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Application of Hybrid Structural System Using Coupled Vibration Control Structure and Seismic Isolated Structure in High-Rise Building

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Abstract

This building is a forty-eight story, 170 meters high multiple dwelling house with Dual Frame System (DFS), a coupled vibration system connecting two independent structures with hydraulic dampers. Generation of large deformation between two structures during earthquakes contributes to make the hydraulic dampers effective. To improve the aseismic performance more, this building adopts DFS hybrid system that consists of DFS and base isolation system. About typical floors, columns and beams are constructed with LRV precast concrete method that shorten the construction period greatly by integrating column-beam joints in column members.

Keywords: Oupled vibration system, Hydraulic dampers, Precast concrete members

1. Introduction

The building "PARK TOWER HARUMI" is a reinforced concrete high-rise multiple house with 48 stories above ground, 1 story below ground, about 170 m of building height, 120,000 m^2 of total floor area and 1076 residences.

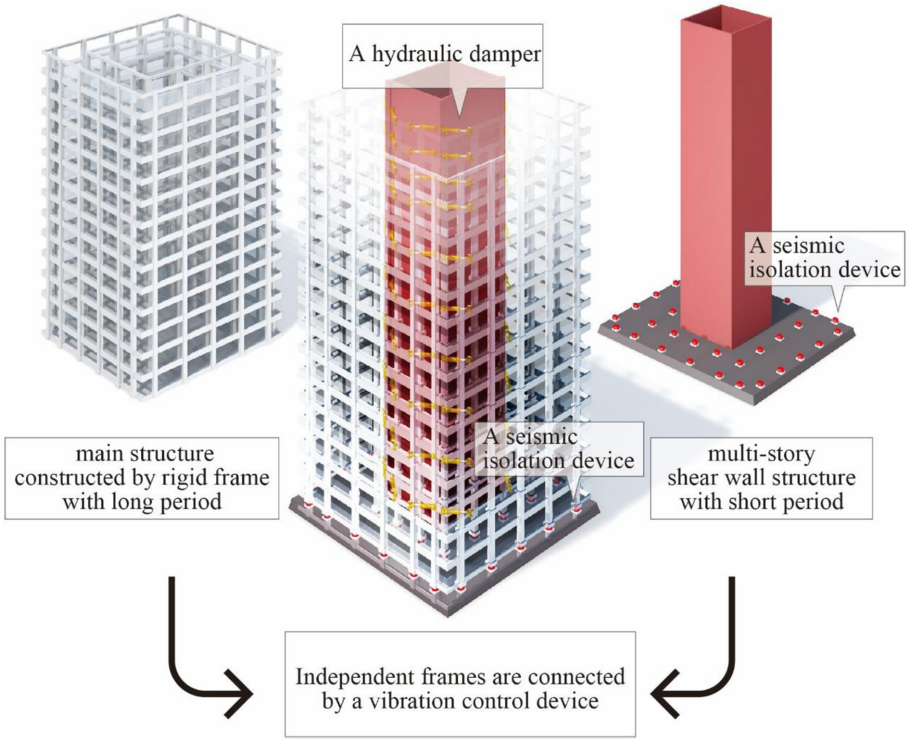


Figure 1. Image of the DFS hybrid.

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Photo 1. Exterior photograph.

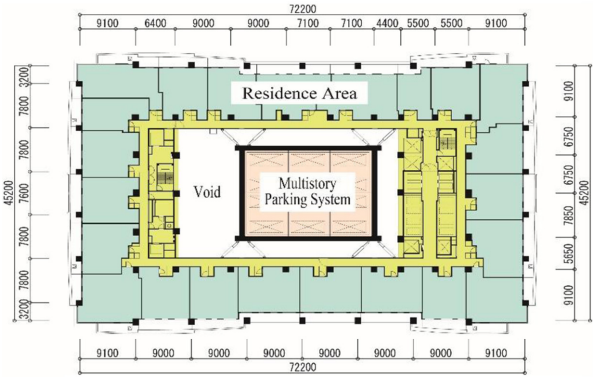


Figure 2. Floor plan of the reference floor.

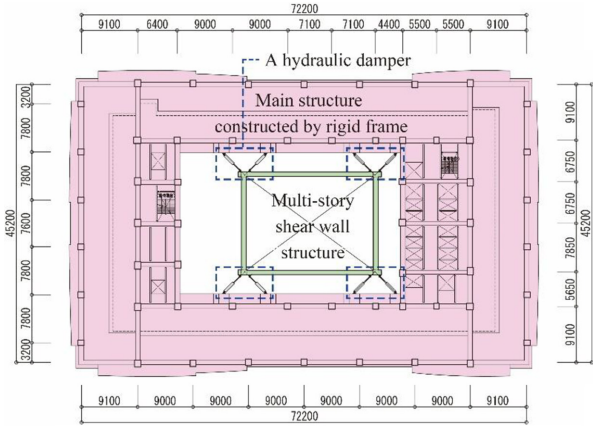


Figure 3. Framing plan of the reference floor.

This building adapts a coupled vibration control structure "DFS hybrid" system to improve an aseismic performance and flexibility of the residential area.

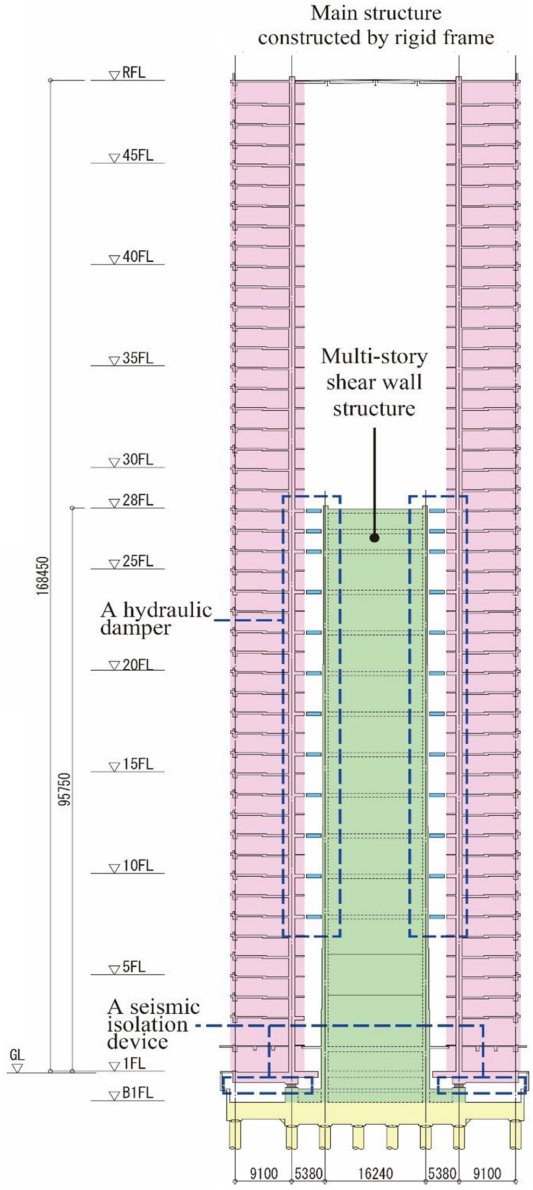


Figure 4. Framework diagram.

"DFS (Dual Frame System)" is formed by connecting two independent structures with hydraulic damper: multi-story shear wall structure with short natural period and rigid framing main structure with long natural period (Fukumoto, Nishimura, and Wada, 2008). Generation of large deformation between two structures during earthquakes contributes to make the hydraulic dampers effective. To improve the aseismic performance more, this building adopts DFS hybrid system that consists of DFS and base isolation system. Figure 1 shows an image of the DFS hybrid. Photo 1 shows the exterior photograph. Figure 2 shows a floor plan of the reference floor, Figure 3 shows framing plan of the reference floor, and Figure 4 shows a framework diagram.

In the reference story, columns and beams are constructed by "LRV (H) construction method" to shorten a construction period.

2. Overview of Structure

2.1. Overview of Frame Plan

The above grand part of this building consists of main structure consists of rigid frame structure and multi-story shear wall structure located in the void space at the center of the main structure. A multistory parking system is located inside the multi-story shear wall structure to improve the sound insulation performance of the residence. The main structure adopts a base isolation system at top of columns on first basement floor. The main structure of a seismic isolation system and the multi-story shear wall structure are connected by hydraulic dampers, hence this building has a combination of seismic isolation system and vibration control system. The main seismic isolated structure is capable of reducing the input seismic motion and obtaining a more effect of connected vibration damping thanks to the effects of an increase in the equivalent mass.

The underground structure has reinforced concrete walls around multi-story shear wall structures, as the main seismic structure elements. The building shape in plan is about 72 m × 45 m with hollow space about 35 m × 32 m in the center, the framing on a standard story consists of moment-resisting frames with 8 spans in the X-direction and 7 spans in the Y-direction. The plan shape of the multi-story shear wall structure is a about 22 m × 16 m. The height of the standard floor is 3.45 m, and the aspect ratio to the building height is 2.36 in the X direction and 3.78 in the Y direction.

2.2. Overview Of Seismic Isolation Device

Figure 5 shows a layout of the seismic isolation device.

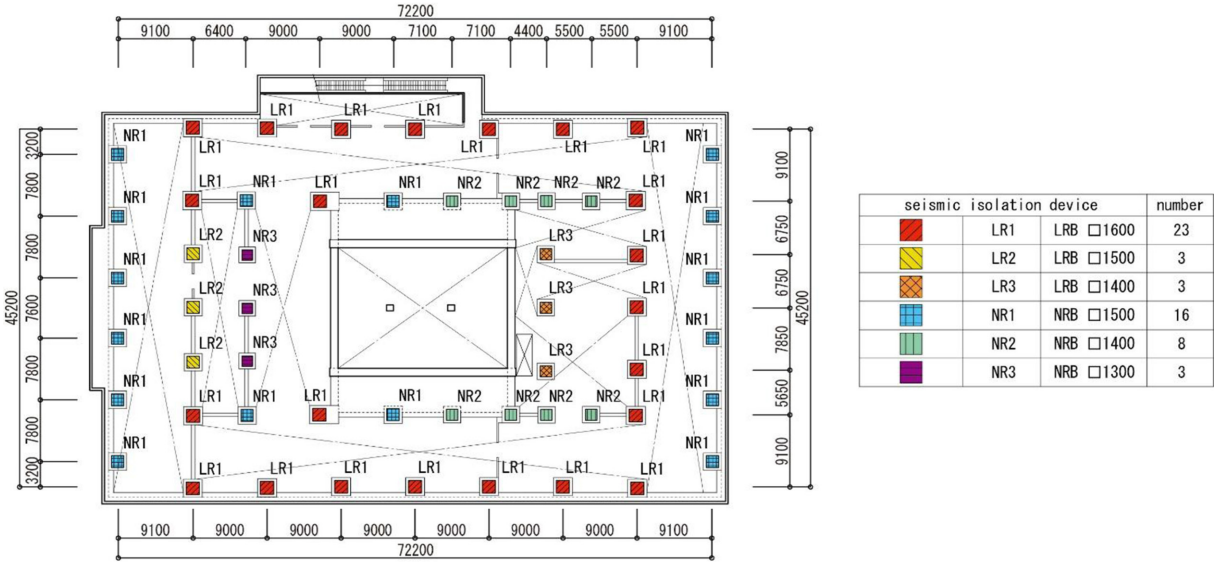


Figure 5. Layout of the seismic isolation device.

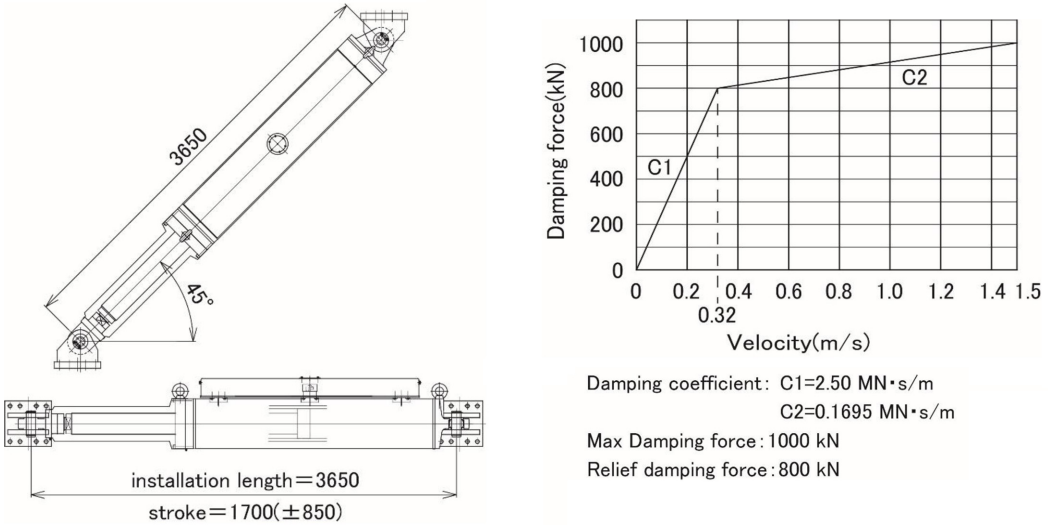


Figure 6. Specification of hydraulic damper.

For the seismic isolation device, 29 lead plug-containing laminated rubber bearings and 27 natural rubber laminated rubber bearings are adopted, the shear modulus of the rubber is $G = 0.392\ N/mm^2$, and the size of the rubbers are 1300 to 1600 square. Lead plug area of lead plug-containing laminated rubber bearings is decided so that the amount of absorbed energy per unit time of the lead plug is not less than the specified value. And the seismic isolation devices are placed so that the eccentricity of the seismic isolation layer should be 3% or less under small deformation or deformation by earthquake.

2.3. Overview of Vibration Control Device

96 hydraulic dampers, 8 per a story × 12 stories, are installed between the main structure and the multi-story shear wall structure. The damping force of the hydraulic damper is proportional to the relative velocity between both frames. The hydraulic dampers are arranged at an angle as about 45 degrees with the main axis direction of the building so that the damping force of the hydraulic dampers become same in each X and Y directions. Figure 6 shows the velocity-damping force relationship diagram of the hydraulic damper.

3. Overview of Seismic design

3.1. Design Criteria And Input Seismic Motions

Table 1 shows the seismic design criteria of the building. Table 2 shows the input seismic motions of Level 1 and Level2. Figure 7 shows the velocity response spectra of the "extremely rarely occurring seismic motions" (Level 2 seismic motion). The input seismic motions used for design are simulated based on the spectrum pre-scribed in Ministry of Construction Notification No. 1461 of the year 2000 (hereafter: Notification wave), and representative seismic waves that are measured in the past (hereafter: Observation wave), and simulated seismic motions based on the distribution of active faults around the construction site, fault failure models, past seismic activity, ground structure, etc (hereafter: site wave). Two levels are set for the input level of the Notification wave, the "rarely occurring seismic motion" (Level 1 seismic motion) and the "extremely rarely occurring seismic motion" (Level 2 seismic motion), and at each level three waves are adopted with different phases.

The input level of the observation wave is set assuming the maximum velocity amplitude for the "rarely occurring seismic motion" (Level 1 seismic motion) as 0.25 m/s, and for the "extremely rarely occurring seismic motion" (Level 2 seismic motion) as 0.50 m/s.

To evaluate the behavior of the building during earthquakes, three-dimensional non-linear pushover analysis and seismic response analysis with a lumped mass model

Table 1. Seismic design criteria

Level 1	[Main frame structure] · Interlayer deformation angle ≦ 1/200 [Multi-story shear wall structure] · Story shear-force ≦ shear crack strength · Displacement between structures ≦ 1000 mm [seismic isolation device] · Seismic isolation layer displacement ≦ 390 mm [hydraulic damper] · Damping force ≦ 1000 kN · Velocity ≦ 150 cm/sec
Level 2	[Main frame structure] · Interlayer deformation angle ≦ 1/100 [Multi-story shear wall structure] · Story shear-force ≦ shear crack strength · Displacement between structures ≦ 1000 mm [seismic isolation device] · Seismic isolation layer displacement ≦ 390 mm [hydraulic damper] · Damping force ≦ 1000 kN · Velocity ≦ 150 cm/sec

Table 2. Input seismic motions

Input seismic motions		Maximum acceleration (cm/s^2)		Abbreviation
		Level1	Leve2	
Notification wave	Notification wave1 Kobe phase	83.6 (12.1 cm/s)	431.0 (63.0 cm/s)	Notification wave1
	Notification wave2 Hachinohe phase	93.4 (11.3 cm/s)	546.7 (50.4 cm/s)	Notification wave2
	Notification wave3 Random phase	66.0 (11.2 cm/s)	455.9 (54.5 cm/s)	Notification wave3
Observation wave	EL CENTRO 1940 NS	255.4 (25.0 cm/s)	510.8 (50.0 cm/s)	El Centro
	TAFT 1952 EW	248.4 (25.0 cm/s)	496.8 (50.0 cm/s)	Taft
	HACHINOHE 1968 NS	174.5 (25.0 cm/s)	349.0 (50.0 cm/s)	Hachinohe
Site wave	Northern Tokyo Bay Earthquake	-	476.9 (60.3 cm/s)	Tokyo Bay
	Kanto Earthquake	-	214.9 (36.2 cm/s)	Kanto
	Tokai/Tonankai/Nankai Earthquake	-	50.2 (35.7 cm/s)	3 Combination

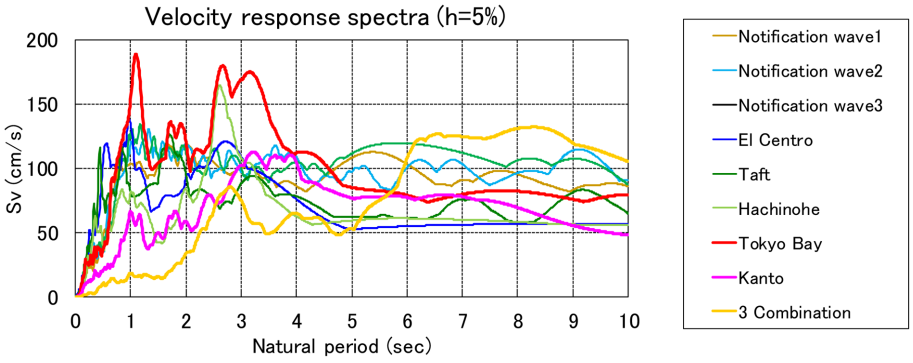


Figure 7. Velocity response spectra.

are carried out.

3.2. Seismic Response Analysis Model

The analysis model used in the seismic response analysis is fixed at the first basement floor, and the main structure and the multi-story shear wall structure are branched as shown in Figure 8. The main structure is an equivalent bending and shear model with 49 nodes at which the mass of each story from the 1 level to the R level is concentrated. The multi-story shear wall structure is a 29-story model with column elements from the 1 level to the 28 level, and a rotating spring is provided on the legs as a rigidity of the foundation. The seismic isolation devices are modeled as a shear spring with the hysteresis of laminated rubber bearings.

The hydraulic dampers are modeled as a Maxwell model in which a bilinear viscous damping and the stiffness of the supporting members are connected in series.

The assumed damping of the main structure and the multi-story shear wall structure is a viscous damping of 1% proportional to the initial rigidity from the natural frequency of 1st mode respectively. The primary natural period is shown in Table 3, and the natural mode is shown in Figure 9.

The primary natural period of the main structure is 4.76 seconds at X-direction, and 5.26 seconds at Y-direction when the seismic isolation layer is fixed. Considering the deformation of the seismic isolation layer during the Level 2 earthquake, the 1st natural period of the main structure is 6.95 seconds at X-direction, and 7.26 seconds at Y-direction. The 1st natural period of the multi-story shear wall structure is 0.81 seconds at X-direction, and 0.94 seconds at Y-direction.

3.3. Results of Seismic Response Analysis

Figure 10 shows the response analysis results for the Level 2 seismic motions in the X direction. (Main structure: maximum story shear-force, story shear-force coefficient and interlayer deformation angle. Multi-story shear wall structure: maximum story shear force, displacement between structures and the hydraulic damper damping force).

The maximum story shear-force of the main structure

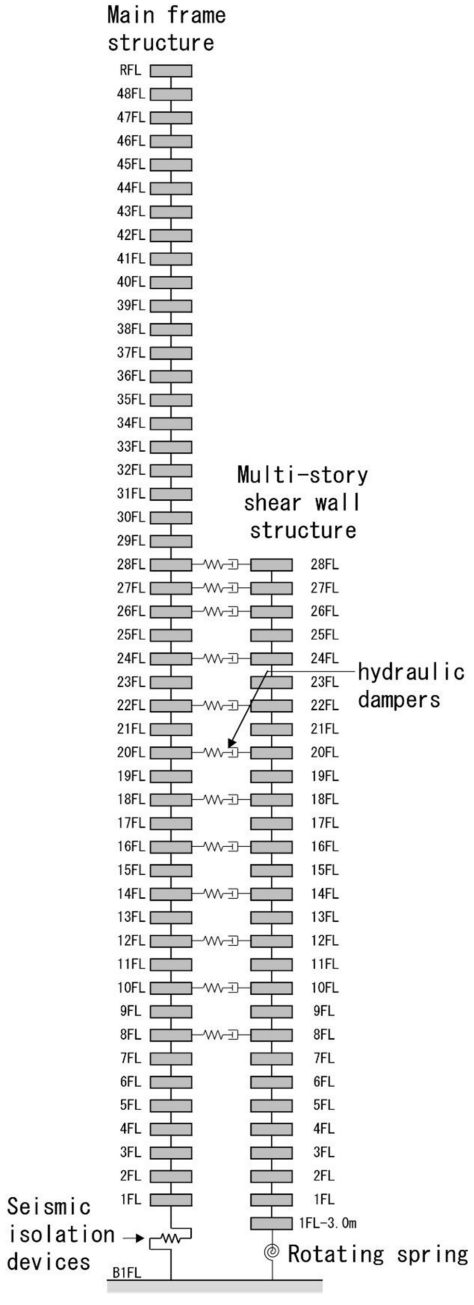


Figure 8. Analysis model.

Table 3. Natural period

Main frame structure Seismic isolation layer is fixed		
	X direction	Y direction
1 mode	4.76	5.26
2 mode	1.64	1.76
3 mode	0.97	1.01

Main frame structure Deformation of Level2 earthquake		
	X direction	Y direction
1 mode	6.95	7.26
2 mode	2.28	2.47
3 mode	1.22	1.28

Multi-story shear wall structure		
1 mode	0.81	0.94
2 mode	0.14	0.17
3 mode	0.07	0.08

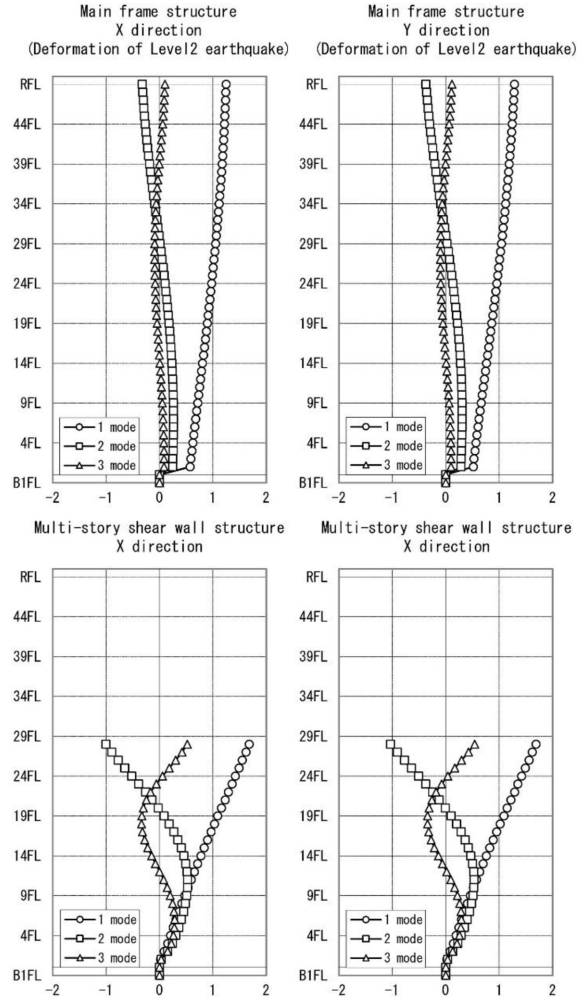


Figure 9. Natural mode.

decreases on the lower stories from the 28th story, then it is confirmed the effect of reducing the response shear force by the coupled vibration control structure. The maximum interlayer deformation angle of main structure in the X-direction is 1/159, thus the seismic design criteria of 1/100 is satisfied. The maximum response story shear-force diagram of the multi-story shear wall structure shows a stepped shape since the shear force increases on the floor where the hydraulic damper is installed. The maximum response story shear-force of the multi-story shear wall structure is less than the shear crack strength of the wall. In order to provide the performance of the coupled vibration control structure constantly, the decrease in the rigidity of the wall due to crack is controlled even during the Level 2 earthquake.

3.4. Energy Absorption Percentage

In order to determine the effects of the coupled vibration control structure, the amount of energy absorbed during the earthquake is calculated and the percentage of the input energy is obtained as shown in Figure11. The energy absorption rate of the hydraulic damper is about 55% to 70% during the Level 2 earthquake in the X direction, and about 80% including the seismic isolation device.

4. Precast Construction Method

4.1. Overview of Construction Method

In order to improve workability and shorten the construction period, the precast method is adopted for the columns, beams and slabs of the main structure in this building. For the columns and beams, the precast construction method (LRV method (H) (H: Horizontal)) (Fujiu and Sugimoto, 2009) with integrated column and beam joints is adopted. Figure 12 shows the overview of the construction method. This is a construction method that uses the full precast column member (H-column) integrating the joint and the half precast beam member (H-beam) continuous between the columns. The column member is provided with horizontal holes for the main reinforcement bar of the beam. The main reinforcement bar of the beam passes through the hole and are connected to the other bar for the opposite side beam by a mechanical joint. Then columns and beams are connected by mortar filled in the gap between them, horizontal holes and mechanical joints. With this method, the following advantages can be obtained.

- It is possible to regard both columns and beams as precast members by omitting conventionally required site-casting concrete at the column-beam joints.
- It is not necessary to provide the main reinforcements joint of beam in the column-beam joint, that simplifies reinforcement arrangement .
- Because the columns and beams have independent member configurations, the member shape is simplified, and manufacturing efficiency is improved.
- Normally, the concrete strengths of columns and beams are different, but since the columns and beams have independent member configurations, it is not necessary to separate the concrete strengths.

A half precast slab is used for the core area, and a half precast void slab is used for the Residential area.

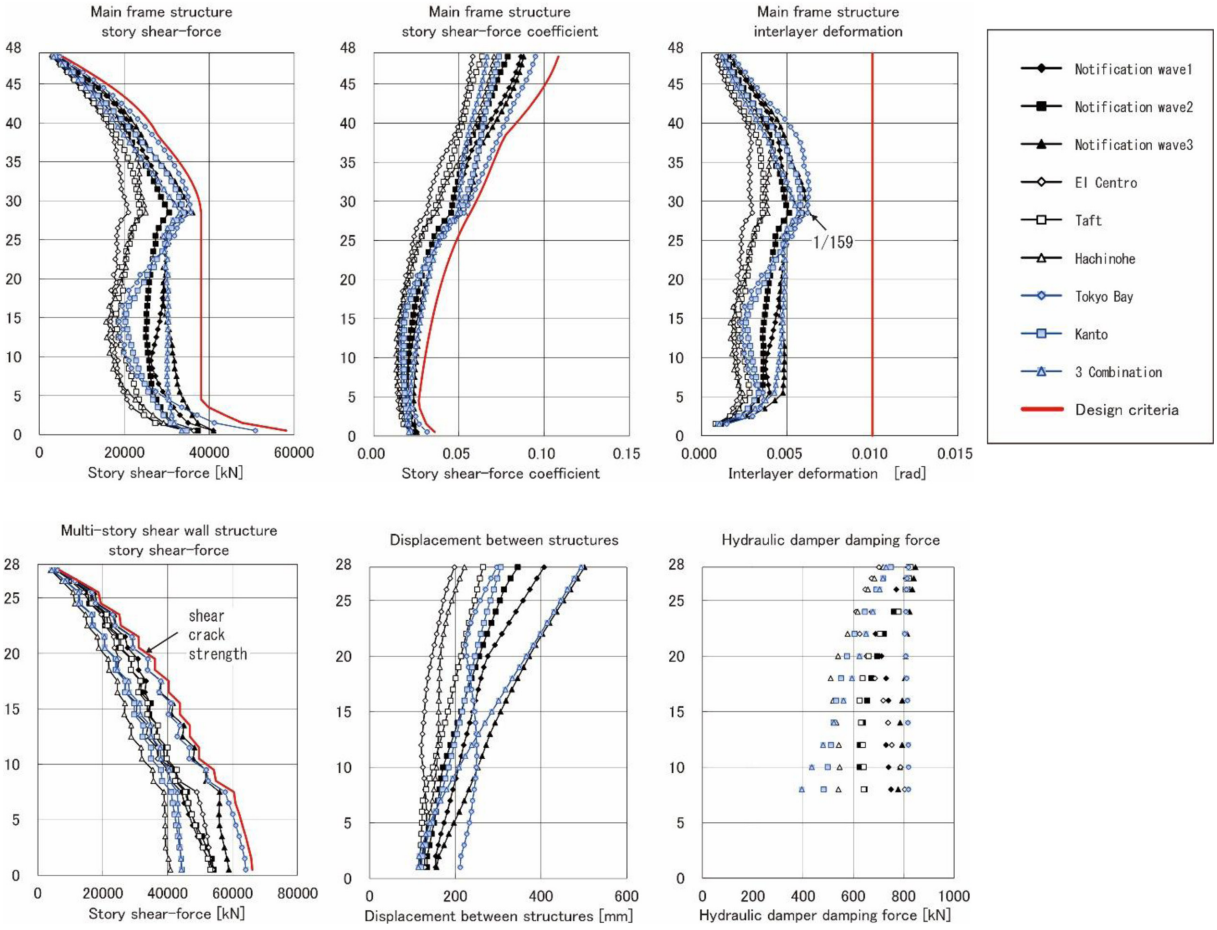


Figure 10. Maximum response analysis results.

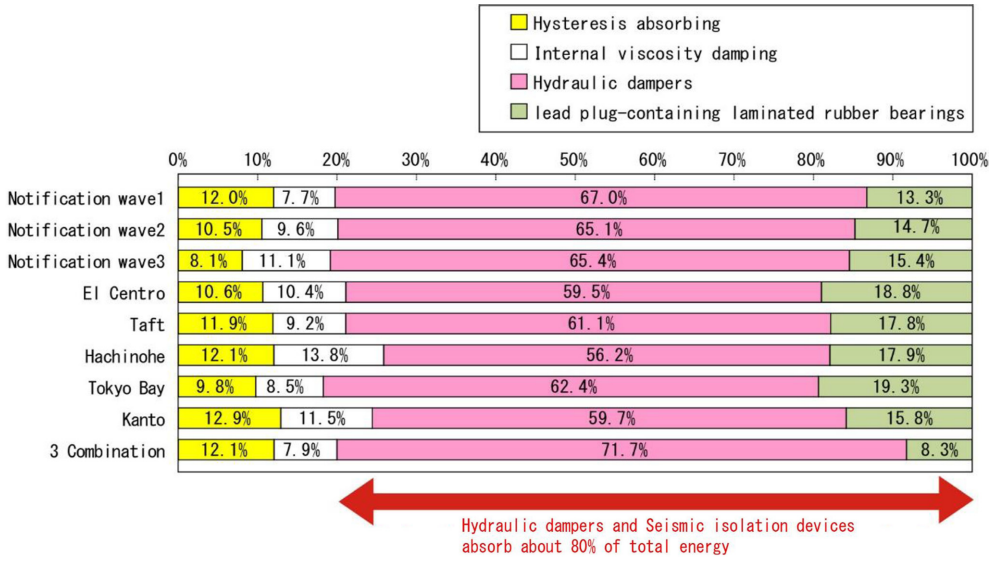


Figure 11. Percentage of the input energy.

4.2. Construction Overview By LRV Method (H)

Photos 2 to 7 show the assembly status by the LRV method (H). Photo 2 shows the installation status of the half precast slab, Photo 3 shows the construction status of the H-column and Photo 4 shows the situation that the H-beam is inserted horizontally into the H-column. Photo 5 shows the mortar injection status at the joints of columns, Photo 6 shows the mortar injection status at the beam-

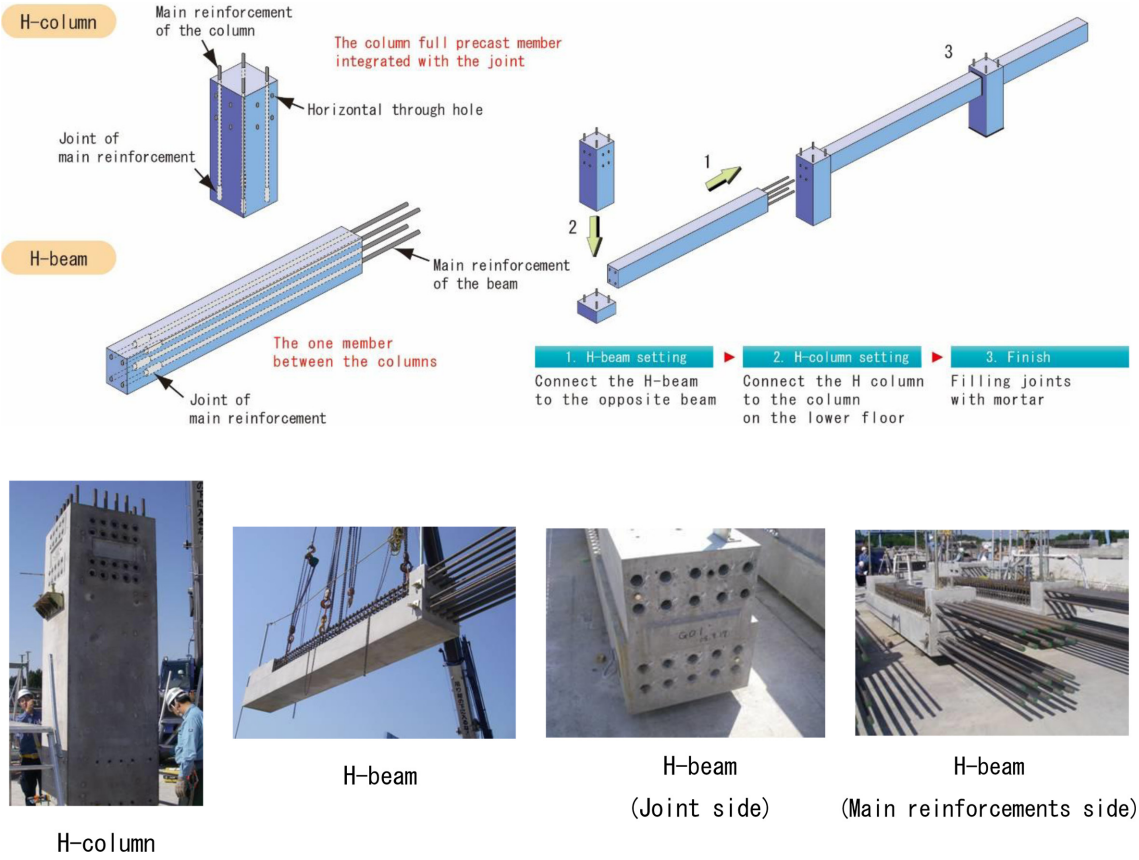


Figure 12. Overview of the construction method.

column joints and Photo 7 shows the top concrete placement of slabs and beams.

Figure 13 shows the construction cycle by the LRV method (H). The building is divided into 3 sections, and the structure is constructed in 4 days per a story.

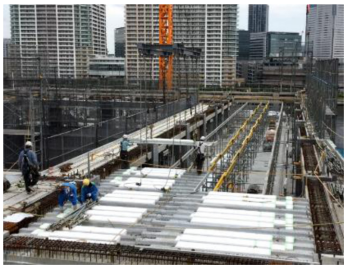


Photo 2. Half precast slab.



Photo 3. H-column.



Photo 4. H-beam.



Photo 5. Joint of column.



Photo 6. beam-column joint.



Photo 7. Concrete.

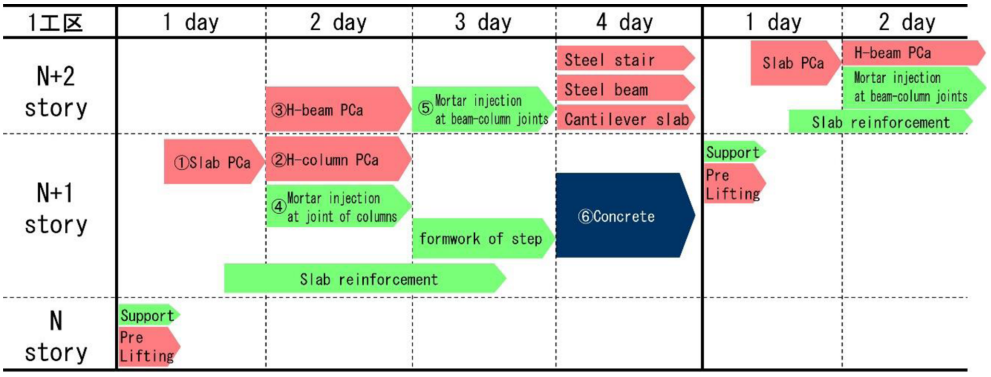


Figure 13. Construction cycle.

Conclusion

This paper presents the structural design of DFS hybrid system and the precast construction method (LRV method (H)).

Using DFS Hybrid system, the main structure is capable of reducing the input seismic motion and obtaining a more effect of connected vibration damping.

In order to improve workability and shorten the construction period, the LRV method (H) is adopted for the columns and beams of the main frame.

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