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PROPOSAL FOR NEW DEFORMATION AMPLIFICATION SYSTEM TO INCREASE EFFECT OF SEISMIC DAMPERS

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Abstract

The amount of energy dissipated by seismic dampers increases with their deformation. In typical structures with passive energy dissipation systems that utilize seismic dampers to withstand earthquakes, the dampers displace along with with respect to the story drifts in the building. This however restricts the displacement of the damper to the story drift, limiting the amount of energy the dampers dissipate. Deformations larger than the story drift need to be applied to maximize the effect of dampers, while ensuring that encompassing frame is strong enough to withstand the forces of the dampers. In this paper, a new method is introduced, which creates a deformation amplification mechanism to maximize the effect of seismic dampers. Stiff frames are extended from columns and at the end of these frames, dampers are attached using pin connections. Using this method, oil dampers and tuned viscous mass dampers (TVMD) can be placed on high-rise buildings to exhibit larger effects than in the typical installation of dampers. Earthquake response analysis is conducted to confirm the effects of this new method.

Keywords: seismic damper, damper deformation amplification system, tuned viscous mass damper (TVMD), oil damper

1. Introduction

Currently in Japan, there are different kinds of seismic dampers which utilize hysteretic, velocity-dependent, acceleration dependent, or a combination of mechanisms to dissipate energy, creating many options when designing passive energy dissipation systems to reduce the seismic response of building frames.

The shear-link type is the most common type of installation where a damper is attached to supporting members, shown in Figure 1. There are also different installation types, such as brace, post column, and wall type, shown in Figure 2, which are used to suit the conditions of the design. Large amounts of energy can be dissipated when large deformation is applied, but in typical installations, it is difficult to apply deformation larger than the story drift. In order to increase the displacement of dampers, a new deformation amplification mechanism to maximize the effect of seismic dampers is proposed. To confirm the effectiveness of this mechanism, earthquake response of a high rise building with oil dampers and tuned viscous mass dampers (TVMD) installed is analyzed.

The tuned mass effect of the TVMD makes it possible to increase the overall mass of the system to several thousand times the actual mass. By adding a stiffness component in line with the mass, the natural period of the system can be tuned to a desired value. The damping mechanism of the TVMD is placed in parallel to the mass and stiffness to dissipate energy effectively.

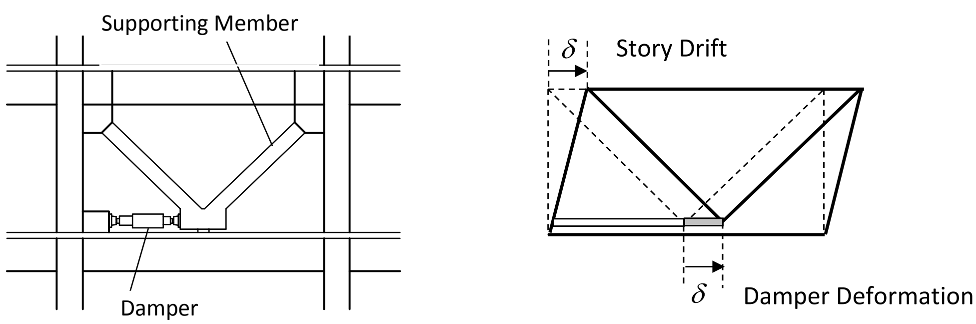


Fig. 1 – Installation of Dampers Utilizing Story Drift（Shear-Link Type）

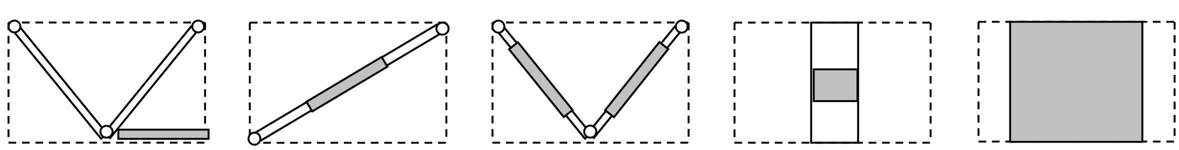


Fig. 2 – Various Installations

2. Proposed Deformation Amplification Mechanism to Increase Effect of Dampers

2.1 Theory of Deformation Amplification Mechanism

In order to increase the effect of each damper, the following conditions needs to be met:
1) The damper experiences large deformation.
2) The surrounding frame doesn't deform due to the forces applied by the damper. If the frame deforms, then the effect of the damper diminishes.

In the proposed method, the encompassing frame and the supporting members are devised so that the deformation of the damper is amplified beyond the story drift and the mechanism is able to withstand the forces of the damper. As shown in Figure 3, two stiff frames are extended from the main structure composed of beams and columns, and are connected together by beams with pin connection. The seismic dampers are then arranged in the area between the two stiff frames. The dampers can be arranged in the combinations as shown in Figure 2.

When the main structure deforms horizontally, because of the resulting vertical deformations of the two extended stiff frames, the deformation of the damper is amplified, and the extended stiff frames transmit the force from the dampers to the main structure.

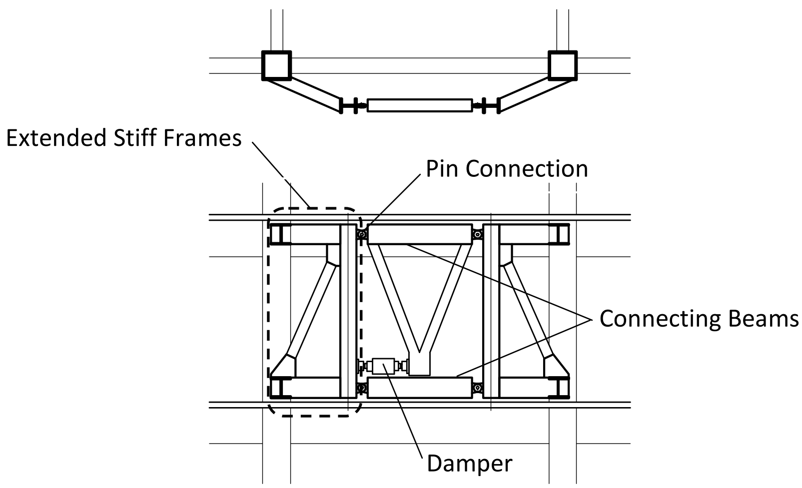


Fig. 3 – Deformation Amplification Mechanism

As shown in Figure 4, the span of the entire system is labeled "L" and the width of the extended stiff frame is "a." When the main structure deforms and story drift is δ, then assuming that the extended frames, connecting beams, and damper supporting members are rigid bodies, the damper will deform by β times to the drift δ. The relation between a/L and β can be represented by formula (1) and the rate of increase can be seen in Figure 5. As a/L increases, the deformation amplification increases. When a/L=0.25, the deformation of the damper is amplified by β=2.0 times.

$$\beta = 1 + \frac{2a}{L - 2a} \tag{1}$$

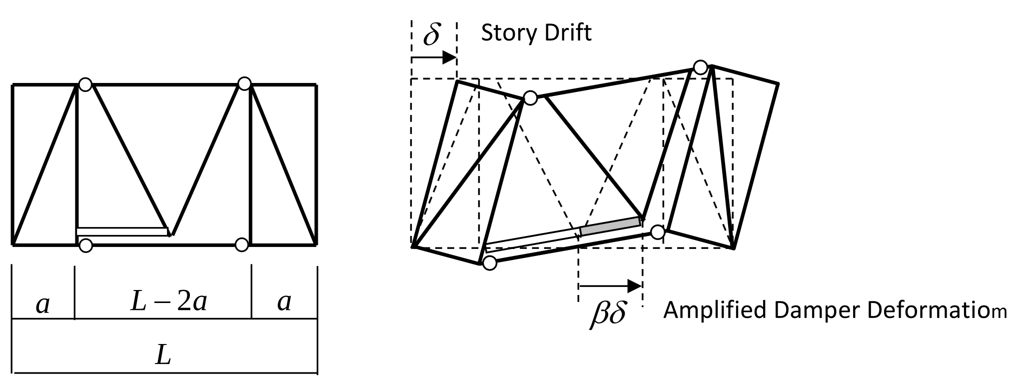


Fig. 4 – Deformation Amplification compared to Story Drift

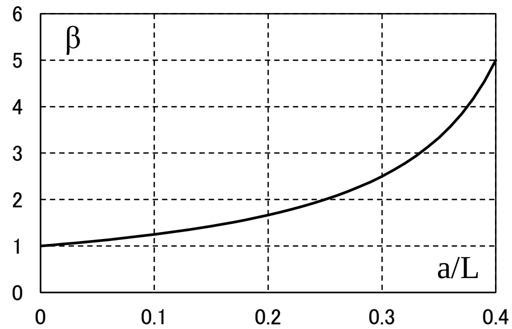


Fig. 5 – Deformation Amplification Rate compared to Story Drift (Effective Damper Deformation Ratio)

2.2 Installation of Deformation Amplification Mechanism in Void Areas

As shown in Figure 6, when the deformation amplification mechanism is installed across several floors, the damper can be installed between several floors to increase the deformation and effectiveness of each damper. This arrangement is most beneficial in void spaces, such as elevator shafts. However, when the supporting members span across several floors, the members become longer and buckling needs to be considered.

2.3 Installation of Deformation Amplification Mechanism within Frames

The extended stiff frame can also be installed within the main frame. However, since beams of the main structure are going to be removed in this case, the stiffness of the main frame will decrease. In addition, the stiffness and strength of the surrounding frame of the extended rigid frame need to be considered. As shown in Figure 7, it is ensured that the surrounding frames have adequate stiffness and strength by the provision of seismic braces and walls.

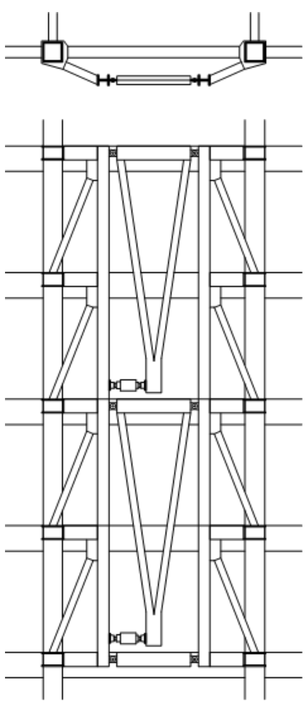


Fig. 6 – Installation Across Several Floors Using Void Areas

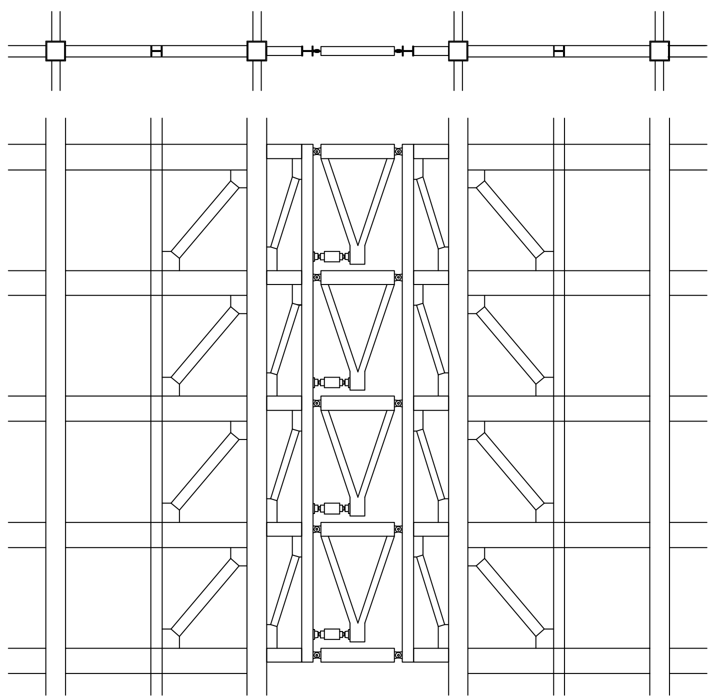


Fig. 7 – Installation within the Main Frame across Several Floors

3. Example of Deformation Amplification Mechanism in High-Rise Building

3.1 Building Model, Damper Properties, and Study Cases

As shown in Figure 8, a 23 story building, with height around 100m is considered. Dampers are installed along the lower floors using deformation amplification mechanisms or normal method, spanning across one or two floors, and in two frames. Three cases are compared: without dampers, with a 6000ton TVMD installed, and with oil dampers installed. A three-dimensional element model is created and the frame of the structure is assumed to remain elastic. A stiffness proportional damping of 2.0% is applied to the frame. The short Y-direction is examined in the analysis.

In Table 1, properties of the oil damper are listed. In Table 2, properties of TVMD are listed. In Figure 9, the models of the two dampers are shown. For each installation of the TVMD, the mass is 6000ton (2 devices). The supporting members and damping coefficient of the TVMD are tuned to the first modes' modal participation factor of the main frame.

The equivalent mass of the main frame is 25,112t for the first mode. The added mass due to TVMD for the first mode is 1,730t, resulting in an added mass ratio of 0.244. The optimal natural frequency of the TVMD system is 1.08 times the natural frequency of the frame, resulting in optimal damping coefficient of 1,764 kNs/m. Using the values from the equivalent SDOF system, the properties of the TVMD are determined.

In Figure 10, the placement of the dampers using the deformation amplification mechanisms is shown. The dampers are installed using the shear-link type. The dampers are placed in two frames. For each frame, the installation spans two floors across four floors. For each installation, there are two dampers, with a total of eight dampers. The span of the deformation amplification mechanism L is 12m, and the length of the extended stiff frame is 3m, making the ratio between a and L as 0.5 and the deformation magnification factor as 2.0.

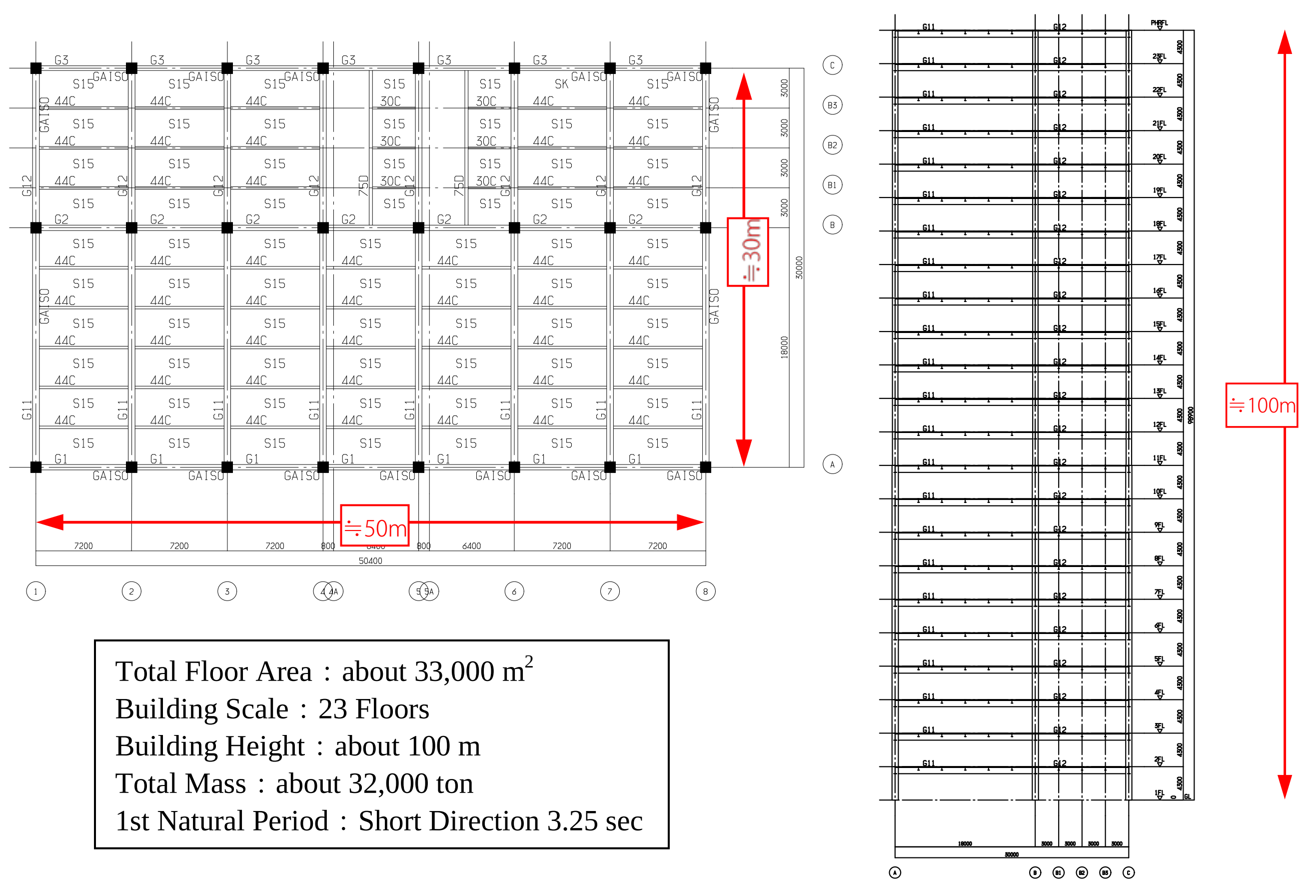


Fig. 8 – Building Plan/Elevation

Table 1 – Oil Damper Properties（per Damper）

Apparatus Stiffness k_d	1st Damping Coefficient c_1	2nd Damping Coefficient c_2	Relief Velocity v_y	Relief Force f_y	Maximum Damping Force f_{max}
4000	875.0	14.2	1.83	1600	2000

Table 2 – TVMD Properties（per Device）

Additional Mass m_d (ton)	Supporting Member Horisontal Stiffness k_c (kN/cm)	Additional Damping Coefficient c_d (kN/(cm/s))	Axial Force Limit fy（kN）
3000	158.5	30.5	2000

Table 3 – Optimal TVMD Properties for Equivalent SDOF System of First Mode

Item	**Symbol**	**Unit**	**Value**
Total Mass of Building	M	ton	32774.
Equivalent Mass of First Mode	M_1	ton	25112.
Equivalent Mass Ratio	M_1/M	-	0.766
Period of Main System	T_1	sec	3.25
Circular Frequency of Main System	ω_1	1/sec	1.94
Additional Mass of TVMD	M_d	ton	1730.
Ratio of Additional TVMD Mass	μ	-	0.0689
Magnification Ratio of Optimal Additional Tuning Vibration	γ	-	1.08
Correction Ratio of γ	γ_a	-	1.10
Optimal Additional Damping Constant	h_{opt}	-	0.244
Optimal Additional Damping Coefficient (Equivalent SDOF system)	C_d	kN/(m/s)	1764.
Optimal Additional Stiffness (Equivalent SDOF system)	K_d	kN/m	9152.

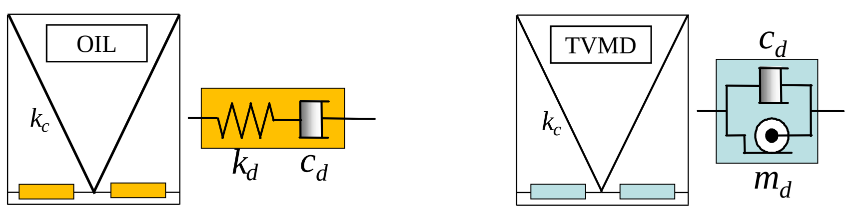


Fig. 9 – Damper Models for Oil Damper and TVMD

In order to confirm the effectiveness of the deformation amplification mechanism, case studies using oil dampers are conducted at the same installation points in the building with the parameters of the number of the devices (2, 4, or 8 devices per frame, 4, 8, or 16 devices in total), with or without amplification mechanism, and the number of stories (a single story or double stories). Table 4 shows the types in the case studies.

Study using TVMD is carried out for A2-4 type with the deformation amplification mechanism using 4 devices per frame, installed between two stories (Fig. 10), and a comparison with the cases with oil dampers is made.

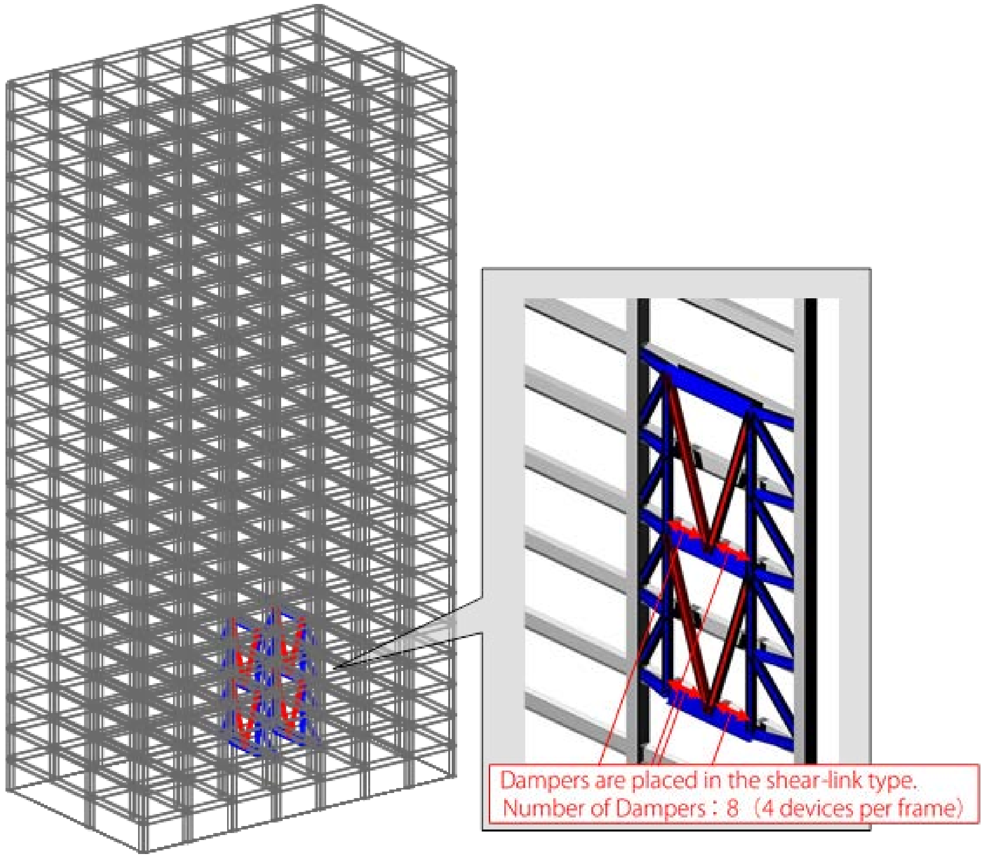
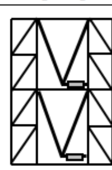
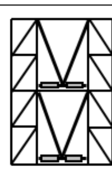
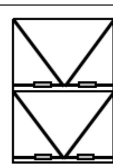
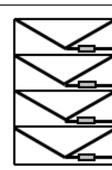
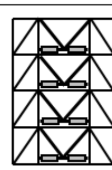
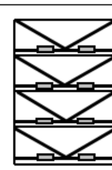


Fig. 10 – Damper Placement (A2-4 Type)

Table 4 – Case Study Types with Oil Dampers

	Across 2 floors Amplify [A2]	Across 2 floors Normal [N2]	Across 1 floor Amplify [A1]	Across 1 floor Normal [N1]
2 devices per frame [-2]	 A2-2	 N2-2		
4 devices per frame [-4]	 A2-4	 N2-4	 A1-4	 N1-4
8 devices per frame [-8]			 A1-8	 N1-8

3.2 Earthquake Responses Used in Study

The pseudo-velocity response spectra of the ground motion used in this study are shown in Fig. 11. Time history analyses are performed using a strong earthquake with a large response at a period that corresponds to the first natural period of the frame. The dashed lines in the figure show the first to the third natural periods of the building in the short direction. The acceleration time-history of the ground motion is shown in Fig.12.

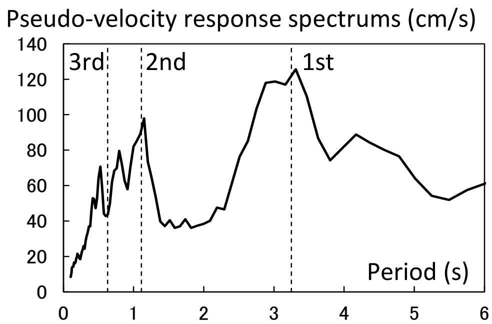


Fig. 11 – Pseudo-velocity response spectra of ground motion

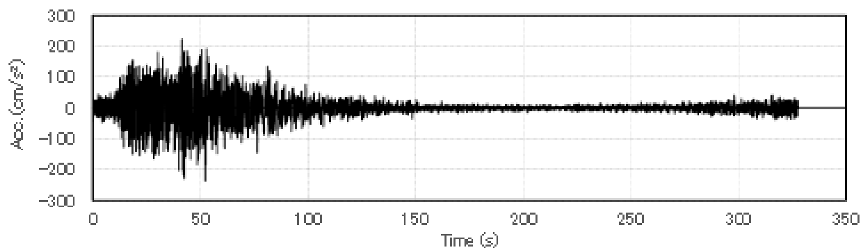


Fig. 12 – The acceleration time-history of ground motion

3.3 Investigation of Analysis Results on oil damper cases

Figure 13 shows the time histories of relative one or two story deformation of the damper installation positions, and the effective deformation of dampers. Figure 14 shows maximum top displacements, and figure 15 shows the effective damper deformation ratios in each case.

The effective damper deformation ratios mean the ratios of maximum values of the effective deformation of dampers against the maximum story drifts of the damper installation positions. It is observed that in the cases N1 and N2 without the amplification mechanism, the effective deformation of dampers are relatively small compared to the story drifts, and increasing the amount of the dampers per position doesn't affect the effective deformation ratios very much (between N1-4 and N1-8, or N2-2 and N2-4).

In the cases A1 and A2 with the amplification mechanism, the effective damper deformation ratios are larger than 1.0. The damper effective deformation ratios decrease from A1-4 to A1-8, or A2-2 to A2-4, where the amount of dampers increase. Specifically the difference of the effective deformation ratios observed between A2-2 and A2-4 is remarkable where the dampers are installed between 2 stories. It is assumed that this is due to the increase in the deformation of the extended stiff frames as the increase in the damper force per position.

In Figure 16 and 17, the story drift and shear force for each floor are plotted for 4 cases with 4 dampers per frame installed (A2-4, N2-4, A1-4, N1-4). N1-4 case where the damper is installed normally has a remarkably small effectiveness in the response reduction compared to the other cases. Response reduction effect at the points of dampers installed is significant, while the response reducing effect in the other stories are also observed. N2-4 and A1-4 cases have similar deformations and shear forces, showing that there is high dissipation effects. A2-4 case has higher dissipation effects, and at the lower floors the story drift is reduced by 50% compared to the model with no dampers.

In Figure 18 and 19, the story drift and shear force for each floor are plotted for 4 cases with maximum numbers of dampers installed (A2-4, N2-4, A1-8, N1-8). A2-4 and A1-8 cases have similar deformations and shear forces, showing that there is particularly high dissipation effects. A2-4 is the case which maximizes the effectiveness of the each damper due to the double-story installation and the effect of deformation amplification mechanism. It is observed that in the A1-8 case, the effectiveness of the dampers is significantly greater than that in the Case N1-8 case due to the deformation amplification mechanism.

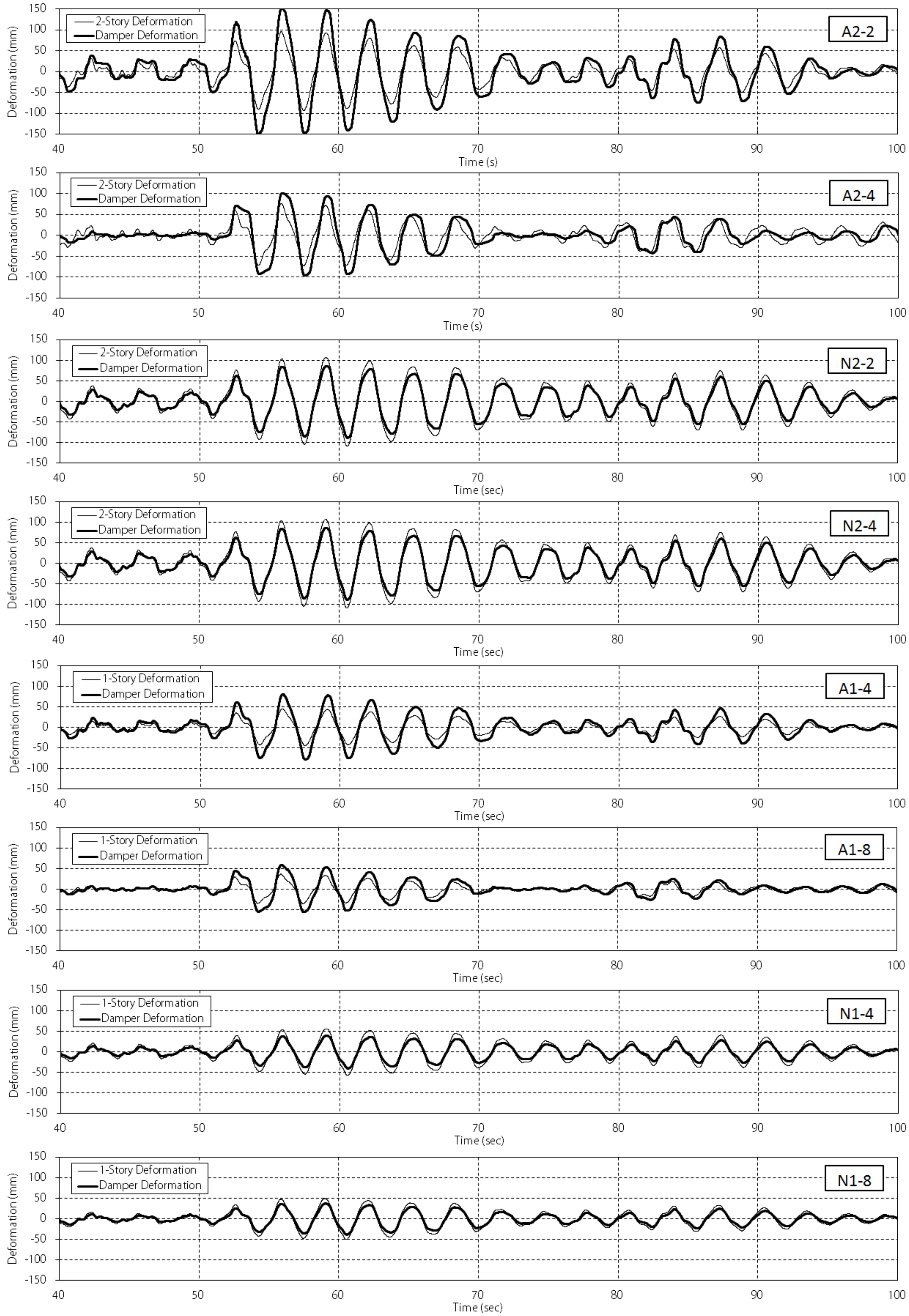


Fig. 13 – Time Histories of Relative Story Drift and Damper Deformation (Oil Damper)

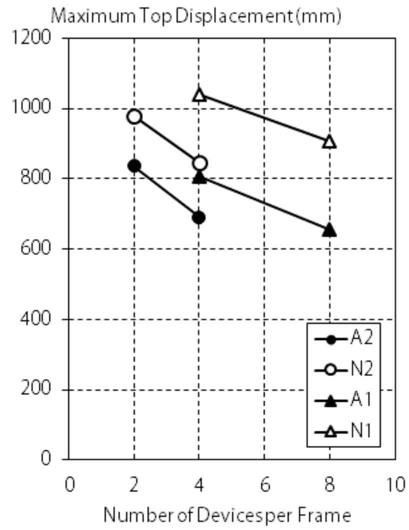


Fig. 14 – Maximum Top Displacement (Oil Damper)

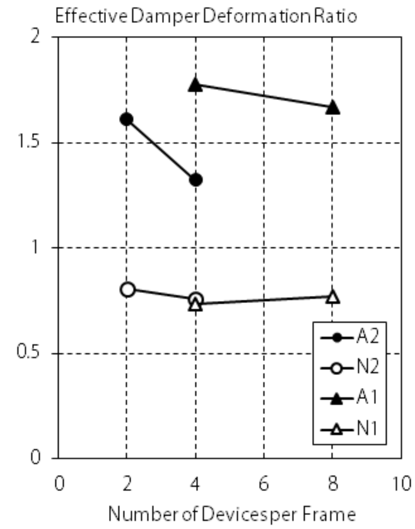


Fig. 15 – Effective Damper Deformation Ratio (Oil Damper)

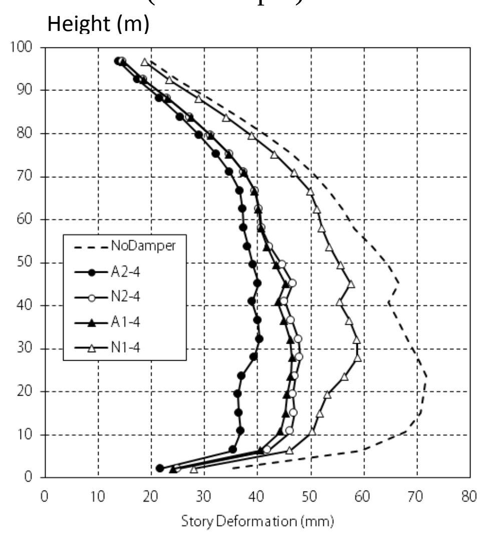


Fig. 16 – Maximum Story Deformation (Oil Damper)

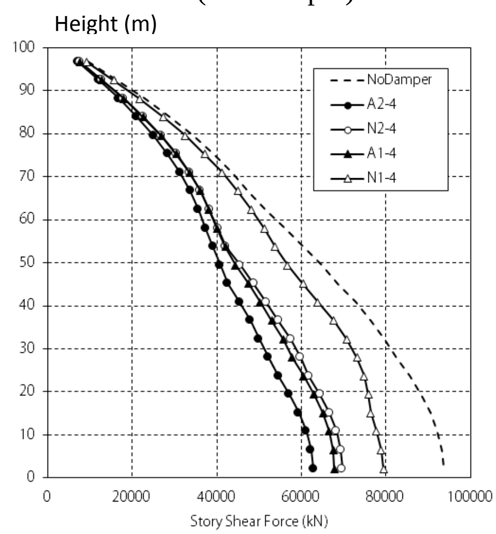


Fig. 17 – Maximum Story Shear Force (Oil Damper)

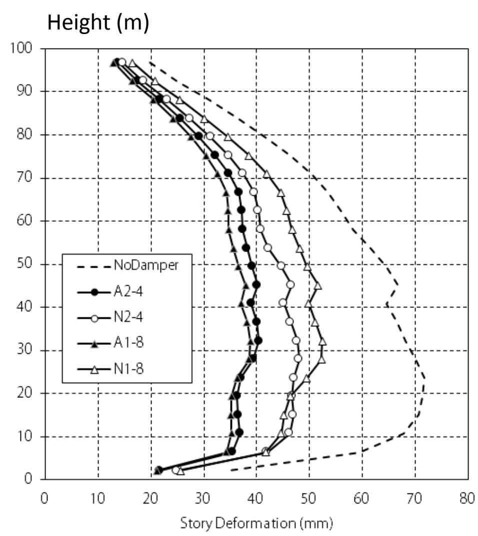


Fig. 18 – Maximum Story Deformation (Oil Damper)

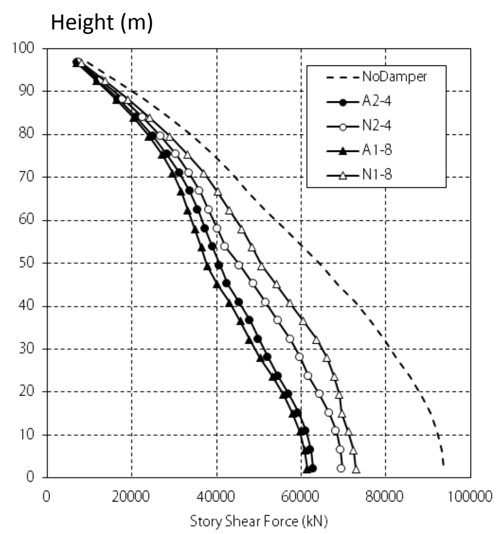


Fig. 19 – Maximum Story Shear Force (Oil Damper)

3.4 Investigation of Analysis Results on A2-4 cases using oil damper and TVMD

In Figure 20 and 21, the story drift and shear force for each floor for the three cases (no dampers, oil dampers of A2-4 installation, TVMD dampers of A2-4 installation) are plotted. The use of oil and TVMD cases lead to similar displacements and shear forces, showing that there is high dissipation effects.

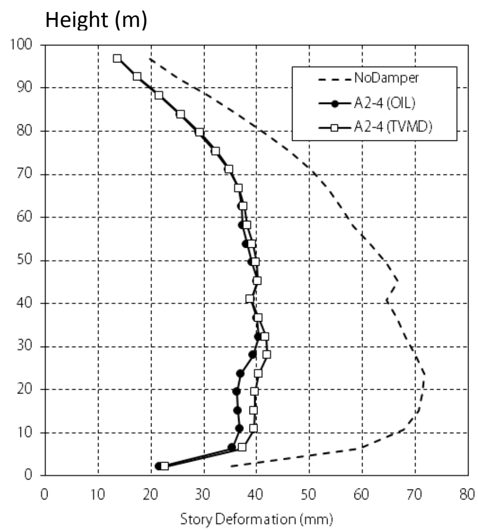


Fig. 20 – Maximum Story Deformation

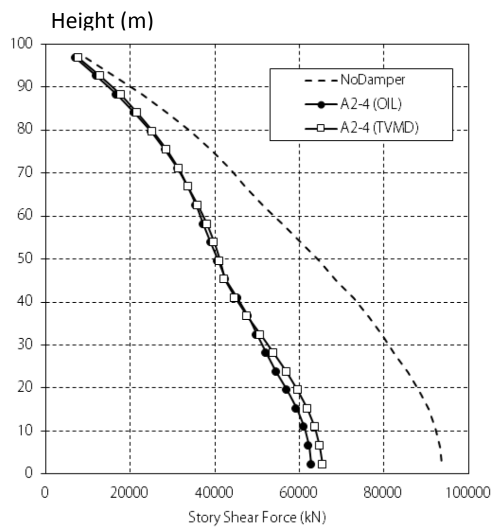


Fig. 21 – Maximum Story Shear Force

In Figure 22, the time history of the 2-story and damper deformations of the TVMD damper A2-4 case are plotted. For the TVMD case, the deformations of the amplification system are similar to the oil damper case, but due to the tuning effect of the additional mass, the dashpot portion of the TVMD is able to deform twice as much as the 2-story deformation.

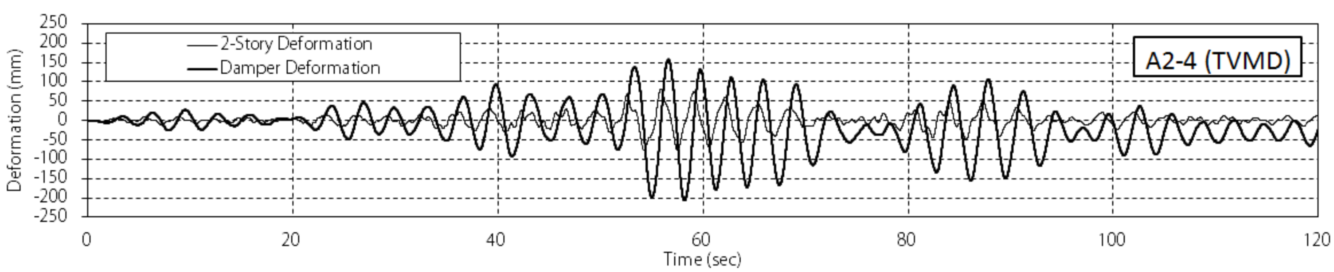


Fig. 22 – Time History of the Story Deformation between the Two Stories and Dampers

Figure 23 shows the force-deformation relationship of the damper in one installation with two dampers. Since the relief force for the two oil dampers is 3200kN, the dampers are able to experience about 4000kN. For the two TVMD, the axial force limit is 4000kN. For the analysis model, the axial yield force of the supporting members is set to be equal to the axial relief force of the TVMD, allowing the upper limit of the model to be defined by the axial relief force of the TVMD.

In Figure 24, the time history of the displacement of the top floor is shown. Compared to the oil damper case, for the TVMD case, after the displacement maximizes at about 60 seconds, the displacement diminishes more rapidly. After 80 seconds, the displacement is very small. Although the maximum displacement is similar to that for oil damper for long period-long duration earthquakes, TVMD is able to diminish the after shaking more effectively.

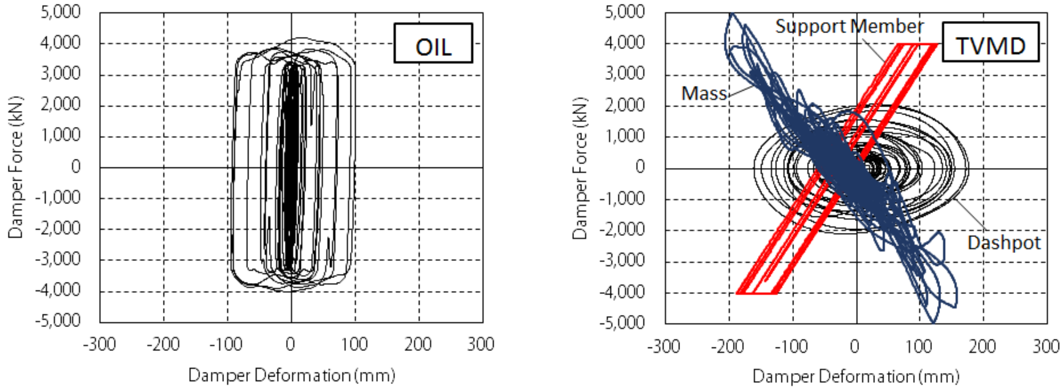


Fig. 23 – Hysteresis Loop of Damper Force and Displacement (Two Devices per Installation)

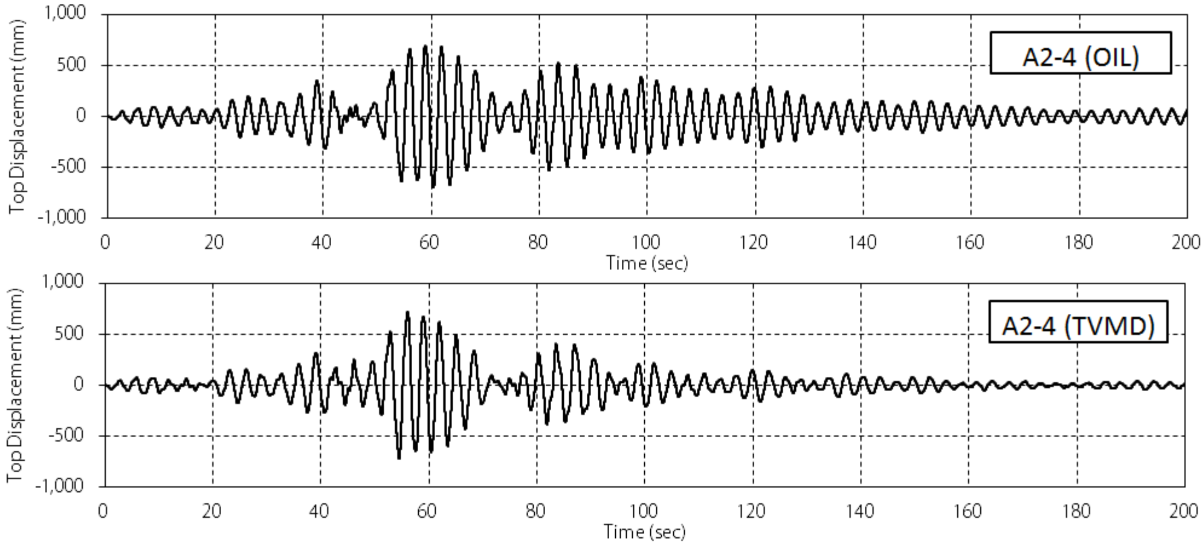


Fig. 24 – Time History of Top Floor Displacement

4. Conclusions

A new deformation amplification mechanism to increase the effectiveness of seismic dampers is proposed. The effectiveness of the mechanism is proven using time history analysis of a high-rise building. For this proposed deformation amplification mechanism, the deformation of the damper is amplified compared to the story deformation, also when properly designed to have adequate strength and stiffness, the mechanism is able to transmit the forces of the damper to the main frame.

An installation method is proposed considering architectural schemes. Void areas such as elevator shafts are used, where the mechanism is placed across several floors. With this method, less installation locations are required, and higher effect can be seen.

Compared to oil damper, TVMD are able to diminish the after shaking due to long period-long duration earthquakes more effectively.

5. References

[1] M. Ishii, H. Kazama, K. Miyazaki, and K. Murakami (2014): Application of Tuned Viscous Mass Damper to Super-High-Rise Buildings. *the 6th World Conference on Structural Control and Monitoring*, Barcelona, Spain