The column shape is switched from pipe column during upper part to +-shaped plates temporarily, and switched to cross H-shaped column immediately. Vertical axial force of the upper pipe column is transmitted thorough welded lines between the steel of the pipe column and +-shaped plate, and transmitted to H-shaped column gradually. Since these welded lines have been sufficient length in Fig. 13, weld leg length could have been reduced. Having made smaller weld leg length caused to reduce construction costs.

4.2. Steel Walls for Transferring Vertical Loads

Because the lower part of the building has atrium spaces

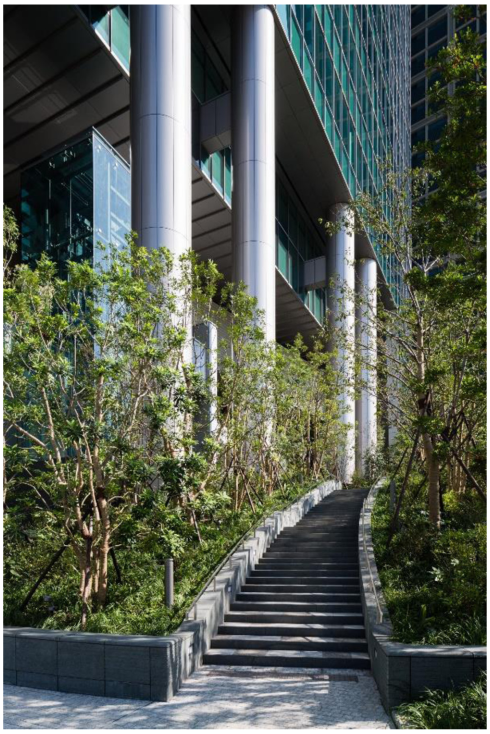


Figure 14. CFT Long Column (Photo by: SS Tokyo).

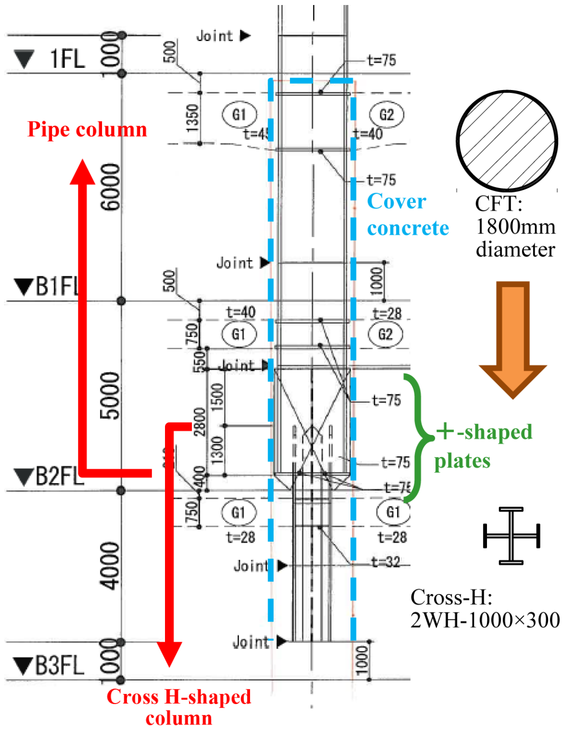


Figure 15. Detail of Underground CFT Column.

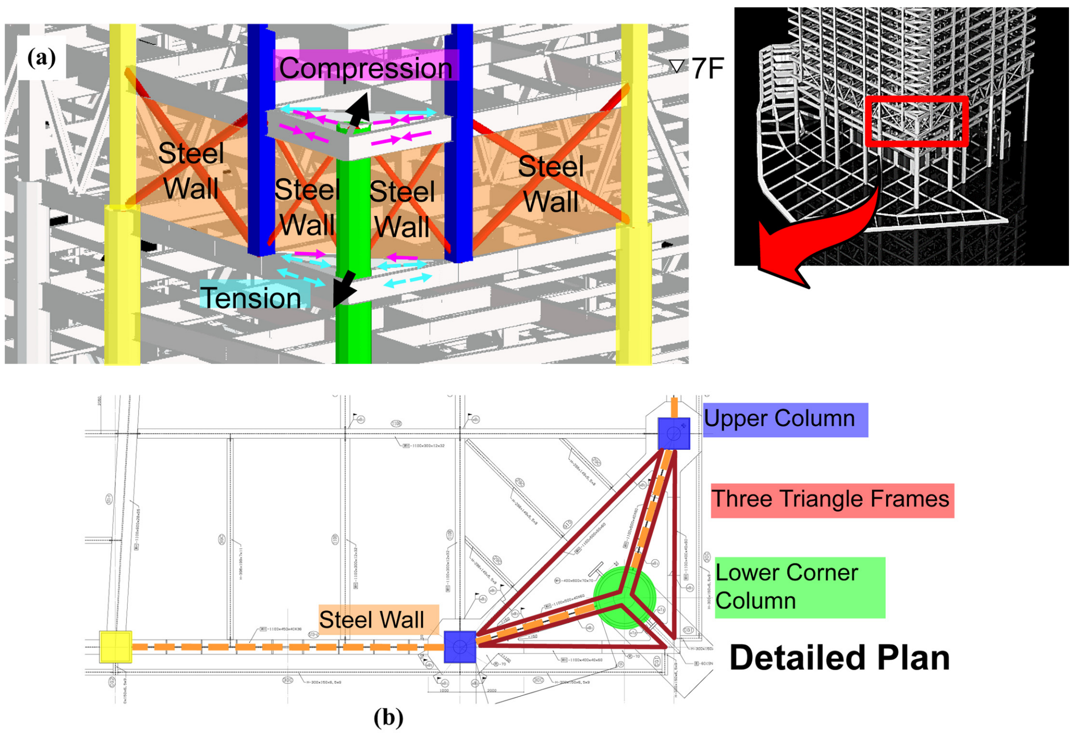


Figure 16. Structural Scheme of Transfer Steel Walls; (a) Perspective, (b) Detailed Structural Plan.

as shown in Fig. 11 and the long columns are low horizontal rigidity, a transfer story is installed below the 7th floor for securing the rigidity as the whole of the lower part. In addition, the office floor corner view was required and CFT long columns was set in corners of the lower part. To satisfy these given conditions, transferring vertical force

Figure 17. Constructions of the Steel Walls.

in this transfer story was demanded.

Fig. 16 shows the structural scheme of transfer steel walls. In Fig. 16(a), the vertical axial force of blue columns is transmitted to the green and yellow columns through the steel walls.

Blue and green columns are not on a straight line, therefore green column tends to bend toward the center of floor like black arrows over here. For controlling these deformation, three triangle frames installed on the upper and lower floors in Fig. 16(b). Four corner of this building has same structure and the forces in the corners balance in the structural frame on the upper and lower floor.

Fig. 17 shows the construction of the steel walls.

5. Conclusion

This paper presents the structural design of mid-story isolated super high-rise building – Roppongi Grand Tower. Remarkable conclusions is as follows:

Firstly, in general, although super high-rise building hardly has the effect of seismic isolation system, the reduction effect in the aspect of acceleration and shear force was found in this building.

Secondly, in the lower part of the isolation story, relatively low rigidity of the lower structure caused this building to be high performance regards of vibration characteristics.

Thirdly, the arrangement of seismic isolation devices enabled to design the isolation story with no torsion.

Fourthly, CFT column of largest diameter in Japan as building installed as long column in the lower part secured proper rigidity as the whole of the building.

Finally, Transfer steel walls were installed in the 7th floor and were designed considering the balance between the eccentric forces deriving from not being on a straight line of the four corners.

These conclusions would be able to contribute to future design of mid-isolated super high-rise buildings.

Acknowledgements

In October 2016, 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 Roppongi 3-Chome East Block Redevelopment Consortium, Taisei Construction Co., Ltd. and all other parties involved.

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