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# Compact TMD (Tuned Mass Damper) for Long-Period Earthquakes in an Existing High Rise Building

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## *Abstract*

Reinforcing existing high-rise buildings has become more important after the Great East Japan Earthquake. We installed a tuned mass damper (TMD) on the top of a high rise building as a countermeasure against long-period earthquakes. When a TMD is applied to an existing high-rise building, the size of the TMD tends to be increased to synchronize with the frequency of the building. Therefore, we developed a compact TMD that can be installed in a penthouse. The weight of the iron mass was 1400 t, which was approximately 2.4% of the superstructure's weight. Rubber bearings and bi-directional linear sliders were used to support the mass of the weight. Oil dampers were used to absorb the vibration energy of not only earthquakes but also strong wind. We adopted a larger value for the coefficient of damping than the theoretical value based on fixed-point theory so that we could fit the TMD within the building.

*Keywords: TMD(tuned mass damper); existing building; retrofit; seismic strengthening*

## 1. Introduction

Large long-period earthquakes shook skyscrapers during the Great East Japan Earthquake, which intensified the demand for countermeasures against long-period ground motions. Mass dampers are commonly utilized as long-period earthquake ground motion countermeasures not only for newly constructed buildings but also for existing high-rise buildings [1, 2]. Modifications that utilize seismic control members such as oil dampers require construction work over multiple floors. For mass dampers, however, the scope of the construction work is limited to their installation locations. In view that mass dampers are capable of efficiently controlling vibration, they are considered to be an effective means of modifying existing structures. However, serious consideration needs to be given to determine its suitability to different applications because gigantic masses will be required to achieve high degrees of vibration control, and enough installation space to accommodate the large displacement of a mass must also be made available.

In the case of the seismic control modifications works for the Shinjuku Nomura Building, the long-period earthquake ground motion countermeasure was adopted. Seismic control using conventional oil dampers and large-scale mass dampers degrades the external appearance of a building or extends the scope of the construction work into the tenanted portions of the building. In the present study, conventional large-scale mass dampers for earthquakes were made smaller and more compact and installed in a rooftop structure for seismic control modification in order to eliminate the effects on the building's external appearance and tenants. The vibration control and restrictions on the mass damper strokes were considered to realize intentionally high damping.

This paper summarizes the mass dampers applied to the Shinjuku Nomura Building and introduces a design method that is applicable to a 50-story building with similar features.

## 2. Summary of seismic control modifications

Figure 1 shows a representative floor plan and framing elevation diagram of the Shinjuku Nomura Building. The skyscraper is about 210 m in height and has a plan area of about 51 m × 33 m. The existing building has a rigid frame structure with ribbed steel plate walls installed along both the long and short sides of the building. There is a difference of more than 1 s in the natural periods of the lengths along the long and short sides. Damage to the boundary beams between the steel plate walls in the direction of the long side and deformation in the direction of the short side were issues of concern.

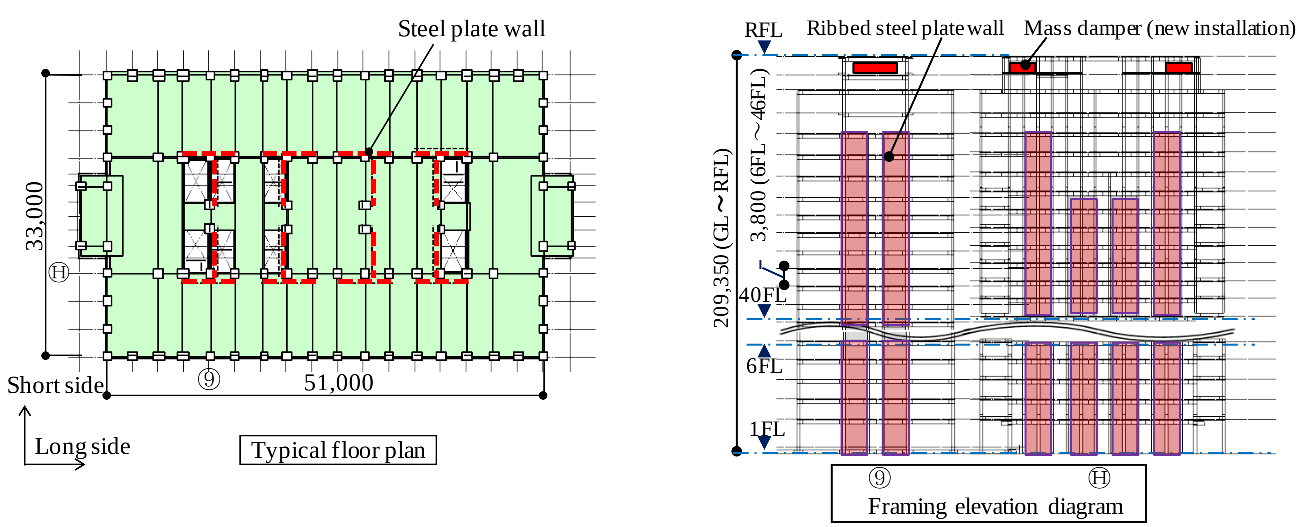


Fig. 1 – Representative floor plan and framing elevation diagram of Shinjuku Nomura Building

It was decided to install two units of mass dampers in the machine room located on floor 53 (i.e., the top floor) to reduce damage to the boundary beams along the long side of the building and deformation along the short side as a part of the seismic modification work. These mass dampers included inhibited strokes to intentionally make the damping high so that they could be installed in the limited space available within the machine room. Slider-type weights supported by linear guides and double-layered laminated rubber were adopted to reduce the height and realize a compact system.

Figure 2 shows the configuration of the mass damper. Table 1 lists the constituent component. The masses of the mass dampers were made of steel with a total weight of about 7000 kN. The ratio of the mass weights (for two units) with respect to the aboveground building weight was about 2.4%, and the ratio of the generalized mass of the building to the masses of the mass damper was about 7%. The weight of the masses was supported by a two-phase support mechanism comprised of four units of double layered laminated rubber (N1) and four units of two-way linear guides (S1).

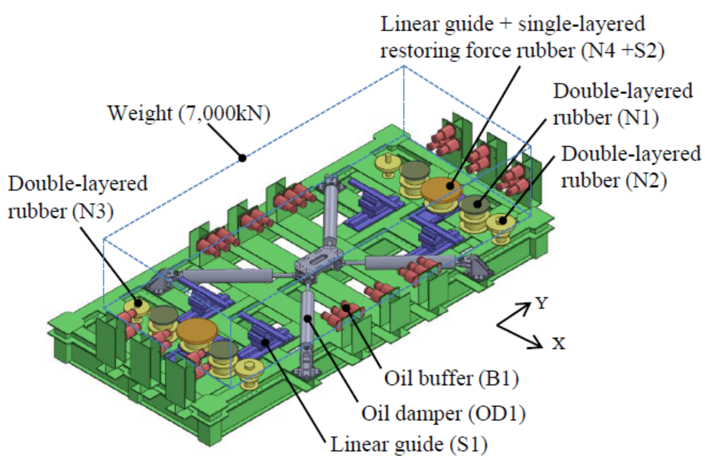


Fig. 2 – Composition of our mass dampers

Table 1 – List of constituent components of our mass dampers

| Member name | Function |
|---|---|
| N1:<br>Double-layered rubber | ・Supports perpendicular loads (masses) when TMD control or horizontal deformation (small) occurs.<br>・Effective in X and Y directions. |
| N2 and N3:<br>Double-layered rubber | ・Used for adjustment of periods.<br>・No support of vertical load.<br>・Effective in X and Y directions. |
| N4:<br>Single-layered restoring force rubber | ・No support of vertical load.<br>・Effective in X direction. |
| S1:<br>Linear guide | ・Bearing for linear drive.<br>・Vertical loads supported when horizontal deformation (large) occurs. |
| S2:<br>Linear guide | ・No support of vertical load.<br>・Effective in X direction. |
| OD1:<br>Oil damper<br>Stroke:±1000 mm | ・Absorbs energy of earthquakes and wind.<br>・Effective in X direction. |
| B1:<br>Oil buffer | ・Failsafe mechanism for large deformations due to earthquakes and wind response (stopper for TMD). |

The rigidity of the mass dampers was determined according to the double-layered laminated rubber (N1) and double-layered restoring force rubber (N2 and N3). The restoring force was only exerted along the long side in order to synchronize the mass damper in this direction with short frequencies. Single-layered restoring force rubber (N4) was installed on the one-way linear guides (S2) to adjust the rigidity.

The mass dampers used velocity-dependent oil dampers (OD1) with four units having a 1.0-m stroke arranged diagonally at 45° to minimize the required space.

Oil buffers (B1) were installed on the four peripheral sides of the masses as a failsafe mechanism against an intended deformation.

The mass dampers were fitted with a two-phase support mechanism that uses double-layered laminated rubber (N1) for smaller displacements while the building is at standstill or under strong winds and linear guides (S1) for larger displacements during earthquakes, as shown in Figure 3. The linear guides (S1) that comprise this support mechanism featured upper and lower clearances of a few millimeters that were allocated to the block section so that the mass weights would not be supported with smaller displacements due to strong wind or the like to ensure that no frictional force acts on the structure. Figure 4 shows the transition of the mass weight support bearing load. When a significant displacement occurs due to an earthquake or the like, the overlapping areas of the layered laminated rubber are eliminated. The double-layered rubber with a small shape factor then buckles rendering it incapable of supporting the masses. The masses supported by the double-layered laminated rubber follow to experience a displacement which eliminates the initial gap in the block section. Once in contact, the linear guides then take over to support the masses in place of the double-layered laminated rubber. Adopting such a two-phase support mechanism made it possible to avoid the impact of friction on the linear guides due to strong winds while still realizing a mechanism capable of tracking larger displacements of masses in a stable manner during earthquakes.

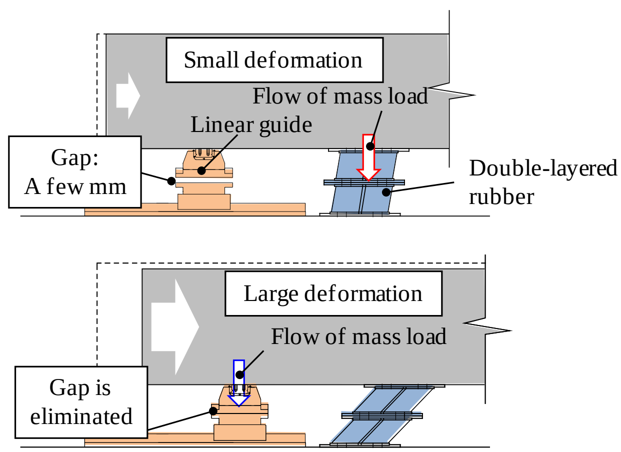


Fig. 3 – Overview of two-phase support mechanism

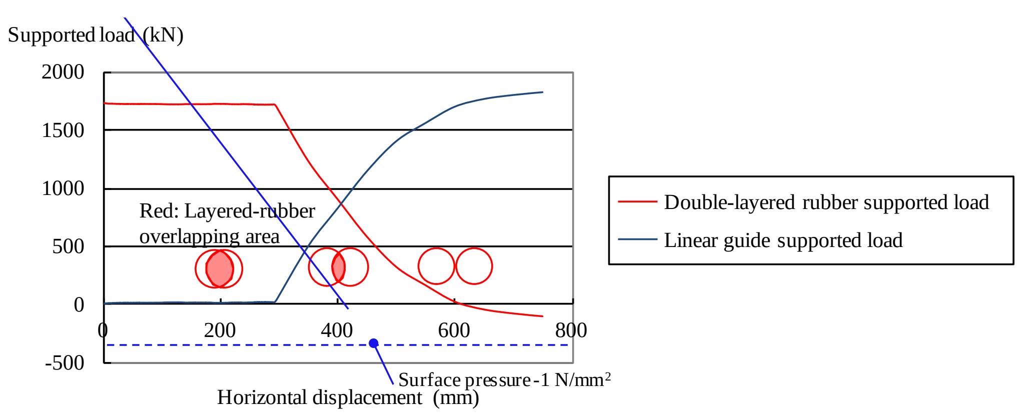


Fig. 4 – Transition of the mass weight support bearing load

## 3. Design example

This section presents the design of an equivalent shear model for a 50-story building having a triangular distribution for its elastic durability and initial rigidity, as shown in Figure 5. The restoring force characteristics were set with the equivalent viscous damping and a proportional rigidity of $h$ = 2% for the primary mode.

The design consisted of a set of slider-type compact mass dampers inside the structure on the top floor. The damping force derived from the oil dampers, and the restoring force derived from the laminated rubber, as shown in Figure 6. The damping force can be expressed by a bilinear model that starts providing relief at the velocity $V_1$, and the restoring force can be expressed by an elasto-plasticity model comprising a linear model representing laminated rubber and a frictional force provided by linear guides ($Q_f = 0.0025 \times M$).

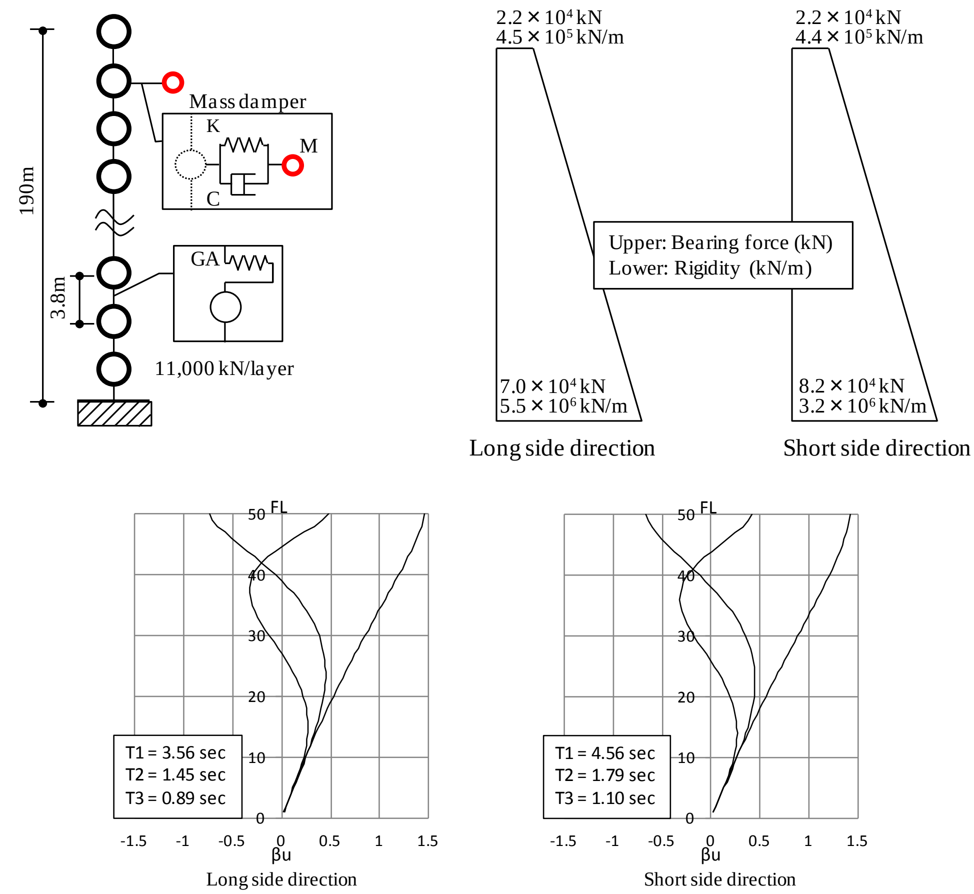


Fig. 5 – Structural analysis model for design

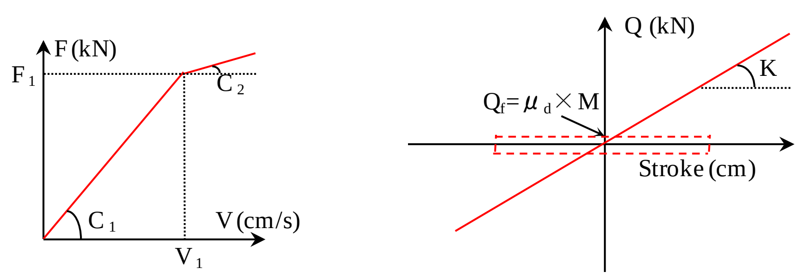


Fig. 6 – Modeling of damping and restoring forces

Three seismic wave types were adopted for examination: two waves from national specifications (a random phase wave and Kobe phase wave) and the wave of a long-period earthquake [3], as shown in Figure 7.. Table 2 lists the examined earthquakes.

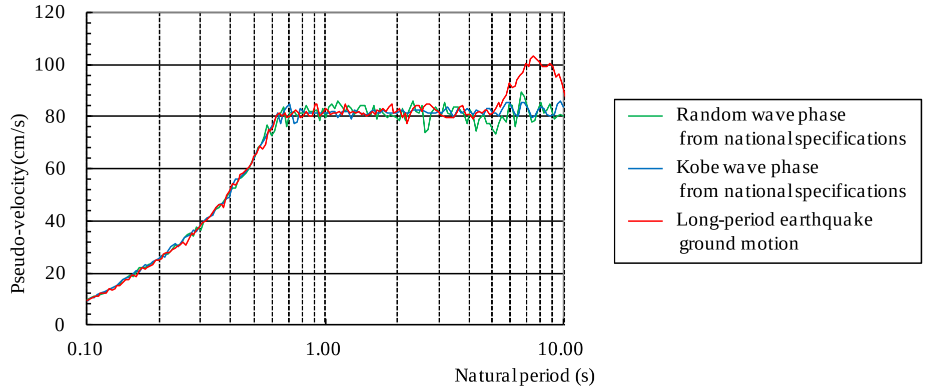


Fig. 7 – Seismic motions for examinations: simulated velocity response spectrum

Table 2 – List of earthquakes for examination

| Earthquake name | Max. acceleration ($m/s^2$) | Sustained time (sec) |
|---|---|---|
| Random wave phase from national specifications | 3.62 | 120.0 |
| Kobe wave phase from national specifications | 3.56 | 120.0 |
| Long-period earthquake ground motion | 3.26 | 920.0 |

The optimal damping and rigidity were calculated for the design of the mass dampers by using the optimal synchronization conditional expression [4] represented by Equation (1), (2). This was derived by Den Hartog. The synchronization was to the primary mode of the building:

$$k_a = \frac{\mu}{(1+\mu)^2} M_1 \omega_0^2 \tag{1}$$

$$c_a = 2\mu M_1 \omega_0 \sqrt{\frac{3\mu}{8(1+\mu)^3}} \tag{2}$$

where $M_1$ is the generalized mass evaluated during the mass damper installation phase, $\omega_0$ is the fundamental circular frequency of the intended vibration mode for the building, and $\mu$ is the mass ratio of the generalized mass for the building and mass damper.

Adopting the optimal damping coefficient $c_a$ from Equation (2) causes the stroke of the mass damper to be extremely large, which makes it impossible to install the mass dampers inside a rooftop structure. The mass ratios shown in Figure 8 were therefore used as parameters to derive the critical relationship between the damping factors (damping coefficients of damper/optimal damping coefficients) and building to set reasonable damping coefficients. The mass ratios and damping factors were determined by setting the plasticity rate of the level with the highest relevance as the plasticity rate, the cumulative plastic deformation ratio of the boundary beams along the long side of the building to 1.5 or lower, the stroke of the mass dampers to 75 cm or less, and the inter-story deflection angle along the short sides of the building to 1/125 or less as criteria. The long-period earthquake (along the long sides) with the largest response and the random phase of the national specifications (along the short side) were selected as seismic waves for examination.

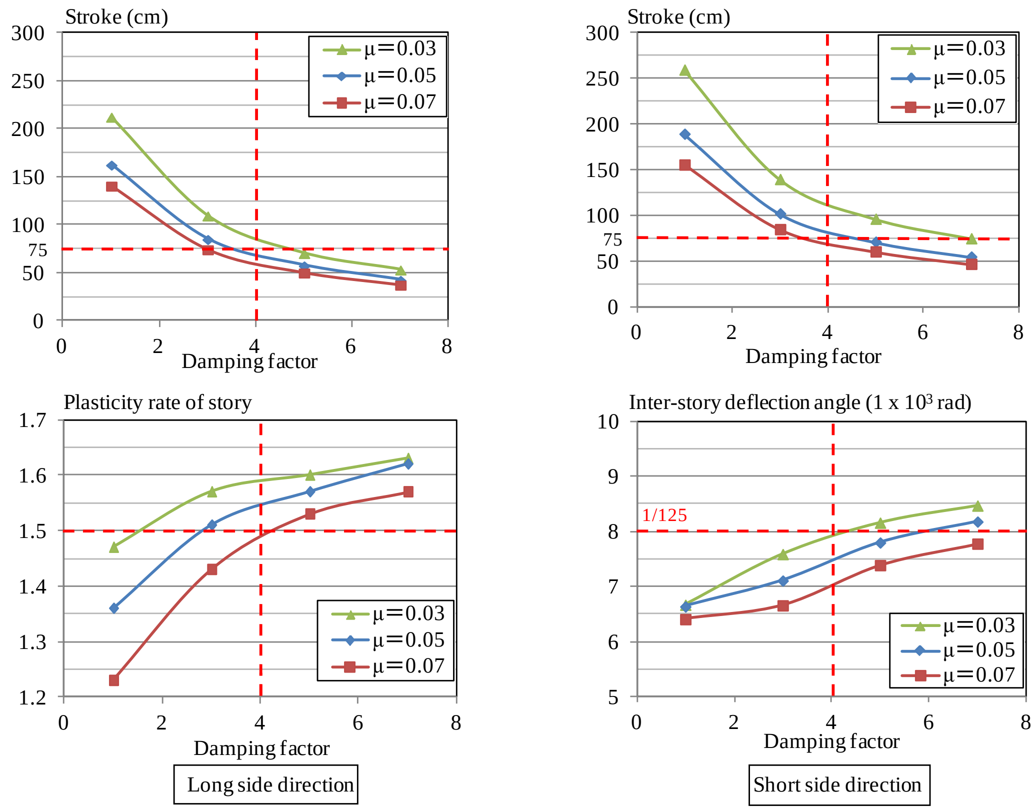


Fig. 8 – Relationship between damping factors and respective parameters

As shown in Figure 8, the mass damper stroke, plasticity ratio of the layers, and inter-story deflection angles decreased as the mass ratio increased. The stroke decreased and the building response increased as the damping factor increased. In order to satisfy the criteria based on such results, the mass damper was set so that the mass weight was 14,000 kN, which was equivalent to the mass ratio for the mass damper of about $\mu = 0.07$, and the damping factor was set to about 4 in the direction of the long sides. Table 3 presents the adopted specifications, which are herein referred to as adopted values. The specifications derived with Equation (1) are referred to herein as the optimal values.

Table 3 – Specifications of mass dampers

| Direction | Mass ratio μ | Optimal value | | Adopted value | |
|---|---|---|---|---|---|
| | | Rigidity kN/m | Damping coefficient kN/(m/s) | Rigidity kN/m | Damping coefficient kN/(m/s) |
| Long side | 0.074 | 3.77 | 0.74 | 3.77 | 2.96 |
| Short side | 0.068 | 2.33 | 0.56 | 2.33 | 2.96 |

An examination was conducted prior to the installation of the mass dampers. The examination of the adopted and optimal values during an earthquake and with a strong wind is shown below.

Figures 9–11 show the results for the earthquake. Although the values varied depending on the seismic waves, the designed mass dampers satisfied the criteria by significantly reducing the inter-story deflection angle to less than 1/100 in the direction of the short sides of the building compared to the values obtained prior to installation. Furthermore, the plasticity ratio of layers in direction along the short sides was also reduced significantly when compared to the value obtained prior to their installations to under 1.5, which satisfied the criteria. The mass damper stroke was kept under 75 cm, which satisfied the criteria.

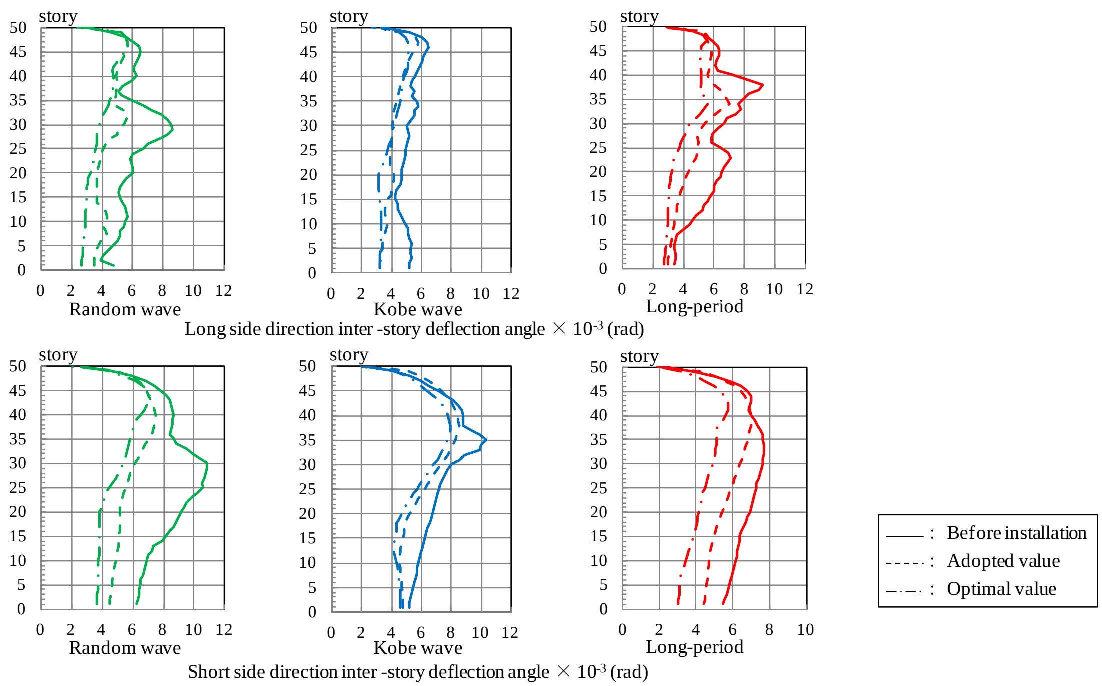


Fig. 9 – Response results: inter-story deflection angles

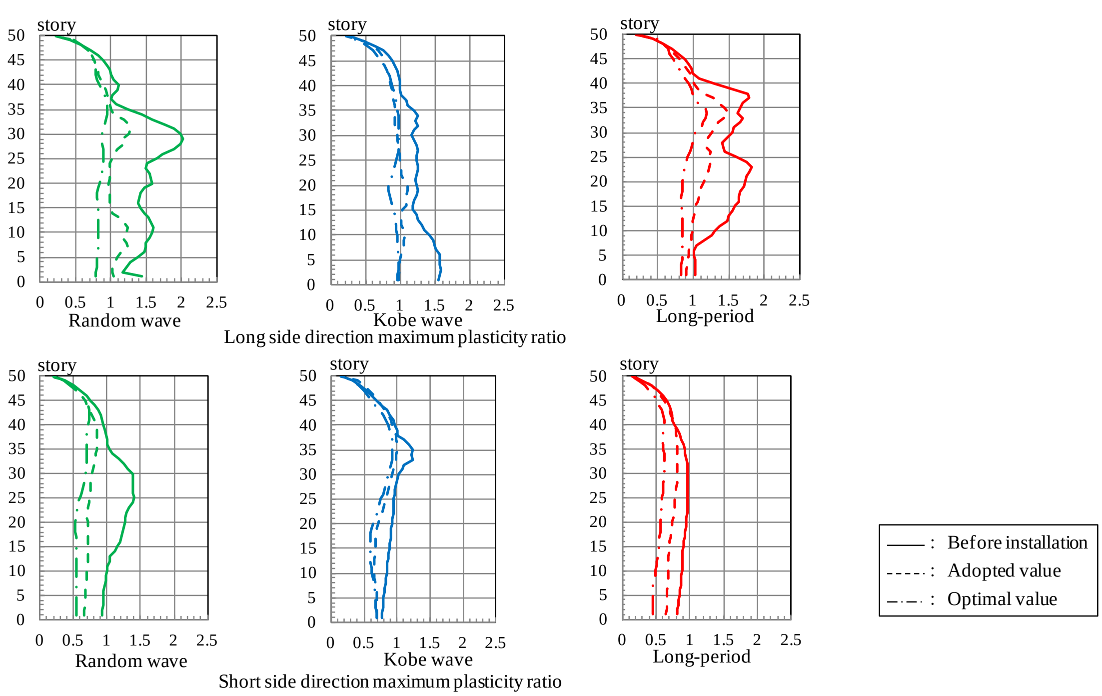


Fig. 10 – Response results: maximum plasticity ratios

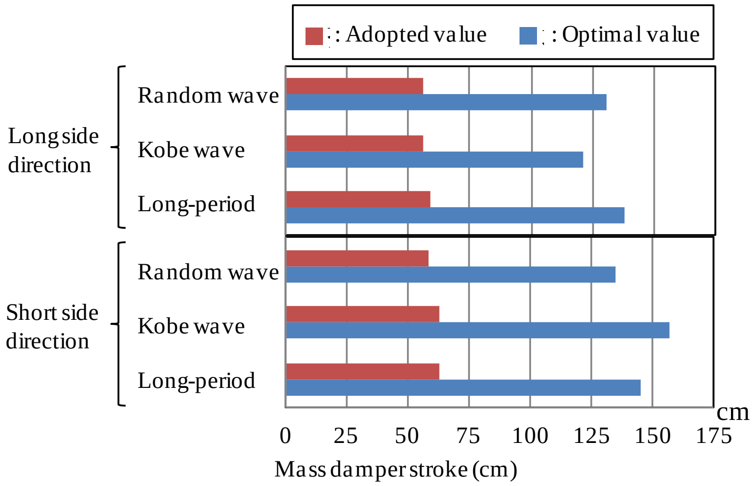


Fig. 11 – Response results: mass damper strokes

Figure 12 shows the results for the absorption ratio of the input energy. About 20% of the hysteretic energy was due to plasticization of the building in the direction of the long sides prior to the installation of the mass dampers, but installing the designed mass dampers resulted in their absorption of about 40–50% of the energy. This satisfied the criteria by reducing the hysteretic energy due to plasticization of the building to under 5%.

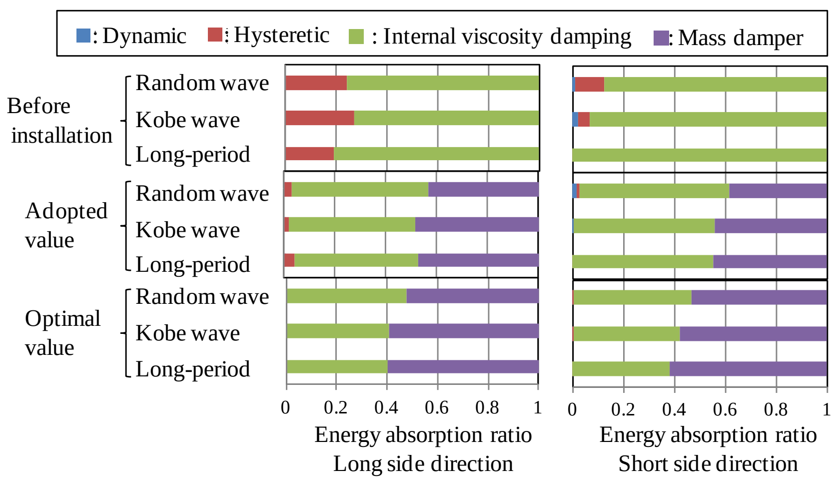


Fig. 12 – Response results: energy absorption ratios

The optimal values were compared with the results for the adopted values in relation to the respective response values and energy absorption ratios. The results indicated that the responses of the adopted values were greater than those of optimal values by about 20% on average, but the strokes were less than half.

Figure 13 shows the examination results for the strong wind. The analysis was conducted by using a simulation model for the external wind force that reproduced the maximum acceleration. This was prepared based on the power spectra and random phases [5]. The installation of the designed mass dampers decelerated the maximum response acceleration by about 60%, although the values were inferior to those of the optimal values. The potential for suspended elevator operation in the building was clearly reduced.

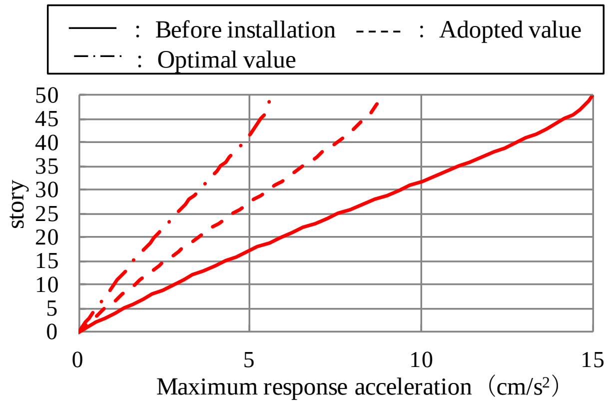


Fig. 13 – Maximum response acceleration subject to strong wind

Therefore, the installation of the designed mass dampers satisfied the criteria for the different building responses described above. The installation of mechanisms with reduced strokes so that they could remain within a rooftop structure was confirmed to make possible the design of practical and compact mass dampers.

## 4. CONCLUSION

This paper summarizes the large-scale mass dampers installed in the Shinjuku Nomura Building as countermeasures against long-period earthquakes. As an example, a model simulating a skyscraper was used to show the rational design of mass dampers where the strokes of the dampers are inhibited while the building criteria are satisfied. Mass dampers for the Shinjuku Nomura Building were designed by using the method described in section 3 to deliver a similar reduction in the building response while limiting the mass damper strokes.

## 5. ACKNOWLEDGMENTS

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## 6. References

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