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Structural Design of Damper Controlled Tall Building utilizing Sliding Core Wall

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Abstract This paper introduces innovative damper system adopted on TAMACHI TOWER, which locates in Tokyo and has 29 stories above grade. Introduced damper system utilizes lower levels building core which is designed by concrete core sitting on slide bearing devices and being isolated by surrounding steel moment frame where levels concrete core is designed. Following designed sliding core, large differential lateral displacement is generated between sliding core and surrounding ductile steel moment frame. Viscous dampers expecting this differential displacement building are assigned at the clearance between core and steel frame and succeeds in dissipating seismic energy efficiently under extremely rare earthquake. The innovative system has led greater disaster prevention under earthquake as well as mitigating required number of dampers to 10% of conventional system and result in providing improved floor area efficiency.

Keywords: Damper Controlled High-rise, Sliding Core Wall, Building Resiliency

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1. Introduction

When Japanese tall building locating in a high seismic hazard region is designed with performance based structural design (PBSD), an efficient energy-dissipating structural system is significant to satisfy design criteria under earthquake. To improve building performance under earthquake, there are several options. Base-isolated or intermediate story isolated structural system is one of them and damper controlled structural system is another one. However, in the case of base-isolated structural system, excessive tensile force due to tall building overturning moment often need be addressed. Although an intermediate story isolated structural system provides better solution to mitigate such tensile force, it introduces challenges related to special vertical shaft and elevator design to accommodate large displacements at the isolation layer. Based on such reasons above, typically damper controlled structural system is adopted for Japanese tall building over 100 meters high above grade. Among damper controlled structural systems, there are also various options however, installing viscous damper on multi stories expecting single story drift under earthquake is major choice (Fig. 1 left). Obviously, this is robust and reliable method having long history. But each dampers energy dissipation is not so large therefore, in order to make sure sufficient energy dissipation, large amounts of dampers are typically requested and loses floor efficiency. To address this issue, proposed system focuses on typical building component which recent mix-use building has and optimizes dampers seismic energy dissipation. This paper describes the innovative structural system having building core slide and install limited damper devices between sliding core and surrounding steel frame where large lateral differential displacement occurs under earthquake. Maximizing damper stroke under earthquake, damper efficiency is dramatically improved and system succeeds in inviting clear reduction of the number of installed damper devices in addition to optimized steel frame and sustained robust building performance under earthquake.

2. Building Outlines

TAMACHI TOWER which adopts innovative damper system using sliding core is a new tall building locating on Tokyo Bay area. The site is an urban transportation node connecting to both JR Tamachi Station and Mita Subway Station. Although site is terminal oriented and has high potential to attracts tenant there exist a few other large-scale developments in this district. Therefore client desire the building to be as competitive as possible. To make sure competitiveness, the building aims to achieve high floor efficiency and higher building resilience after a severe earthquake, which remains a concern for central Tokyo.

TAMACHI TOWER is 156 meters high steel moment

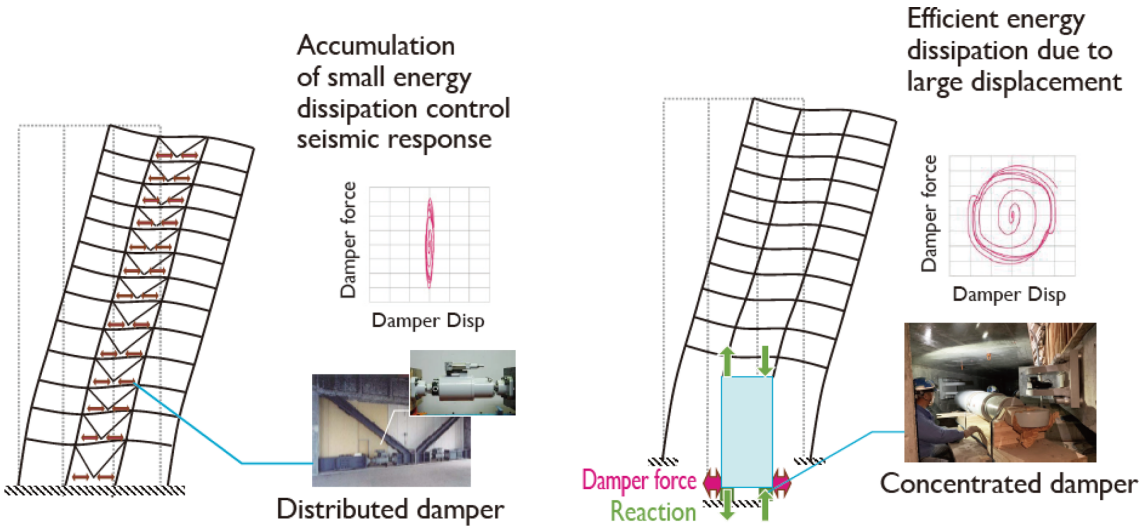


Figure 1. Comparison of damper-controlled structural systems.



Figure 2. Building Elevation.

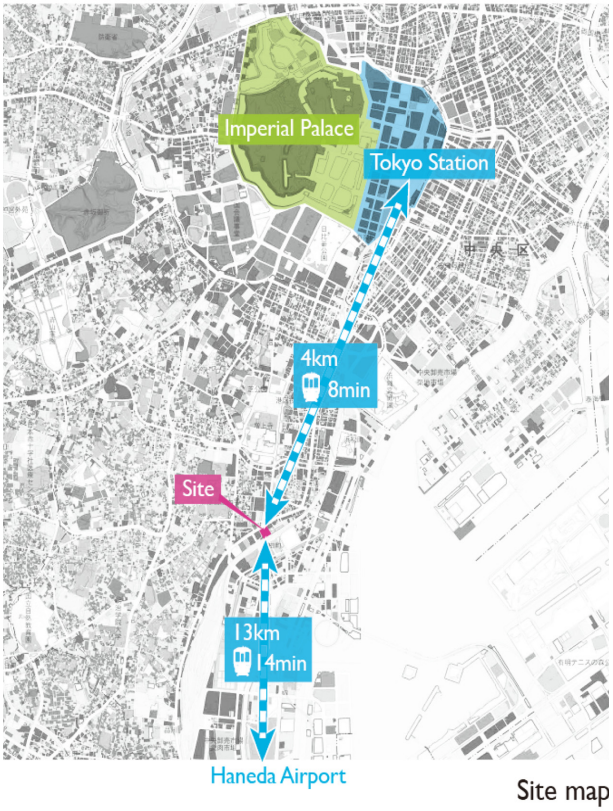


Figure 3. Building Site

frame basis tall building having 29 stories above grade and 2 basements. Building occupancy is composed of office, retail and other occupancy where need to manage building such as MEP floors and/or parking. Major occupancy is office locating on L6 above. L5 and B2 are MEP floors and retail locates from B1 through L4. There is office entrance at L2 where connects to JR Tamachi station through deck above street level. Therefore, visitor to office come across L2 entrance and soon arrive in building core. Then elevator passes through retail floors and passenger reaches to L6 above directly (Fig. 4). As for plan, typical floor is 58 by 67 meters rectangular. Elevators for office floors are composed of 3 banks and assigned on slightly off from floor center. Other vertical shafts are arranged beside elevators shaft and compose a part of building core (Fig. 5). This core layout and

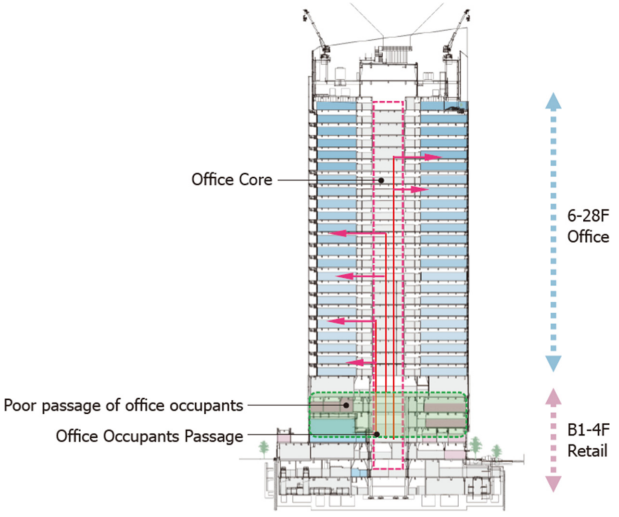


Figure 4. Building Section.

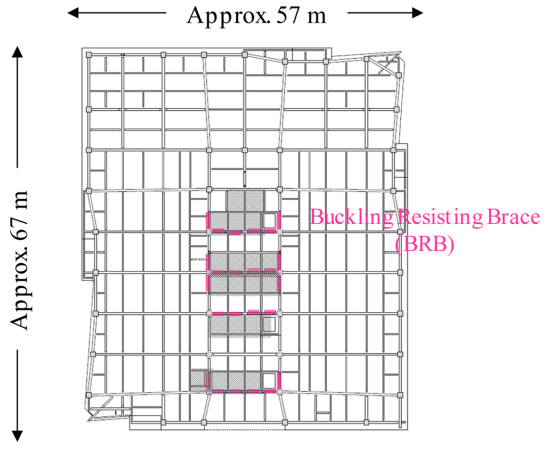


Figure 5. Typical Floor Plan.

building use are recently very typical in this scale Japanese building development.

Regarding seismic design procedure, Japanese building codes requests time-history analysis for over 60 meters high buildings to evaluate design earthquake load. Seismic level is divided into 2 scales, frequent earthquake and rare earthquake. Whereas it is typically said expected mean return period of rare earthquake is close to 475 years. Figure 6 shows rare earthquake design seismic acceleration response spectrum for this project, which target spectrum is defined by code and artificial ground motion records are simulated by structural engineer. When damper-controlled structure is designed, controlled inelastic deformation of the frame is permissive under rare earthquake. Therefore, typically elastic-plastic time history analysis is coordinated, and damper force including viscous dampers are directly evaluated in the time history analysis.

Table 1 describes comparison between ordinary tall buildings satisfying minimum requirements of codes and TAMACHI TOWER design criteria. When building performance under seismic is discussed in Japan, story drift limit is often adopted for criteria. For ordinary tall buildings, 1% drift under rare earthquake is defined as limit and the building satisfying 1% limit is expected to be continuous use after severe earthquake with some repairs. In other word minor damage is accepted under rare earthquake. However, TAMACHI TOWER is expected higher business continuity after earthquake. Based on engineering judgment, additional design earthquake level called Level 3 is defined as 150% amplified seismic of rare earthquake (Level 2). Under Level 3 earthquake, similar story drift limit assigned for Level 2 design criteria of ordinary tall building is set and expects mitigating building damage under Level 2 earthquake. Similar reinforced performance-based structural design is often coordinated in Japanese structural design and the upgraded design criteria is also linked to the assessment of the building's competitiveness as a tenant-focused property.

3. Structural System Outline

Figure 7 shows an outline of proposed structural system.

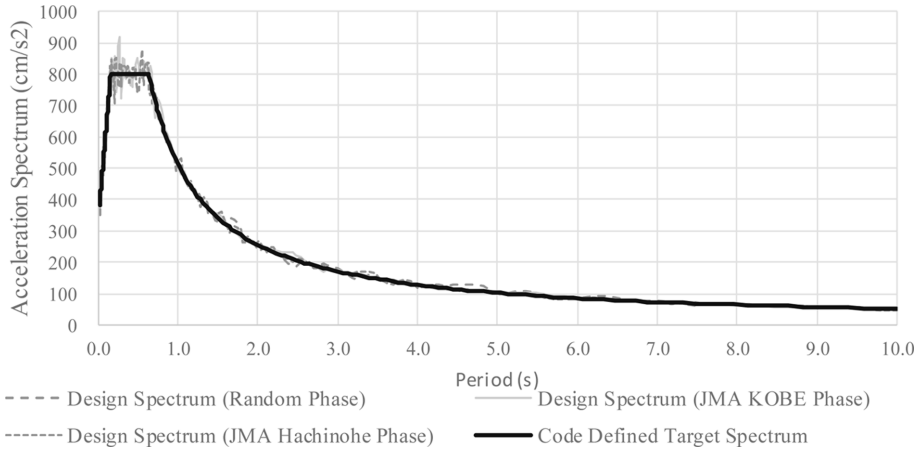
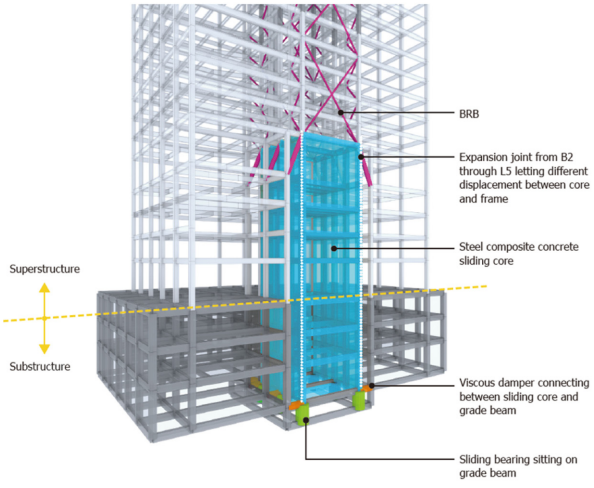


Figure 6. Design acceleration design spectrum.

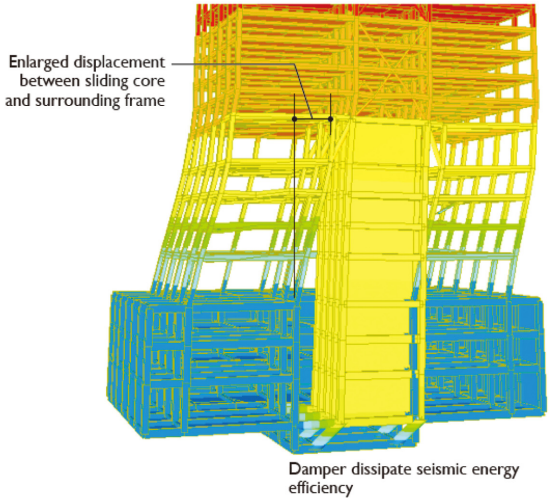
Table 1. Seismic Design Criteria (Extracted)[*1]

Earthquake Level	Frequent Earthquake (Level 1)	Rare Earthquake[*2] (Level 2)	Level 3 (150% amplified Level 2)
Ordinary Tall Buildings	Story Drift: < 0.5 % (Frame Elastic and few damage) (Building Function Continuous)	Story Drift: < 1 % (Frame Partially Yield and Minor damage) (Building Function Recovered after repair)	Not Defined
TAMACHI TOWER	Story Drift: < 0.5 % (Frame Elastic and few damage) (Building Function Continuous)	Story Drift: < 0.75 % (Most Frame Elastic and Minor damage) (Building Function Continuous)	Story Drift[*3]: < 1 % (Frame Partially Yield and Minor damage) (Building Function Recovered after repair)

Notes:
*1: Descriptions in parentheses are expected building condition after earthquake
*2: Earthquake scale expected to be 475 years mean return period
*3: Shear component of story drift is set as limit.



(Damper System using Sliding Core)



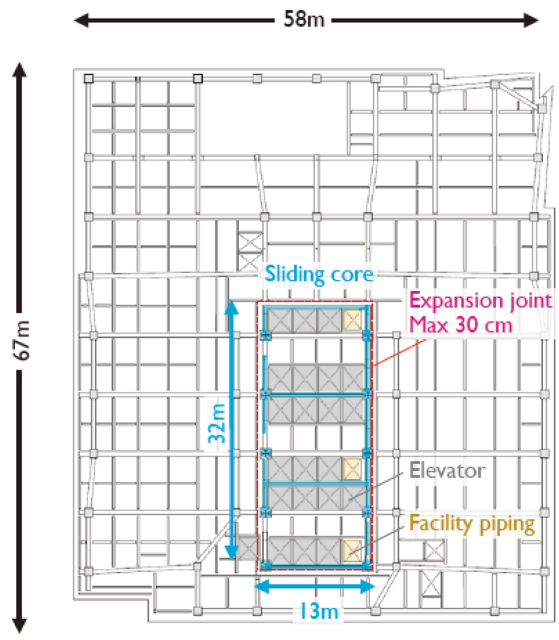
(Lateral Differential Movement under Earthquake)

Figure 7. Damper System Outline.

This innovative damper controlled structural system[1)] is developed focusing on few people across between building core for office where locates on upper levels, and lower retail. As described elevators for upper levels skip lower level, hence lower level of building core is easy to be closed by concrete core and is easy to install movement joints between core and surrounding steel moment frame. When this isolated concrete core sits on slide bearing, however it connects to surrounding steel frame at the top, lateral differential movement between core and frame is generated under earthquake and the displacement is amplified down-ward. To address the amplified displacement, viscous dampers are installed at the core's base to optimize energy dissipation during seismic event. Since sliding concrete core is assigned for B2 through L5 building core, both sliding bearing and viscous dampers are installed beneath B2 where the maximum lateral differential displacement is expected (Fig. 8). A clearance of 5cm to maximum 30cm between the core and surrounding frame is designed with movement joints placed at crossing points for pedestrians. Most MEP vertical shafts are assigned beside core, minimizing the need for movement joint design to enhance cost efficiency. Above L6, there are buckling resisting brace (BRB), which yielding strength is 1,000 to maximum 3000kN, are installed to gradually vary lateral stiffness from rigid concrete core to braced steel moment frame. Without this system, large drifts would occur from L6 through L10, particularly in the few stories directly above sliding core. Additionally, L6 where sliding core and steel frame interact forces, is very significant for this system. To avoid core's over-rocking behavior which cause exceeding shear on L6 link beams, BRBs with 10,000 kN yield capacity are installed as it braces between L5 and L6 (Fig. 9).

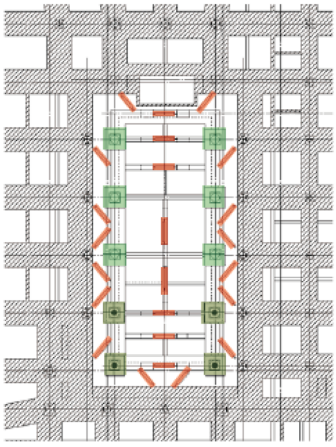
4. Building Response and Damper Efficiency

Figure 10 shows time history response under Level 3 earthquake and Figure 11 shows seismic energy dissipating component under Level 2 earthquake corresponding to random phase. All maximum story drift meet design



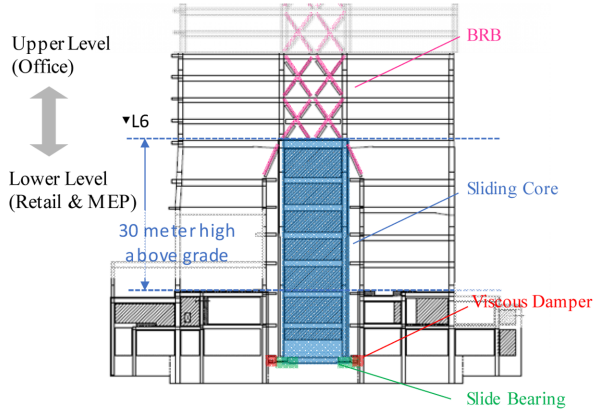
(Sliding Core)

	type	Number of units	note
	Viscous Damper	24	Damper force 2400kN Stroke 30cm
	Sliding bearing	4	Bearing capacity 30 MN with 1% friction
		6	Bearing capacity 35 MN with 1% friction



(Damper and Bearing Devices)

Figure 8. Assignment of Sliding Core Component.



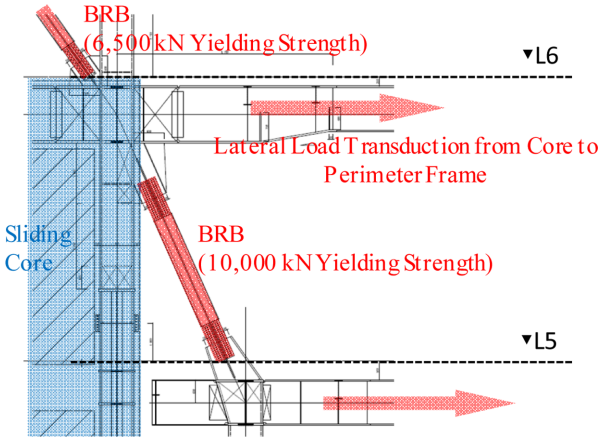


Figure 9. Section of core and frame transaction.

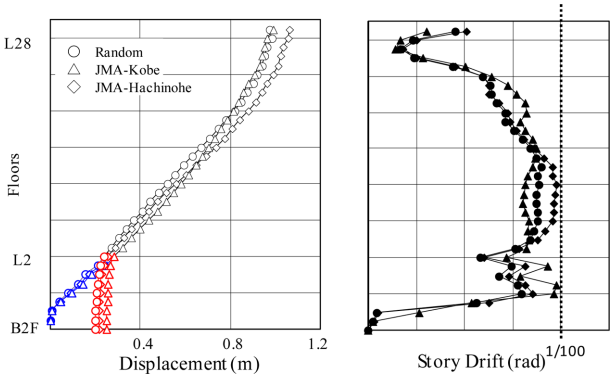


Figure 10. Time History Analysis Results.

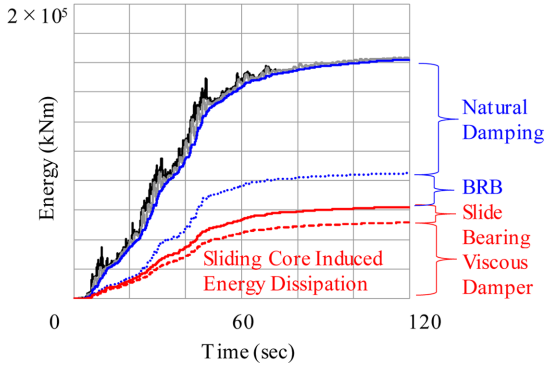


Figure 11. Energy Dissipating Component.

criteria. Regarding energy dissipation, approximately 35% of input seismic energy is dissipated by sliding core related devices including 24 viscous dampers having maximum 30cm stroke and including 12 low friction

slide bearings, however slide bearings dissipate little energy due to its low friction.

5. Benefit of Sliding Core Damper System

This damper system requires additional detail design for clearance between sliding concrete core and surrounding steel moment frame. When passage is allocated, flexible joint panel should be design. Also, MEP duct and/or plumbing should have expensive flexible joint to meet differential displacement between two structures. Therefore, such component passing across the clearance is better to

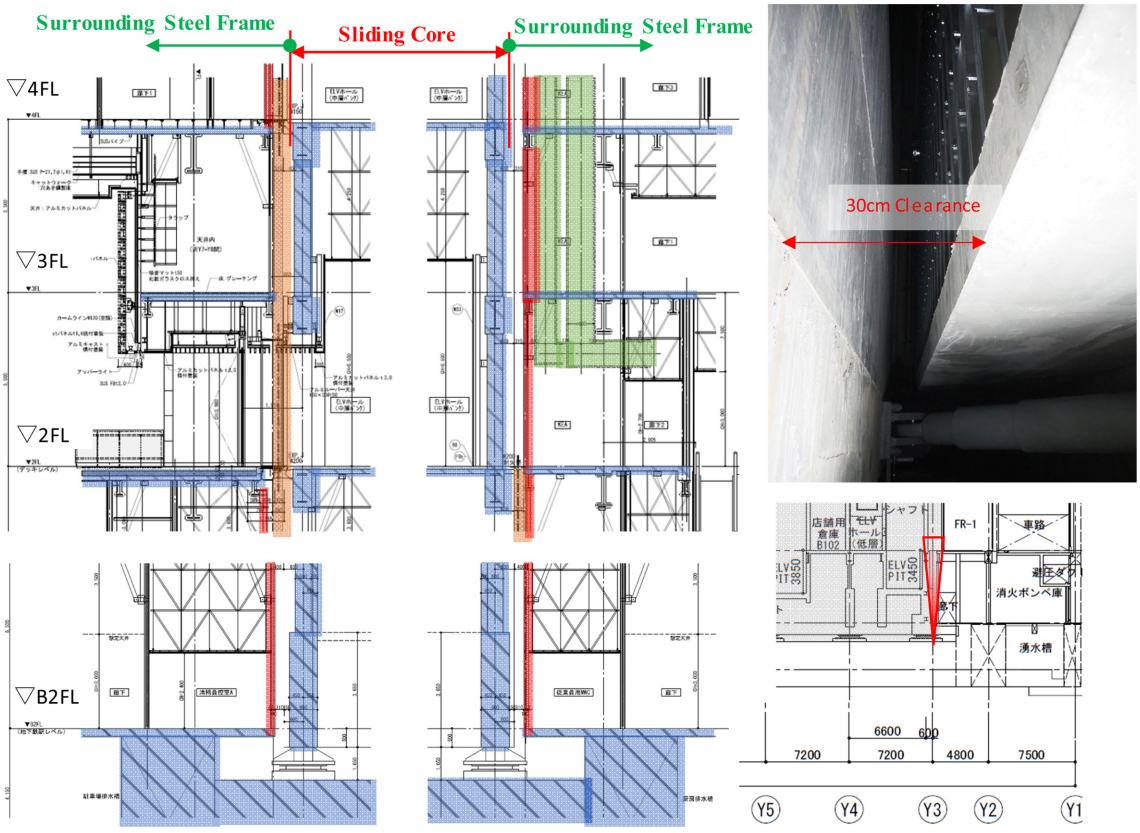


Figure 12. Coordination for MEP and Architectural Across.

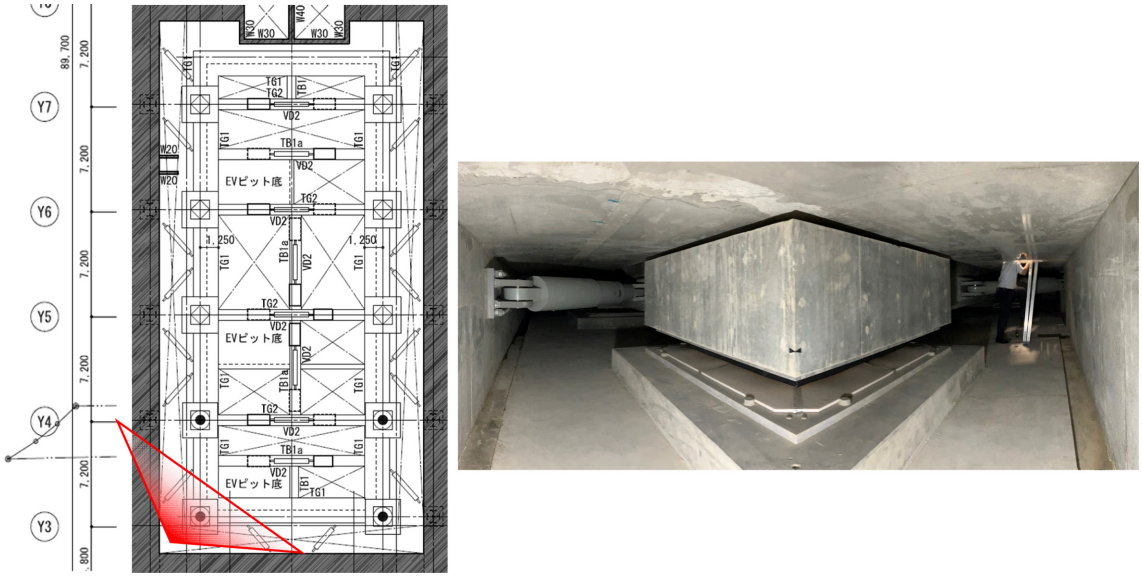


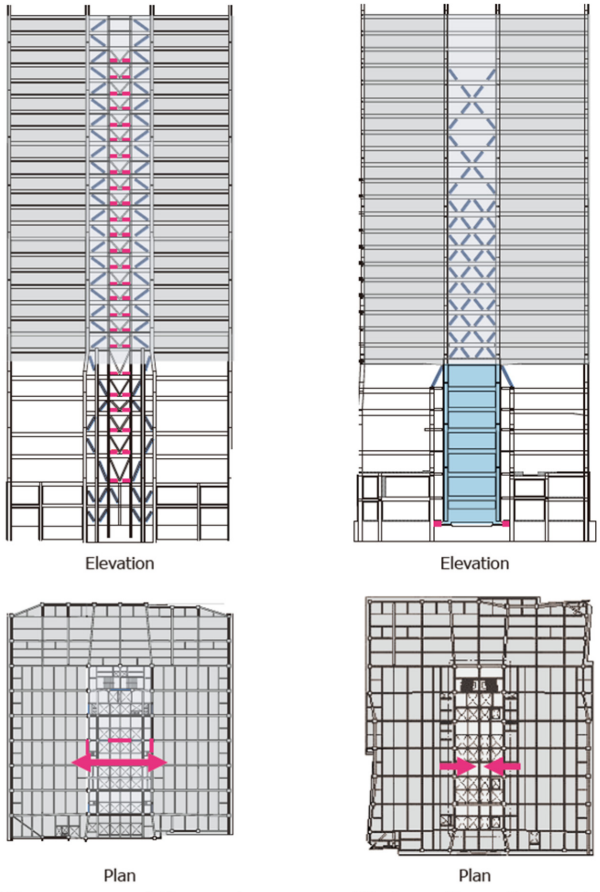
Figure 13. Clearance and Pit for Damper System.

be minimized. For TAMACHI TOWER, MEP vertical shaft space is arranged outside of sliding core and additionally plumbing for rooms arranged at core of typical floors are moving from inside to outside of core using L5 MEP floor where is the top of sliding core. As mentioned on building outline, transportation for office core at the lower level is limited. Therefore, passage between sliding core and surrounding frame where flexible joint are required is originally limited (Fig. 12).

Additionally, clearance assigned for this damper system causes loss of floor efficiency. However, highly efficient damper energy dissipation can reduce damper devices which are typically assigned on typical floors (Fig. 13). A comparison between conventional system and proposed system, tested in the early design stage[2)], shows that proposed system achieves equivalent structural performance under a Level 3 earthquake with only 10% of viscous dampers required by conventional system and succeeded in omitting all viscous dampers initially assigned on 2/3 of office floors. This optimization results in more efficient net floor area and creates additional usable space although losing some floor below L5 to provide clearance around sliding core. Utilizing this buffer, additional building well-being facilities such as small kitchen at the core and semi-outdoor circumstance winter garden – an innovative feather for Japanese high-rise offices – have been incorporated (Fig. 14, Fig. 15).

In terms of construction cost, this innovative system shows significant savings compared to conventional system, achieved through reductions in both steel tonnage and number of damping devices required (Table 2, Fig. 16).

This system also enables a more structurally efficient core wall design even in Japan. Given the high seismic hazard, Japanese buildings typically requires very stringent earthquake load designs and typically results in outstandingly heavy and thick core walls. However, this system can cap core wall's design load by slide bearings induced friction and damper capacity, hence concrete core wall system can be feasible with reasonable dimensions. Replacing superstructure frame from steel to concrete can provide another benefit of embodied carbon reduction. The proposed system achieves 6.5% structural embodied carbon saving compared to studied conventional steel moment frame. The primary saving is undertaken by steel tonnage saving derived from fewer damper devices, while the steel to concrete replacement further contributes to embodied carbon savings.



(Conventional System) *(Sliding Core System)*

Figure 14. Structural Frame Comparison.



(Winter Garden)



(Mini Kitchen beside Core)

Figure 15. Additional Building Function Generated by damper optimization.

Table 2. Structural Comparison

Structure System		Conventional Damper System	Innovative Damper System with Sliding Core
Superstructure Steel Tonnage (kg/m^2)		180 (100)[*1]	167 (93)[*1]
Number of Devices	Viscous Damper	220	24
	BRB	230	280
	Sliding Bearing	0	12
Damping Device Cost Index		100	60
Structural Cost Index		100	95

Notes:*1: Values in parentheses describes cost index where conventional system is assumed as 100

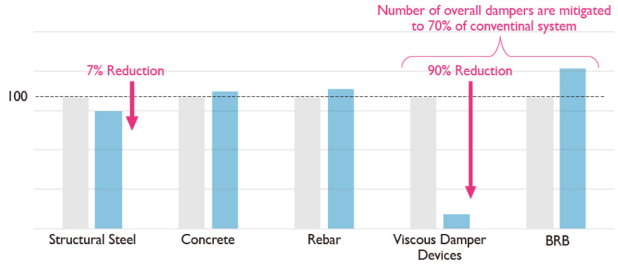


Figure 16. Structural Saving.

6. Conclusions

Innovative damper system using sliding core is introduced. This system provides new possibilities to achieve reinforced structural performance under severe earthquake in addition to coping potential issue which conventional system and/or base-isolation system involves. Additionally, utilizing recent Japanese building type, i.e. vertically combined mixed use, this system can obtain further optimized damper system and provide effective devices reduction. Furthermore, this system is expected to be further developed as adopted for other Japanese typical tall buildings.

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