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SEISMIC RETROFIT OF EXISTING STEEL REINFORCED CONCRETE BUILDINGS BY HIGH-PERFORMANCE TUNED MASS DAMPER

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Abstract

This paper describes several seismic retrofit projects of existing steel reinforced concrete (SRC) buildings for large earthquakes applying a newly developed high-performance tuned mass damper (TMD).

The TMD consists of a weight, four natural rubber bearings, and four oil dampers with unique failsafe functions. The weight is made of concrete filled in the steel frames to minimize the manufacturing cost. The natural rubber bearings have a function of stiffness of the TMD and large deformation capacity. The oil damper works not only damping of the TMD but also failsafe functions, which is automatically increasing its damping coefficient to suppress the excessive movement of TMD.

The characteristics of the TMD are determined through parametric studies to reduce the building responses both transverse and longitudinal directions considering the variation of building periods due to structural plasticization corresponded to the amplitude of earthquakes. By using the least amount of strengthening or improvement of ductility of structural members as a retrofit measure combining with the TMD, it is possible not to interrupt the operation inside the building and there is no disturbance under construction.

This paper first describes outlines of the target building and the applied TMD. Then the results of response analyses for large earthquakes are shown comparing the retrofitted responses with non-retrofitted ones. The control effects of the TMD under middle to large earthquakes are discussed. Finally, the construction process of the TMD is presented.

Keywords: tuned mass damper (TMD), seismic retrofit, existing building

1. Introduction

Seismic retrofit buildings applying tuned mass damper (TMD) for large earthquakes have been appeared in recent years. For example, two high-rise buildings in Japan [1], [2], and a government building and a hospital in Romania [3], [4] have been retrofitted. It is pointed out that the advantage of retrofitting by TMD does not inhibit the usability of indoor space [1], [4]. However, two themes applying TMD for seismic retrofit for large earthquakes are revealed [1]. One is to keep the mass of several hundred tons stable and to permit large stroke in any direction, and the other is to prevent system failure even when the earthquake level exceeds the assumed design level.

The target building mentioned in this paper is a 13-story steel reinforced concrete (SRC) office in Fukuoka city, Japan, which is completed in 1975.When it was subjected to the Fukuoka-ken Oki Earthquake (M=7.0) in 2005 and The 2016 Kumamoto Earthquake (M=7.3), whose epicenter is located approximately 100km south of Fukuoka, there was no severe damage of the structure. However, it had been found that the building did not have sufficient earthquake resistance strength through the diagnosis of earthquake resistance. Then, the authors have proposed retrofitting by the TMD combined with strengthening of shear walls in response to the owner's request of minimizing retrofitting members in the office space. The applied TMD consists of a weight constructed economically and easily, four rubber bearings which have large deformation capacity, and four high-performance oil dampers with unique failsafe functions which is automatically increasing its damping coefficient to limit the velocity of the TMD. The construction has completed only for 10 months in 2019.

In this paper, we first outlines the retrofit project and the target building and the applied TMD are described. Then the results of the response analyses for large earthquakes are shown comparing the retrofitted responses with non-retrofitted ones. The control effects of the TMD under middle to large earthquakes are discussed. Finally, the construction process of the TMD is presented and another project is additionally introduced.

2. Seismic Retrofit Project

2.1 Outline of target building

The target building is a 13-story SRC office as mentioned before. The overview and the location of the building are shown in Fig. 1. The plans of the typical floor and the roof floor are shown in Fig. 2. The size of the floor is 30 m x 22 m. The west and north elevations are shown in Fig. 3. The height of the building is 45.7 m. The building core is designed in the north-west side, in other words, earthquake-resistant walls are located eccentrically.

2.2 Retrofitting concept

The retrofitting concept was planned to aim not to put the retrofit members inside the building and to construct outside the building as possible. It was decided through various studies that shear walls with insufficient strength were reinforced and a high-performance TMD was set on the roof floor to reduce the building responses. Fortunately, the equipment on the roof floor was set in the core side, so that the TMD was able to be put on the best position to reduce both transverse and torsional displacement.

2.3 Configuration of TMD

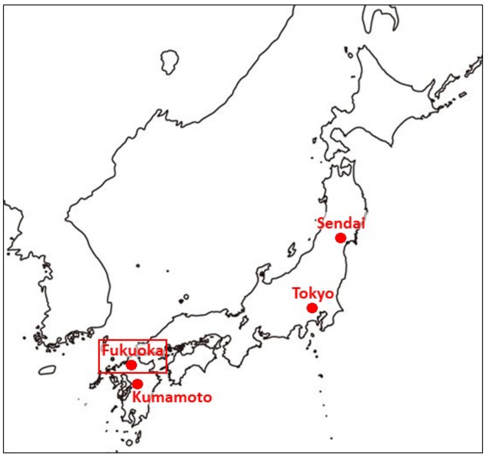
The overview of the applied TMD is shown in Fig. 4(a). The mass weighs 2,400 kN, which is approximately 5% of the effective building weight or 2% of the total. The weight of the TMD is made of concrete filled in the steel frames. Its dimension is 7.4 m x 10.1 m x 1.35 m. The stiffness is provided by four natural rubber bearings, whose diameter is 800mm, total rubber height is 200mm, and elastic shear modulus is 0.6 N/mm^2. The period of the TMD is 1.25 second, which is designed through several parametric studies of response analyses for large earthquakes. The damping devices are high-performance oil dampers which are set 2 units in X and Y directions, respectively. The designated force-velocity relationships is shown in Fig. 4(b). The damping coefficient is set referring to the theory of Den Hartog [5], and the velocity limitation characteristics, which are described in detail in reference [1], are determined by parametric studies. The maximum stroke of the TMD is plus or minus 40 cm in X and Y directions.

The base of the TMD is made of reinforced concrete and connected to the existing beams by post construction anchors.

2.4 Strengthening of shear walls

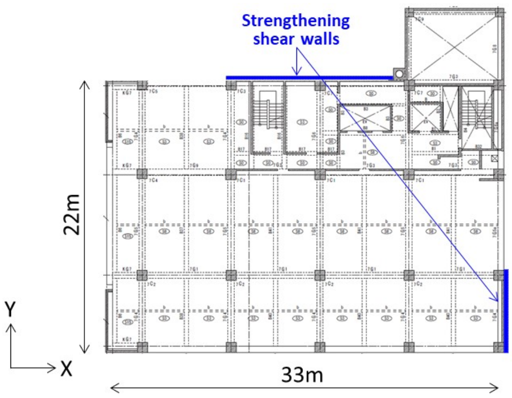
The location of the strengthening shear walls is shown in Fig. 2 and 3. They are set from 6th to 12th floors in X direction, and from 8th to 11th floors in Y direction. The thickness is originally 15 cm and increased up to 35 cm.

(a) Target building applying TMD

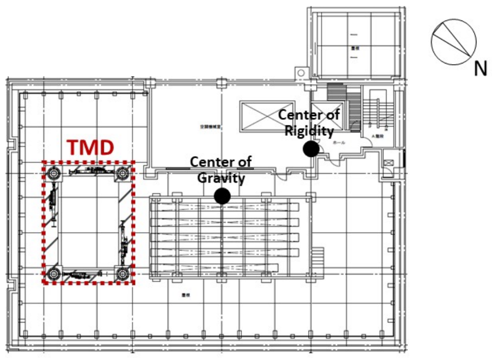


(b) Location of Fukuoka city

Fig. 1 – Overview and location of the target building

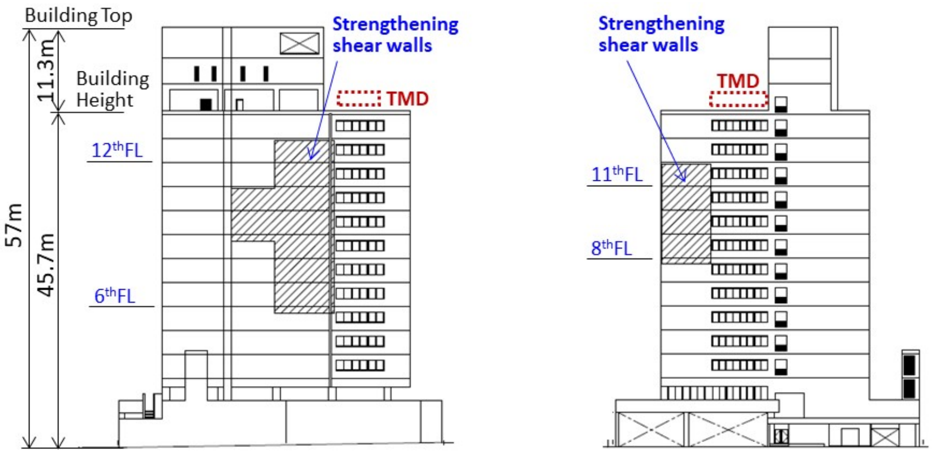


(a) Typical floor plan



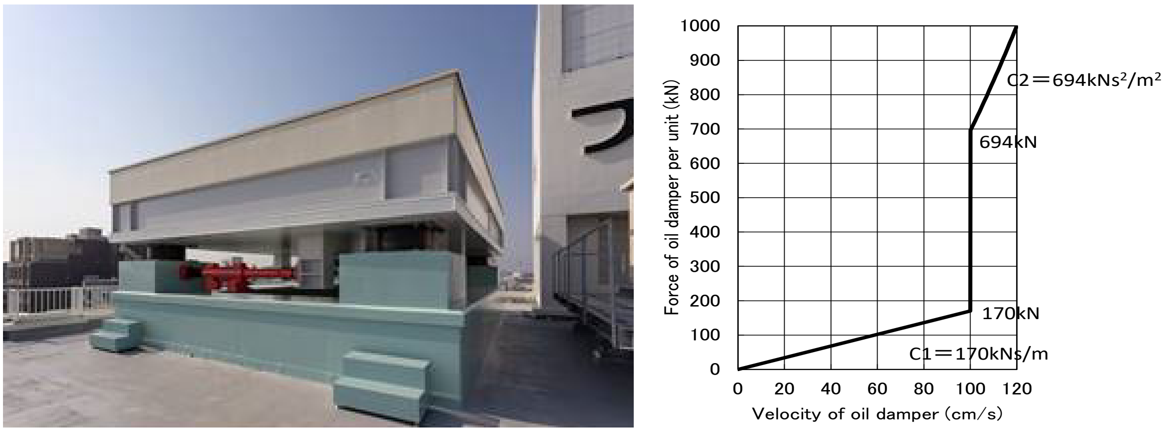
(b) Roof floor plan

Fig. 2 – Plans and location of retrofit members



(a) West elevation (b) North elevation

Fig. 3 – Elevations and location of retrofit members



(a) Overview of TMD (b) Force-velocity relationship of oil damper

Fig. 4 – Overview of TMD and characteristics of oil damper

3. Seismic Retrofit Design

3.1 Earthquakes and design criteria

Earthquakes for design are three usual simulated waves regulated by the Japanese code and three observed records shown in Table 1. Their pseudo-velocity spectra are shown in Fig. 5. They are input at the basement floor level. The criteria of the building are within 1/150 of story drift angle for the frames with earthquake-resistant walls, and 1/100 for the rigid frames without walls.

Table 1 – Earthquakes for design

Earthquake		Max. Acc. (cm/s^2)	Max. Vel. (cm/s)	Duration (sec.)
Japanese Code	Hachinohe-phase	308.0	41.0	120
	Kobe-phase	306.5	46.2	120
	Random-phase	309.6	37.4	120
Observed Record	El Centro 1940 (NS)	408.6	40.0	50
	Taft 1952 (EW)	397.4	40.0	50
	Hachinohe 1968 (NS)	264.1	40.0	50

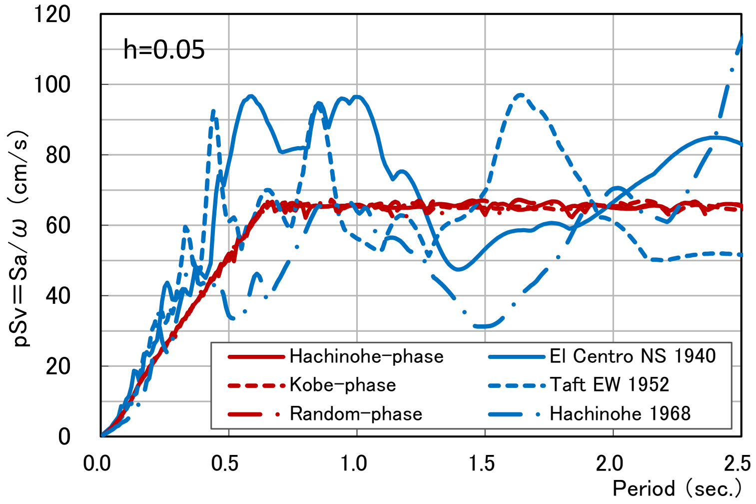


Fig. 5 – Pseudo-velocity spectra of earthquakes for design (damping factor h=0.05)

3.2 Analytical model

The analytical model is a three dimensional 17-story model shown in Fig. 6, which includes a basement floor and three penthouse floors. All the members have non-linear characteristics. Columns and beams are beam elements with degrading tri-linear model. Shear walls are replaced to equivalent truss elements, which are also provided with degrading tri-linear model. The TMD mass is connected on the roof floor with linear spring elements and non-linear dashpot elements, whose characteristics are shown in Fig. 4(b). The periods of the building model are 0.81 second in transverse (Y) – torsional direction and 0.54 second in longitudinal (X) – torsional direction, respectively. The structural damping ratio of 3% is assumed.

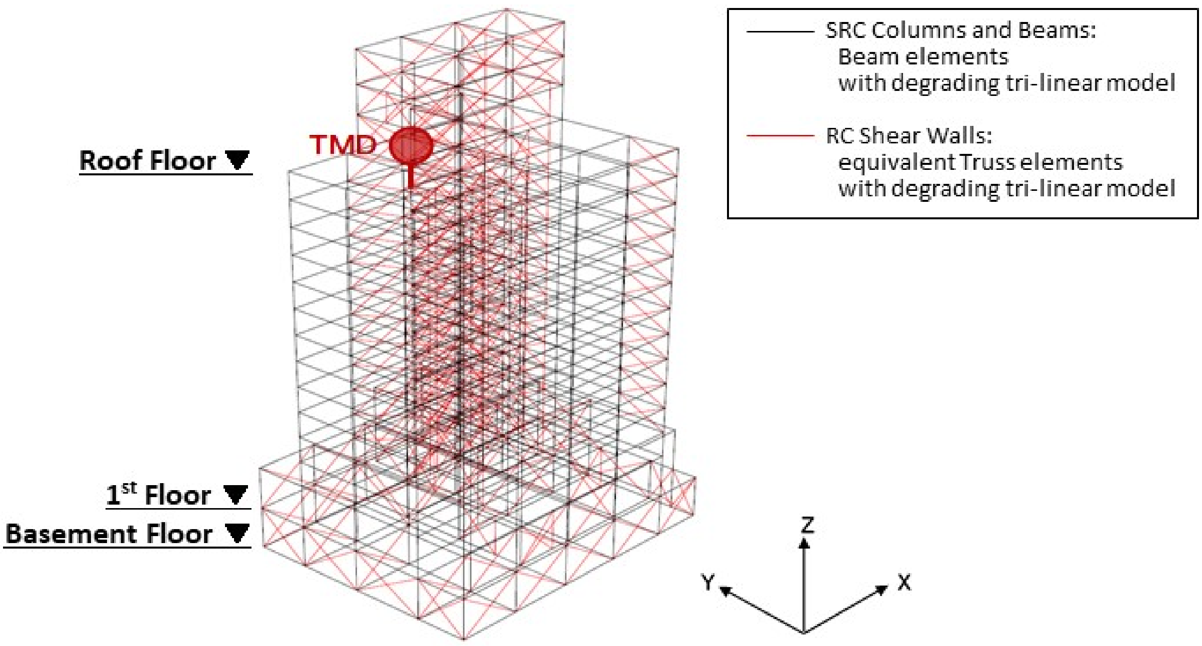


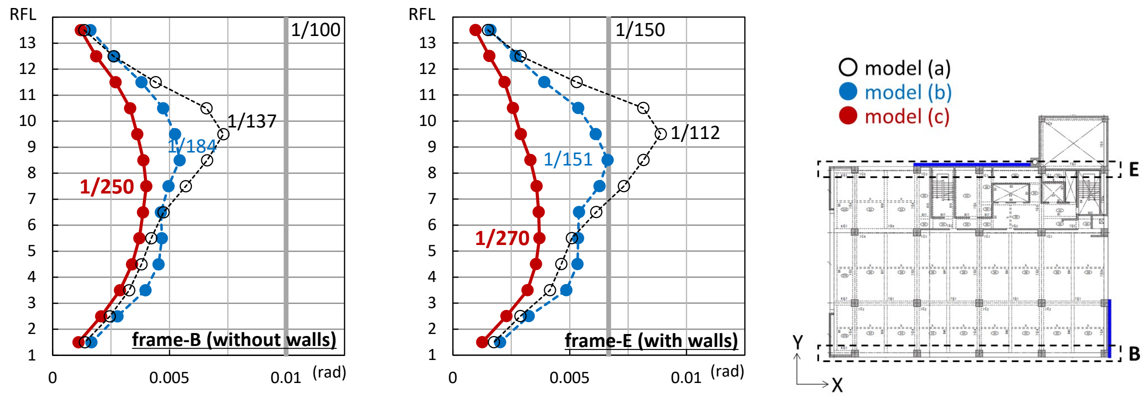
Fig. 6 – 3D analytical model

3.3 Results

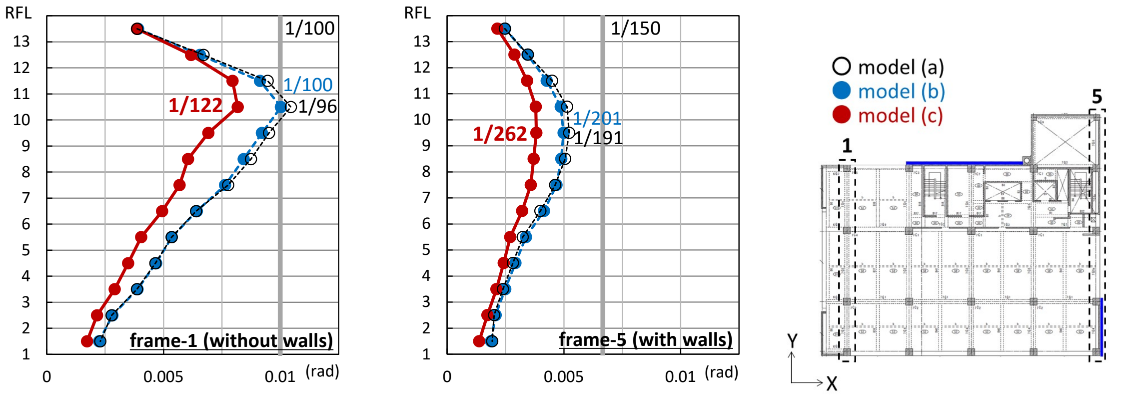
Simulation analyses are conducted for design earthquakes to see the effect of the building response reduction. Three types of analytical models are used below: (a) Original structure (without retrofit). (b) Structure with strengthening shear walls. (c) Structure with strengthening shear walls and the TMD.

Fig. 7 shows the maximum story drift angle. The building responses of model (c) are reduced by around 40% to 50% compared to the responses of the original structure (model (a)) in X direction, and around 70% to 80% in Y direction, respectively.

Fig. 8 shows the displacement time histories of the roof floor with or without the proposed TMD. By introducing the TMD, not only the maximum amplitude but also the duration of large vibrations (from 20 to 35 seconds) are significantly reduced.



(a) X direction, Random-phase earthquake input



(b) Y direction, Kobe-phase earthquake input

Fig. 7 – Distribution of maximum story drift angle

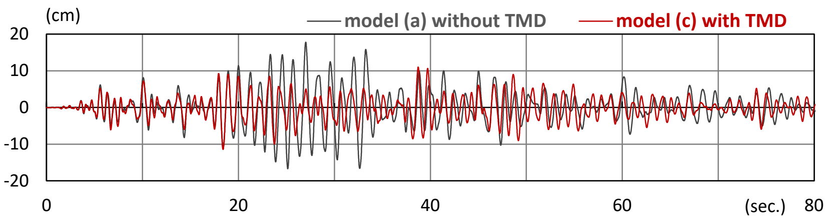


Fig. 8 – Displacement time histories of the roof floor in X direction for Random-phase earthquake

4. Response Reduction Effect by TMD under Middle to Large Earthquakes

The effect of the building response reduction under middle to large earthquakes is discussed in this section. The amplitude of earthquakes is set from 0.25 to 1.5 times as large as the retrofit design level shown in Table 1. The results of Random-phase earthquake input in X direction are shown below as an example.

The maximum response values of the simulated results are shown in Table 2. The equivalent building period is calculated from the peak of the response spectrum of the roof floor response time histories.

Fig. 9 and 10 show the comparison of the maximum story drift angle. To tune the stiffness of the TMD for the retrofit design level, the response reduction ratio is the best against the design level. However, we can see that the applied TMD is effective against middle (0.5 times as large as design level) to large (1.5 times as large as design level) earthquakes.

Fig. 11 shows the energy absorption. Comparing the energy absorption ratio with or without the TMD, we can see that the proposed TMD undertakes around 30% to 40% instead of the hysteretic energy caused by the structural plasticization.

Fig. 12 shows the maximum velocity of the oil damper and the TMD stroke, respectively. Along with rapidly increasing the damping force over 0.75 times as large as retrofit design input level, the TMD stroke is controlled within the stroke limit.

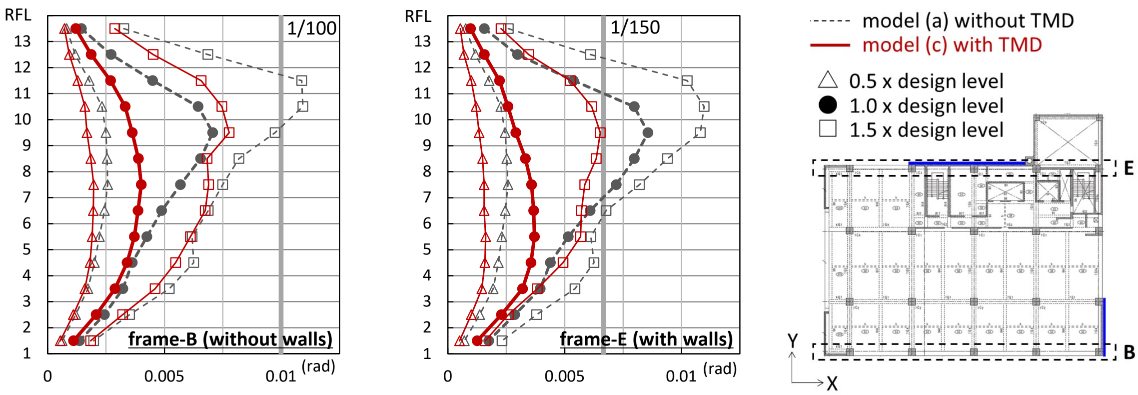


Fig. 9 – Distribution of maximum story drift angle with or without TMD under middle to large earthquakes

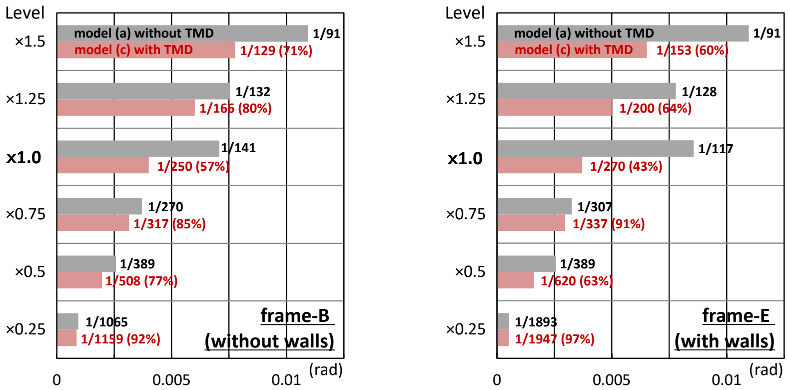
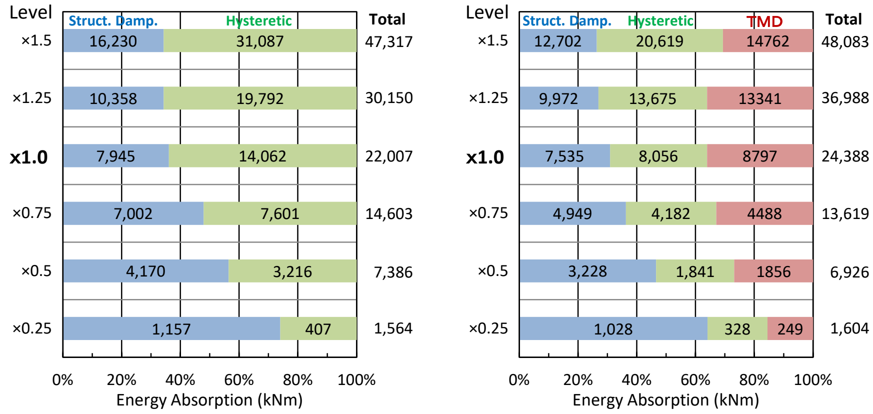
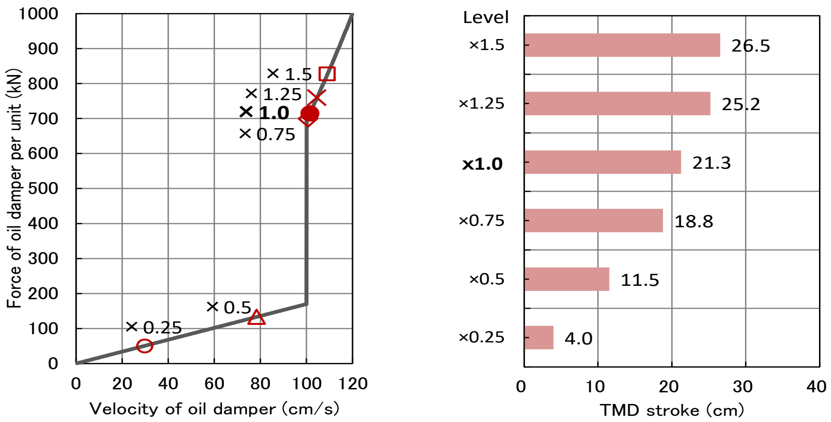


Fig. 10 – Comparison of maximum story drift angle with or without TMD



(a) Without TMD (b) With TMD

Fig. 11 – Energy absorption with or without TMD under middle to large earthquakes



(a) Force of oil damper (b) TMD stroke

Fig. 12 – Maximum Response of TMD under middle to large earthquakes

Table 2 – Maximum responses with or without TMD under middle to large earthquakes

Earthquake / Direction		Random-phase earthquake in X direction					
Amplitude of earthquake		×0.25	×0.5	×0.75	×1.0	×1.25	×1.5
Story drift angle frame-B (rad)	without TMD	1/1065	1/389	1/270	1/141	1/132	1/91
	with TMD	1/1159	1/508	1/317	1/250	1/166	1/129
	[reduction ratio]	[0.92]	[0.77]	[0.85]	[0.57]	[0.80]	[0.71]
Story drift angle frame-E (rad)	without TMD	1/1893	1/389	1/307	1/117	1/128	1/91
	with TMD	1/1947	1/620	1/337	1/270	1/200	1/153
	[reduction ratio]	[0.97]	[0.63]	[0.91]	[0.43]	[0.64]	[0.60]
Equivalent Period (sec)		0.64	0.82	0.91	1.05	1.08	1.22
TMD stroke (cm)		4.0	11.5	18.8	21.3	25.2	26.5
TMD velocity (cm/s)		30	78	101	102	105	109

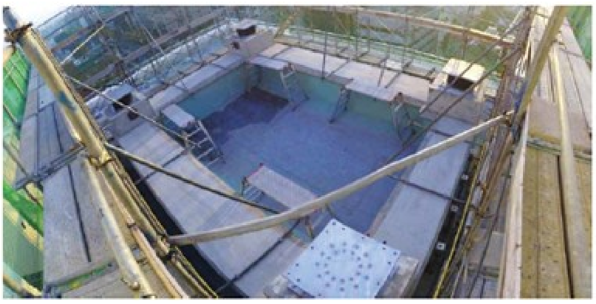
5. Installation of TMD

The construction started in June 2018 and was completed in March 2019 (10 months construction period). Fig. 13 shows the construction process of the applied TMD: (a) Remove the waterproof layer and set post-installed anchors. (b) Set reinforcing bars and the mold of the base of the TMD. (c) Put the rubber bearings. (d) Build the steel frame for the TMD weight. (e) Set an oil damper. (f) Casting of concrete of the TMD weight. The weight was made of concrete in this project, instead of steel, from the viewpoint of work operability, construction performance, cost, and so on.

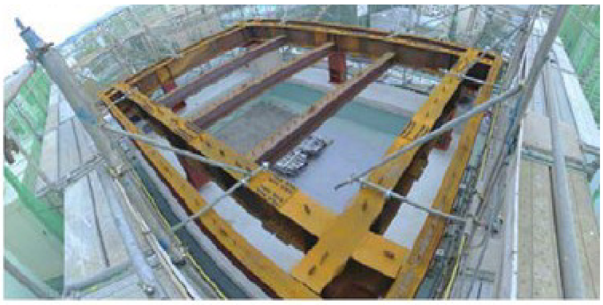
The applied TMD was efficiently constructed because of only stacking up relatively a few members. All the works were done outside of the building, then the usage of the office has not been interrupted both during construction and after completion.

(a) Set of anchors for the base

(b) Reinforcing bars of the base



(c) Set of rubber bearings



(d) Steel frame for TMD weight

(e) Set of an oil damper

(f) Casting of concrete

Fig. 13 – Construction process of the applied TMD

6. Conclusions

Seismic retrofit projects of existing buildings for large earthquakes applying the high-performance TMD were reported. The effect of response reduction of the building by the TMD under middle to large earthquakes was shown through the simulation analyses. The construction process of the TMD is also introduced.

Obtaining an owner's approval with the design concept in this paper, another high-performance TMD has been applied to an existing 11-story office building in Tokyo, combined with carbon fiber reinforcement to some columns, beams, and shear walls to ensure the deformation capacity. It was successfully completed in December 2019, and the construction period is only 7 months. Earthquake observation systems are installed into these buildings. The authors intend to report observation results in the future.

7. Acknowledgements

We received great support from FujiLand, Inc.. We also received enormous cooperation from SENQCIA Corporation and Molten Corporation in the development of the oil damper and the rubber bearing, respectively. We wish to express our deepest appreciation for their considerable efforts.

8. References

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