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Development of Large Tuned Mass Damper with Stroke Control System for Seismic Upgrading of Existing High-Rise Building

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Abstract

This paper describes a large tuned mass damper (TMD) developed as an effective seismic control device for an existing high-rise building. To realize this system, two challenges needed to be overcome. One was how to support a huge mass that has to move in any direction, and the second was how to control mass displacement that reaches up to two meters. A simple pendulum mechanism with strong wires was adopted to solve the first problem. As a solution to the important latter problem, we developed a high-function oil damper with a unique hydraulic circuit. When the mass velocity reaches a certain value, which was predetermined by considering the permissible displacement, the damper automatically and drastically increases its damping coefficient and limits the mass velocity. This velocity limit function can effectively and stably control the mass displacement without any external power. This paper first examines the requirements of the TMD using a simple model and clarifies the constitution of the actual TMD system. Then the seismic upgrading project of an existing high-rise building is outlined, and the developed TMD system and the results of performance tests are described. Finally, control effects for design earthquakes are demonstrated through response analyses and construction progress is introduced.

Keywords: Tuned mass damper, Oil damper, Retrofit, Existing building, Long-period and duration earthquake

1. Introduction

In the Great East Japan Earthquake of 2011, lots of high-rise buildings in metropolitan areas continued shaking with large amplitude and long duration. Even if there was no severe structural damage, residents of those buildings felt uneasy under such vibrations. Furthermore, metropolitan areas can be subjected to stronger long-period ground motions in a Nankai trough consolidated type earthquake, which is expected to occur in the near future. Consequently, demand has increased in Japan for measures to effectively reduce building vibrations. To reduce cumulative damage to old steel members and bodily sensation to vibration, high-performance devices with both sensitivity and toughness, such as oil dampers, are required. It is difficult, however, to find enough space to install such devices in existing buildings because structural core areas are often already occupied by original earthquake-resistant elements such as RC walls or steel braces. In these cases, the only alternative is to install devices into habitable room spaces. However, this always meets with strong resistance. Thus, there is a pressing need for seismic control technologies that do not affect these spaces.

TMDs (Tuned Mass Dampers) are well-known control devices. Since they can be installed on a specific floor such as a roof floor, they can be applied without affecting habitable room space. No conventional TMD systems, however, can control the responses of high-rise buildings in major earthquakes. To realize a TMD system that can, two problems need to be overcome. The first is to devise a rational mechanism that keeps the mass of several hundred tons stable, tunes the vibration period with that of the high-rise building, and permits several meters of translation in any direction. The second, which is more important and difficult, is to control large mass displacements of about 2 meters three-dimensionally, and to prevent system failure even when the earthquake level exceeds the assumed design level. Because of these problems, the target disturbances of conventional TMDs and hybrid TMDs have been limited to small earthquakes or wind forces. We have employed new techniques to solve these problems, and realized an earthquake-proof large TMD system for high-rise buildings.

In this paper, we first examine the requirements of the TMD using a simple analytical model and present a high-function oil damper, which is indispensable to the actual

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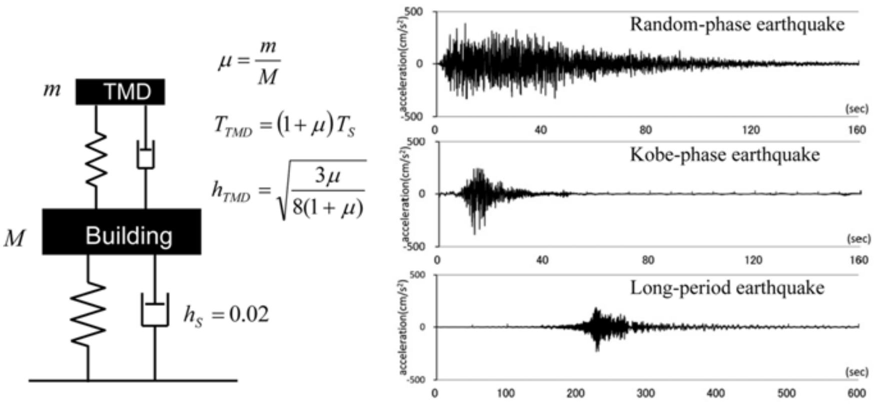


(a) 2DOF analytical model (b) Time histories of earthquakes

Figure 1. Analytical conditions for this study.

system. Then the seismic upgrading project of an existing high-rise building is outlined, and the developed TMD system and the results of performance tests are described. Finally, the control effects for design earthquakes are demonstrated through response analyses, and construction progress is introduced.

2. Fundamental Study on Performance Required for TMD

2.1. Analytical conditions for study

Firstly, we examine the fundamental dynamic response behavior of TMDs during earthquakes. Fig. 1 shows the analytical model and the ground motions used in this study. The parameters T_{TMD} and h_{TMD} are determined based on the optimum conditions given by Den Hartog (Den Hartog J.P, 1956). A structural damping ratio of 2% is assumed. We selected three simulated earthquakes with different phases. Two of them are normally used for seismic design in Japan: Random-phase and Kobe-phase. The third is a simulated long-period earthquake with 600-second duration.

2.2. Seismic response reduction effect of TMD

Fig. 2 shows response spectrums (structural displacement and TMD stroke) calculated with the 2DOF model shown in Fig. 1. The results without TMD (with only structural damping of 2%) are also shown for compari-

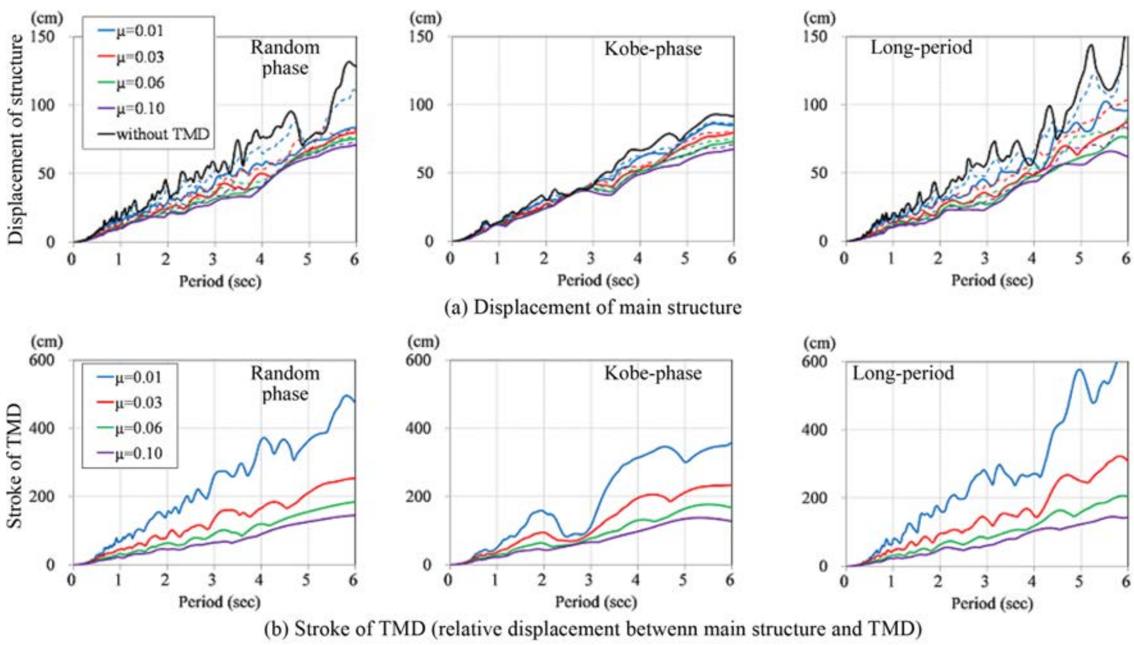


Figure 2. Response spectrum of 2DOF model.

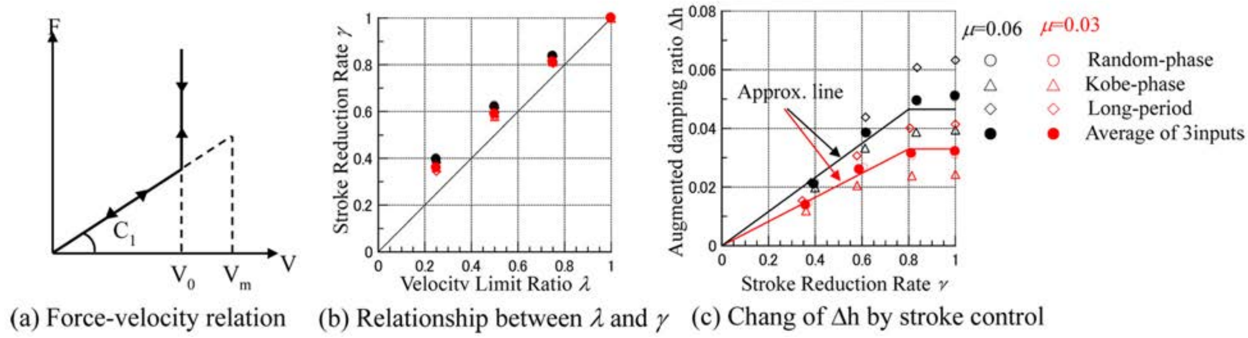


Figure 3. Change of stroke and additive damping by velocity limit.

son. The response reduction effect by TMD is clearly observed when the mass ratio reaches 3%, and gets close to saturation when the mass ratio is over 6%. On the other hand, it is confirmed that the TMD's stroke is greatly influenced by the mass ratio. Compared with the Random-phase earthquake, the structural response looks insensitive to the mass ratio in the Kobe-phase earthquake, which has shorter duration of principle motion. However it is observed that almost the same levels of TMD stroke occurred and the stroke is greatly influenced by the mass ratio as in the Random-phase earthquake.

In order to confirm the change of response reduction effect due to the fluctuation of TMD parameters, the maximum (worst) response displacement of the main structure controlled by the TMD with a variation of ±10% for period and ±20% for damping is also indicated in Fig. 2(a) with dotted lines. The influence of such fluctuation becomes small when the mass ratio *m* becomes large. Considering the robustness of control effects, it is recognized that at least 3% of the mass ratio is necessary and apploximately 6% of the mass ratio is more desirable.

2.3. Stroke control by velocity limitation

In realizing a TMD that is adaptable to a major earthquake, it is important to provide a failsafe function to prevent damages under an unexpected situation, such as an earthquake larger than the design earthquake. Here we introduce a special feature into the TMD's dashpot element. Fig. 3(a) shows the proposed force-velocity relation of a dashpot element. The damping force increases drastically when the relative velocity V between the weight of the TMD and the structure reaches the predetermined velocity V_0, and recovers smoothly to the original damping coefficient C_1 when V falls below V_0. The stroke can be controlled effectively by limiting the velocity (i.e., the kinetic energy) of the weight of the TMD. Fig. 3(b) shows the relation between the velocity limit ratio λ (=V_0/V_m) and the stroke reduction rate *g* (=S_0 / S_m). V_m and S_m are the maximum response velocity and stroke, respectively, with the linear damping of C_1. S_0 is a response stroke with proposed nonlinear damping. The average value with the period of 0-6 seconds is plotted in the figure. We can confirm that the stroke is controlled almost linearly by the velocity limit ratio λ, and is not affected by the input earthquakes. Fig. 3(c) shows the identified additive damping ratio Dh augmented to the structure by the TMD. The stroke reduction rate *g* is selected for the horizontal axis. Dh isnot affected while *g* is larger than 80%. Even when *g* is 60%, Dh decreases only about 25%. Thus, it is confirmed that the velocity limit for stroke control is effective.

3. Component to Realize TMD for Major Earthquake

3.1. Support mechanism of weight

As a weight support system, we adopted a simple suspended mechanism using strong wire cables. Though this mechanism allows the heavy weight to move smoothly in every direction with a target vibration period, it also has a limitation that needs to be considered. Fig. 4 shows the time histories of the normalized horizontal reaction force F_h (horizontal control force) of the pendulum for free vibration with no damping considering geometric nonlinearity. As the angle q becomes large, the influence of geometricalnonlinearity becomes conspicuous. Here we adopted 30 degrees as an allowable maximum angle, and this means that half the suspension length (Lsin30°=0.5L) is the permissible stroke (horizontal displacement) of the TMD.

3.2. Hydraulic circuit of oil damper

To realize the damping characteristics of Fig. 3(b), we

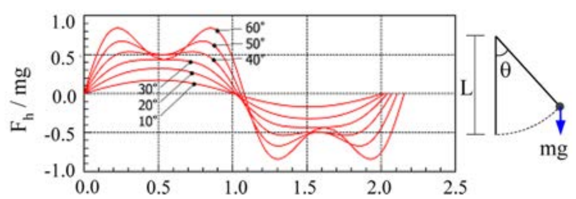
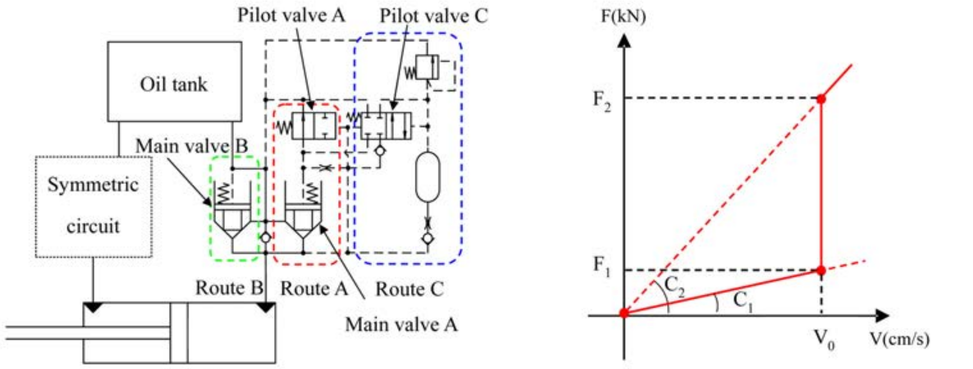


Figure 4. Time history of horizontal reaction force of TMD (Example of T=2.0 sec).



(a) Hydraulic circuit (b) Relationship between reaction force and velocity

Figure 5. Hydraulic circuit of oil damper to realize hardening function.

propose an oil damper with a unique hydraulic circuit shown in Fig. 5(a). The oil damper with this hydraulic circuit automatically switches its damping coefficient using the inner pressure (damper force) to realize the velocity limit function. The force-velocity relation realized by the hydraulic circuit is shown in Fig. 5(b). The circuit includes three different routes of pressure control valves, and when the damper force is lower than F_1, main valves A and B open and realize the initial damping coefficient C_1. When the damper force reaches F1 or the pressure is larger than the initial stress of the pilot valve A, pilot valve A closes and the main valve A closes consequently, and the damping coefficient switches to C_2, which is a characteristics of only main valve B. On the other hand, if the pressure starts to decrease and the damper force becomes lower than F_2, pilot valve C opens via hydraulic route C, which has been developed in the research of a switching oil damper (Kurino et al. 2006). In addition to this hydraulic circuit, we also add buffers at the both ends of the cylinder to soften the shock when the piston reaches the stroke end. An oil damper with these functions realizes a TMD capable of a high control effect and safety compatibly.

4. Seismic Upgrading Project

4.1. Outline of project

The target building, the Sinjuku Mitsui Building, was completed in 1974 and is located in Shinjuku area of Tokyo. It is a 220m-high structural-steel office building with 55 floors above ground. Its natural vibration period is 5.6 seconds in the longitudinal direction and 5.9 seconds in the transverse direction. Although it maintains enough antiseismic strength, the TMD was chosen as an effective countermeasure to long-period earthquakes expected in the near future. Considering the scale of the building, we planned to install TMDs with a total weight of 18,000kN, which is equal to 6.5% of the effective building weight. Considering the size of its parts, the construction method, and the influence of the additional load on the existing frame, we decided to divide the weight into 6 units and arrange them symmetrically on the roof floor.

Fig. 6(a) shows a photograph of the target building and Fig. 6(b) shows an elevation. Fig. 6(c) shows the arrangement of the TMDs on the roof floor. As shown in Fig. 6(b), a total of 48 high-performance oil dampers (Kurino et al., 2006) are also installed into the 5-10th floors in the transverse direction to increase the aseismic margin of this direction, whose vibration period is longer than in the longitudinal direction. To avoid affecting residents, the oil dampers are installed in the wall of the public space in the core area shown in Fig. 6(d), and construction work was carried out mainly at night and on holidays.

4.2. Configuration of TMD

Fig. 7 shows the configuration of the developed TMD for the target building. One unit of the TMD is composed of the following components: (1) A weight made of steel plates piled up on each other and bound by a post-tensioned steel bar, (2) Eight steel wires to support the weight, (3) Four oil dampers with a velocity limit function for the horizontal direction (horizontal damper), (4) Four oil dampers to reduce fluctuations of the wire's tension force against vertical earthquake (vertical damper), and (5) A steel covering frame. We placed the horizontal dampers radially in order to avoid interference with the weight in case of large displacement. Considering the movable range of the weight restricted by the size of the covering frame, we set the maximum stroke of the horizontal dampers to ±205 cm. The movable displacement of the weight is determined by the stroke of the horizontal damper, and the maximum displacement of 270 cm (q=20°) occurs in the diagonal direction, as shown in Fig. 7(a). In order to avoid imposing a heavy load on the existing steel members, a new supporting frame is constructed above the existing beam, as shown in Fig. 7(b). Fig. 8 describes the oil damper for the horizontal direction. The pressure regulating valves (Main valve B in Fig. 5(a)) are changed to a sim-

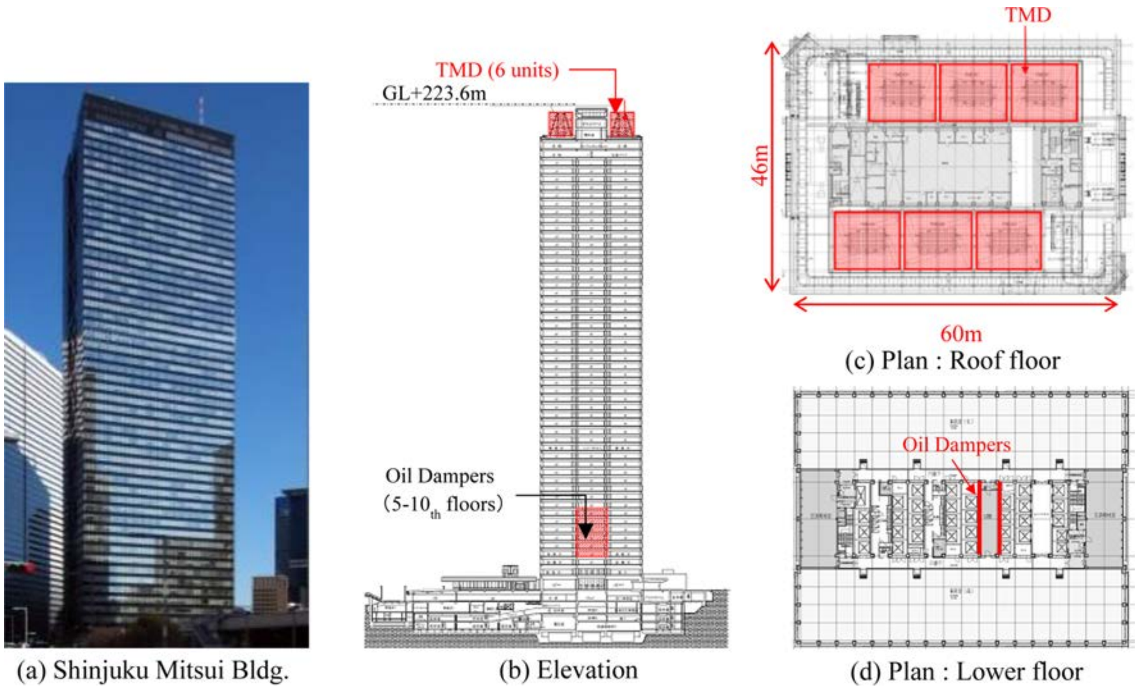


Figure 6. Target building and arrangement of TMD.

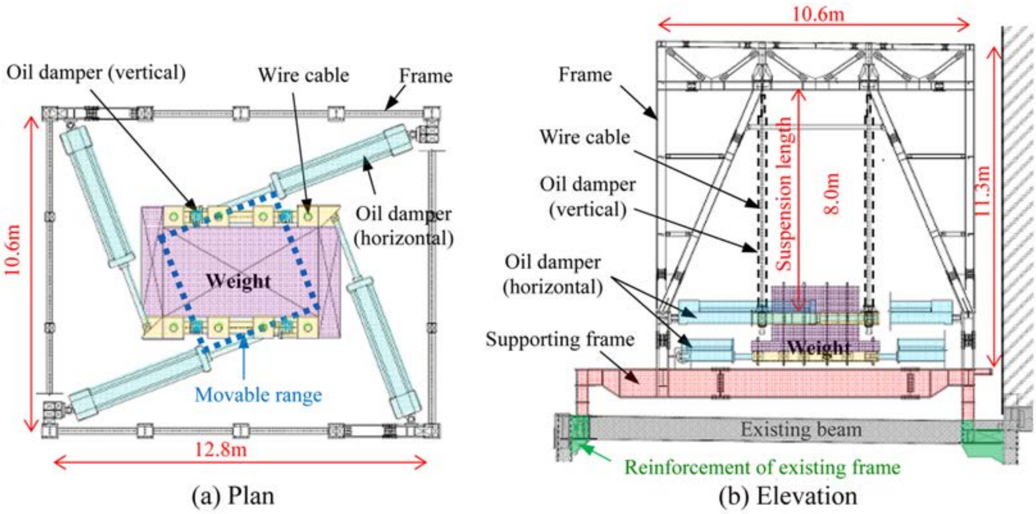
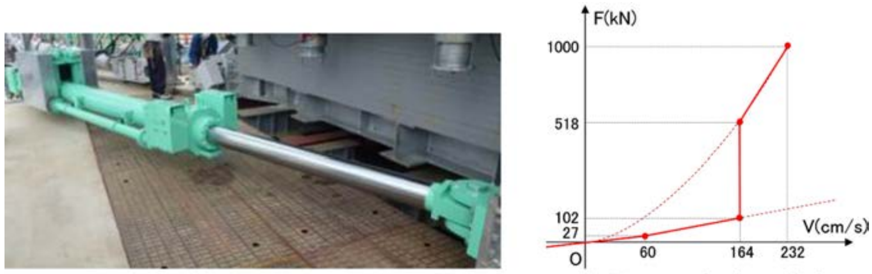


Figure 7. Configuration of TMD.

ple orifice for rationalization. The velocity at which the damping characteristic is switched is set to 164 cm/s (Force =102 kN). Its load capacity is 1000 kN. The length and weight of the horizontal damper are apploximately 8 m and 40 kN, respectively.

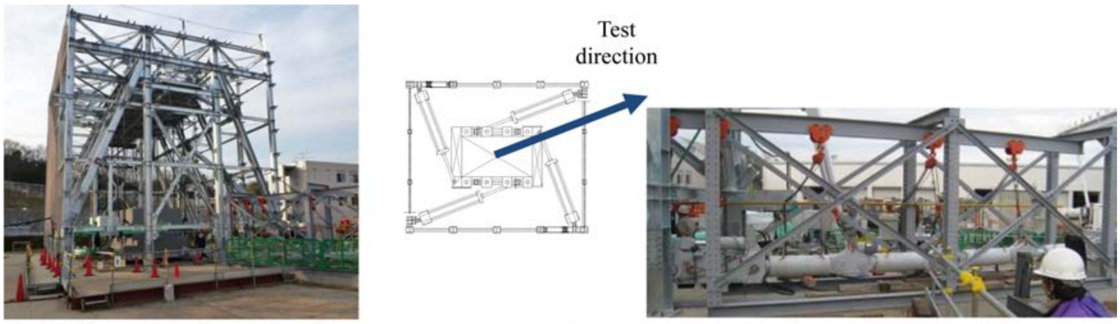
4.3. Experiment on full scale TMD specimen

To confirm the dynamic performance of the developed TMD, we conducted experiments on the full-scale specimen shown in Fig. 9(a). The test specimen was built in the testing field on a concrete foundation. There were two main purposes of the experiment. One was to examine the basic characteristics of the TMD, such as vibration period and smoothness of movement. The second was to confirm the performance of the newly developed oil damper with a velocity limit function. All of the components were the same as those of the actual TMD to be installed in the target building. We gave initial displacement to the weights in the test direction indicated in Fig. 9(b) by hydraulic jacks, and quickly released it to cause free vibration.



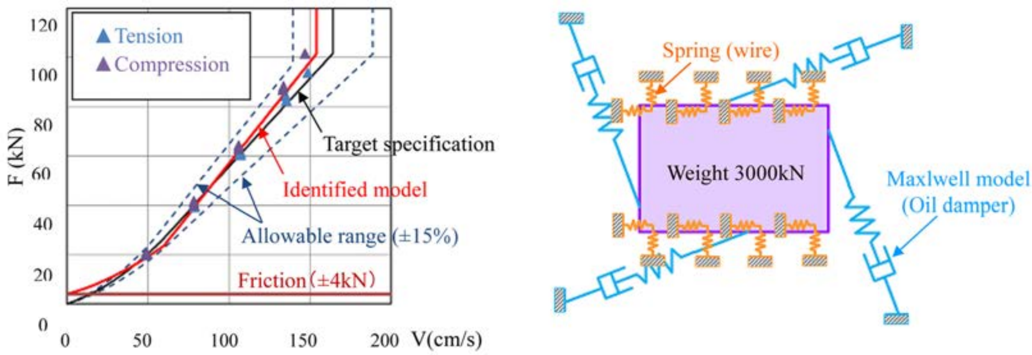
(a) Appearance (b) Force-velocity relation

Figure 8. Developed oil damper with velocity limitation function.



(a) Full-scale specimen (1 unit) (b) Hydraulic jack to give initial displacement

Figure 9. Test specimen TMD.

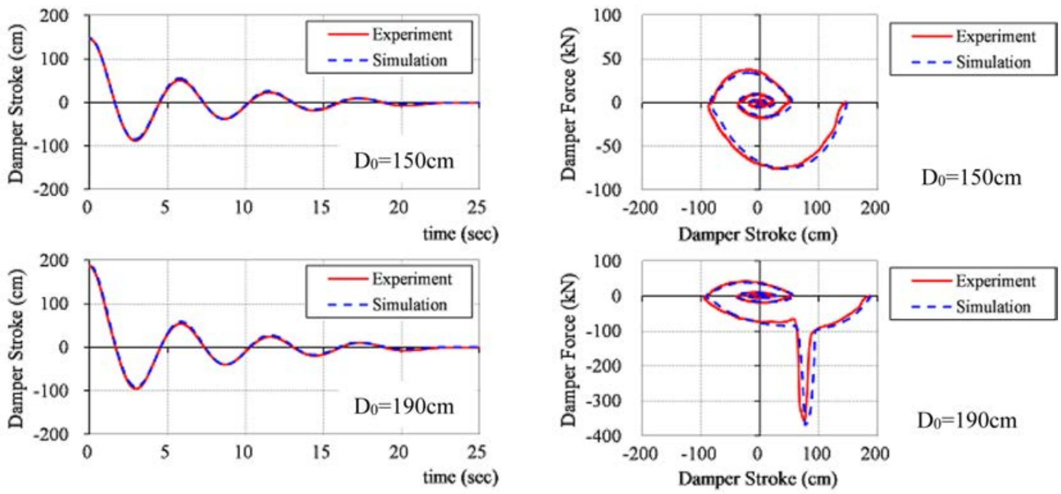


(a) Force-velocity relation of oil damper (b) Analytical model of TMD

Figure 10. Identified oil damper characteristics and analytical model of TMD.

Fig. 10 shows the force-velocity relation of the oil damper obtained from the test conducted by the manufacturer before shipping. The results of both the compression and tension sides under several velocity levels are plotted in the figure. The black line indicates the target specification and the red line shows the identified specification considering the damper's friction. The specification represented by the red line is to be used for simulation analyses discussed later. We can confirm that the experimental values satisfy the predetermined allowable range of ±15% shown by the dotted line in the figure. Fig. 10(b) shows the analytical model of the TMD. The model consists of mass, spring and dashpot, which represent weight, wires and horizontal dampers, respectively. It is confirmed by the prior test that the damping ratio of the pendulum without oil dampers is very small (about 0.3%). This means the suspension mechanism by wires works smoothly.

Fig. 11 shows the results of the free vibration test with



(a) Time histories of horizontal damper's stroke (b) Force-disp. relation of horizontal damper

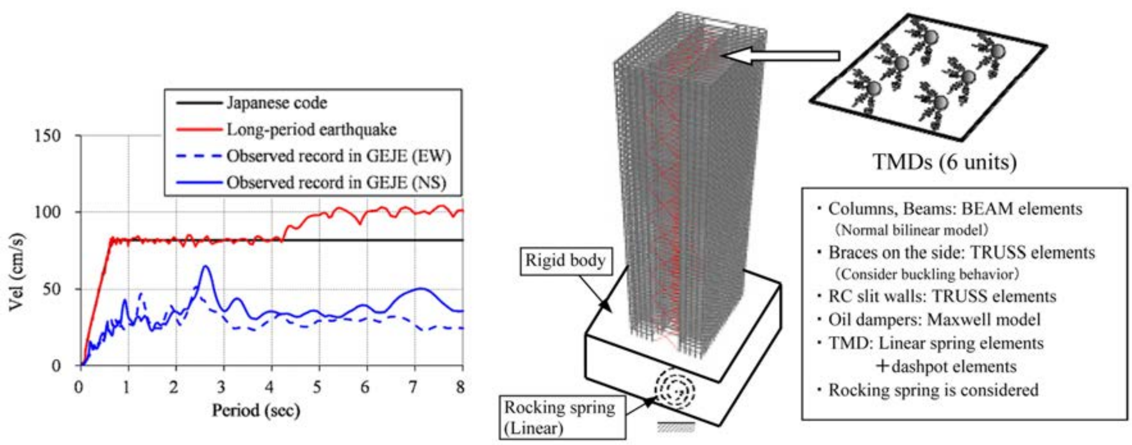
Figure 11. Results of free vibration test and simulation.

horizontal oil dampers. Two different initial displacements, 150 cm and 190 cm, are selected. In the 190 cm case, the oil damper's velocity limit function worked. From the force-displacement relations of the damper shown in Fig. 11(b), we can confirm that hardening phenomenon appears under the initial displacement of 190 cm as expected. The results of simulation analyses by the analytical model shown in Fig 10(b) are also indicated in Fig. 11. It is confirmed that the dynamic behavior of the TMD including the oil dampers can be accurately traced by the simple analytical model.

4.4. Seismic design

In seismic design, we selected the long-period earthquake which is identical to the one in Fig. 1(b) in addition to the usual simulated earthquakes regulated by the Japanese code. Fig. 12(a) shows velocity response spectrums. The spectrums of the ground motions observed at the site during the Great East Japan Earthquake (GEJE) of 2011 are also shown for comparison. As we can see, the level of the observed records in the GEJE is almost half that of the usual design earthquakes in Japan. Fig. 12(b) shows the three-dimensional analytical model of the building developed for the response analysis. To evaluate the validity of the model, a simulation analysis using records observed at this building in the GEJE was conducted. Fig. 13 shows the floor response acceleration spectrums on the roof floor. The simulation results "without TMD" agree very well with the observed records, and this confirms the accuracy of the developed building model.

To see the control effect of the proposed TMD in the Great East Japan Earthquake, we conducted simulation



(a) Velocity response spectrum of earthquakes (b) 3D analytical model

Figure 12. Analytical model and earthquakes for design.

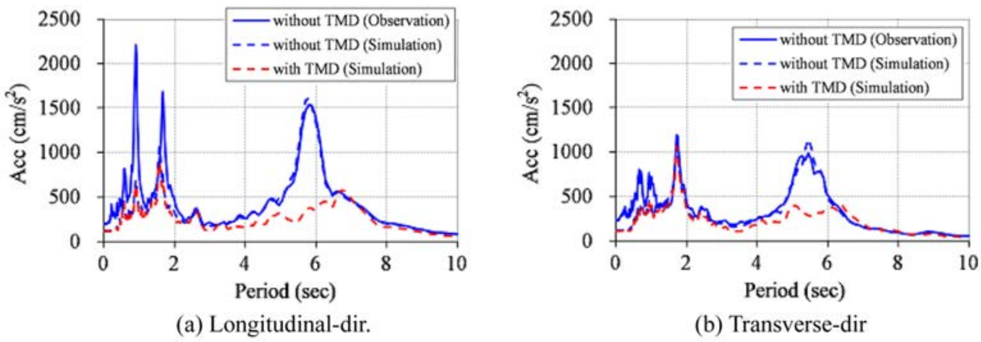


Figure 13. Acceleration response spectrum on roof floor for observed record in Great East Japan Earthquake.

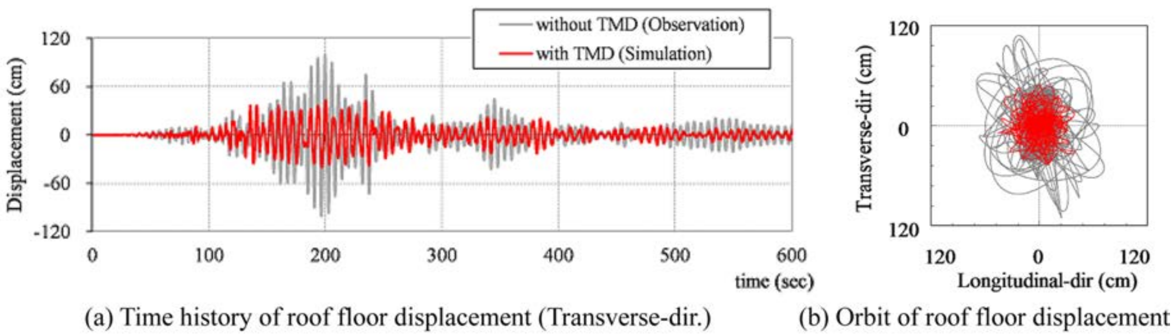


Figure 14. Response reduction effect to observed record in Great East Japan Earthquake.

analyses using the building model with the proposed TMD. Fig. 14(a) shows the displacement time histories of the roof floor. By introducing the proposed TMD, not only the maximum amplitude but also the bodily sensation duration are greatly reduced. Fig. 14(b) shows the displacement orbit of the roof floor. It is also observed that the proposed TMD can reduce the responses in every direction. The roof floor's acceleration response spectrum "with TMD" is also shown in Fig. 13. By introducing the proposed TMD, a large additive damping ratio (about 5%) is augmented to the building.

Fig. 15 shows the maximum story drift angle and the ductility factor of the beam element for a long-period earthquake. The results without TMD are also shown for comparison. With the proposed TMD, the building responses against the severe earthquake are also drastically reduced to almost half those of the original structure and the stresses of the old steel members are mostly kept within

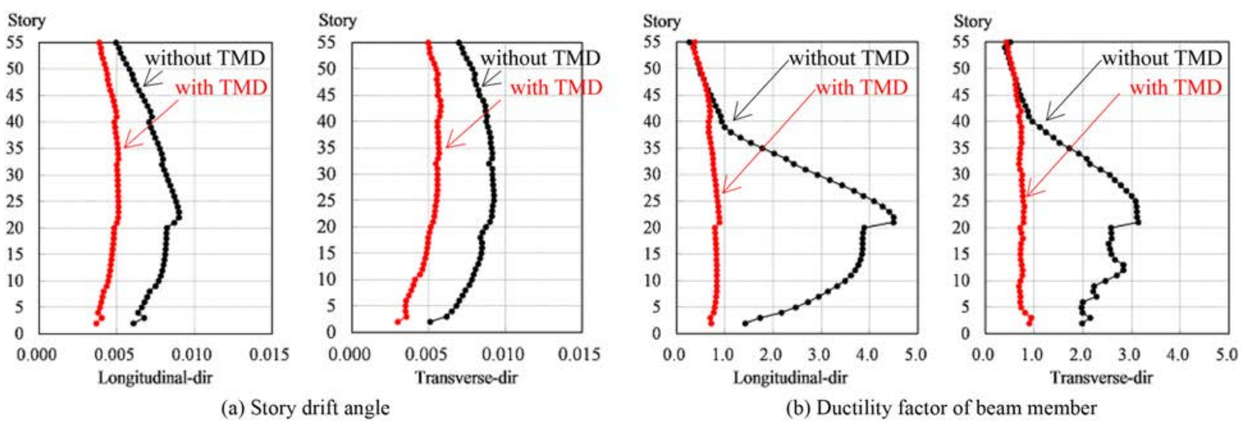
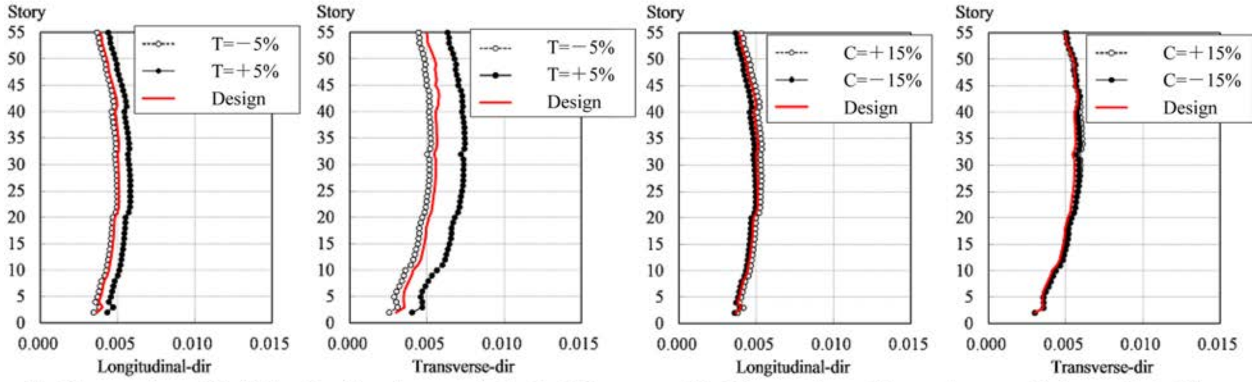


Figure 15. Distribution of maximum response for long-period earthquake.



(a) Fluctuation of building's vibration period of ±5% (b) Fluctuation of damping coefficient of ±15%

Figure 16. Influence of fluctuation of TMD conditions (Story drift angle for long-period earthquake).

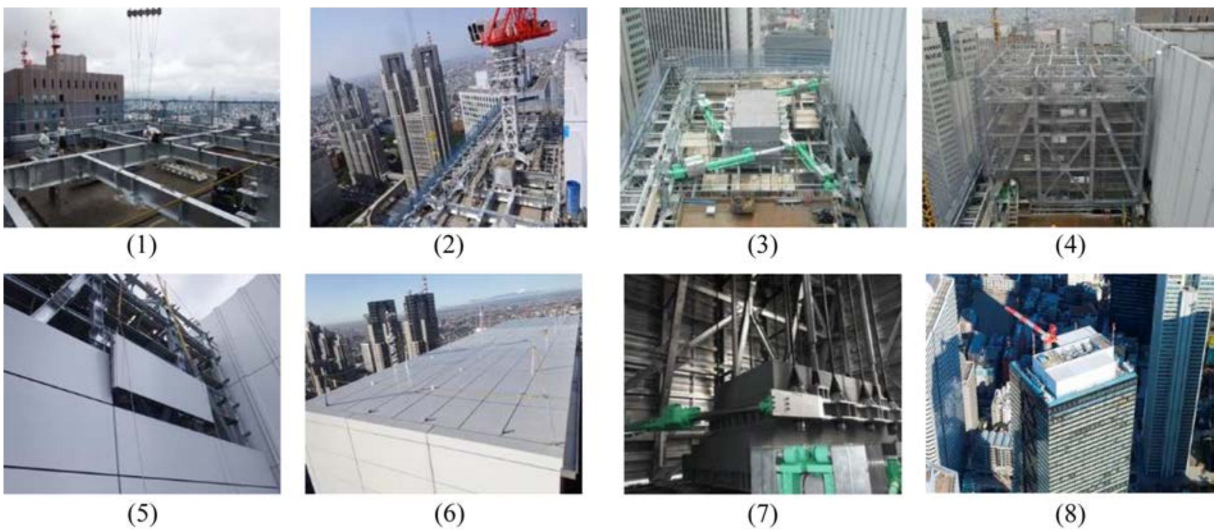


Figure 17. Progress of construction of TMD.

the elastic region.

Fig. 16 indicates the change of response reduction effect with fluctuation of TMD settings. We assume that a fluctuation of the building's vibration period of ±5% and a damping coefficient of the oil dampers of ±15%. Though a small change is observed in transverse period fluctuation, the change in response reduction effect with the proposed TMD is small.

4.5. Construction

Construction started in August 2013 and was completed in April 2015 (21 months). The TMD's construction procedure is outlined as follows (refer to Fig. 17). (1) Build up support frames on the reinforced existing beams. (2) Set up two tower cranes on the support frame. (3) Put the weight and horizontal oil dampers on the support frames. (4) Build the steel frame and lift the weight with hydraulic jacks and set the wires and vertical oil dampers. Then, release the jacks and introduce tension force into the wire and hang the weight. (5), (6) Set the exterior panel on the side and the roof surface of the frame. Fig. 17(7) and (8) show the interior and exterior of the TMD. This building houses an earthquake observation system that can record the TMD's behavior as well as the building's acceleration due to earthquakes or strong winds. We hope to discuss the control effect evaluated by the observed records in the future.

5. Conclusions

This paper reported a newly developed large tuned mass damper (TMD) for high-rise buildings adaptable to major earthquakes. First, we clarified the requirements for the TMD based on a fundamental study using a simple 2DOF model that represented a structure with the TMD system. Next, we discussed essential components required to realize an actual system, especially the oil damper with a unique hydraulic circuit. When the mass velocity reaches a certain value predetermined by considering the permissible stroke, the oil damper automatically and drastically increases its reaction force, and limits the mass velocity to effectively and stably control the mass displacement without requiring external power. Then we described the actual seismic upgrading project of an existing high-rise building. After demonstrating the results of performance tests conducted on a full-scale specimen built in the testing field, we discussed the control effect through earthquake response analyses. This TMD can be flexibly applied to any building regardless of its height or size without affecting habitable room space. We believe that it will contribute greatly to the seismic upgrading of existing high-rise buildings.

Acknowledgements

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