Response Control Effect of Steel Building Structure Using Tuned Viscous Mass Damper

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SUMMARY:
The authors have proposed a new seismic response control system called the Tuned Viscous Mass Damper (TVMD). This system is composed of arranging viscous damping element and inertial mass element in parallel and connecting spring element in series, and can get efficient energy absorption effect because the motion of viscous damping element is expanded by tuning mass element and spring element of damper to those of structure. This paper shows an application of the newly developed TVMD to a steel building structure. First, the outline of this system and a design method based on fixed points theory is shown, and next, a design example of this system applied to a steel building structure is presented. Lastly, the response control effect and an advantage of this system on a practical design are illustrated.

Keywords: Tuned viscous mass damper, Passive response control, Seismic response, Response control effect

1. INTRODUCTION

Many kinds of measures using dampers have been developed and utilized to control seismic response of building structures. Dampers commonly used are made use of energy absorption effect of metal material or viscous material. On the other hand, response control using inertial mass element has been studied, which gets inertial force due to the relative acceleration, but not due to the absolute acceleration (Furuhashi & Ishimaru 2004, Isoda, Hanzawa & Tamura 2009). Saito et al. has proposed a new seismic response control system called the Tuned Viscous Mass Damper (Saito, Kurita & Inoue 2007, Saito el al. 2008, Ikago, Saito & Inoue 2012). This system is composed of arranging viscous damping element and inertial mass element in parallel and connecting spring element in series, and can get efficient energy absorption effect because the motion of viscous damping element is expanded by tuning mass element and spring element of damper to those of structure to be controlled (Fig 1.1.).

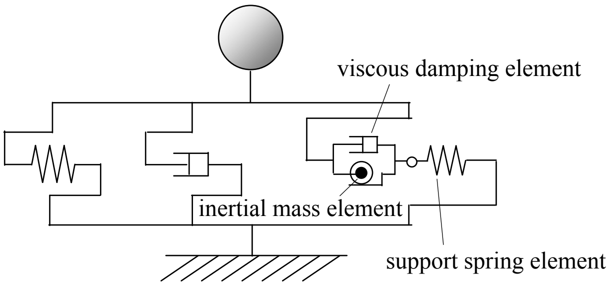

Figure 1.1. Dynamical Model of the Tuned Viscous Mass Damper Seismic Response Control System

In general, the effectiveness of controlling wind-induced response of building structure using mass element like the Tuned Mass Damper (TMD) is recognized, but it could be unrealistic to control seismic response of building structure by mass element. The reason of this is that the amount of supplemental mass becomes very large, which is required to control response sufficiently. However a damper has been developed which can amplify mass effect apparently by means of ball-screw mechanism transforming linear motion to rotational motion, therefore it has become possible to get more efficient response control effect by this damper as the same scale and weight as usual ones. The inertial mass element which is used in the TVMD has an apparent mass amplifying mechanism to obtain a large supplemental mass effect like this (Fig 1.2., Kida et al. 2011).

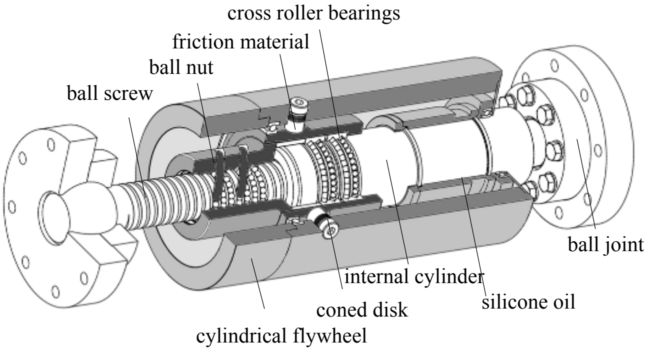

Figure 1.2. Rotary Damping Tube with Inertial Mass

This paper shows an application example of the newly developed TVMD to a steel building structure. First, the outline of this system and a design method based on fixed points theory is shown, and next, a design example of this system applied to a steel building structure is presented. Lastly, the response control effect and an advantage of this system on a practical design are illustrated.

2. OUTLINE OF BUILDING AND STRUCTUAL PLAN

The building incorporated with the TVMD system is located at Tohoku area in Japan, and combines the function of office and the others. The frames consist of steel and the columns are CFT (concrete fixed tube).This building has seismic response control systems to upgrade seismic safety of structure and facilities in the building (Fig.2.1.). As for X direction, it has traditional viscous dampers at lower floors and the TVMD system at upper floors. As for Y direction, it has a “Connect-Wall-Damper System” in addition to traditional viscous dampers (The Building Center of Japan 2011).

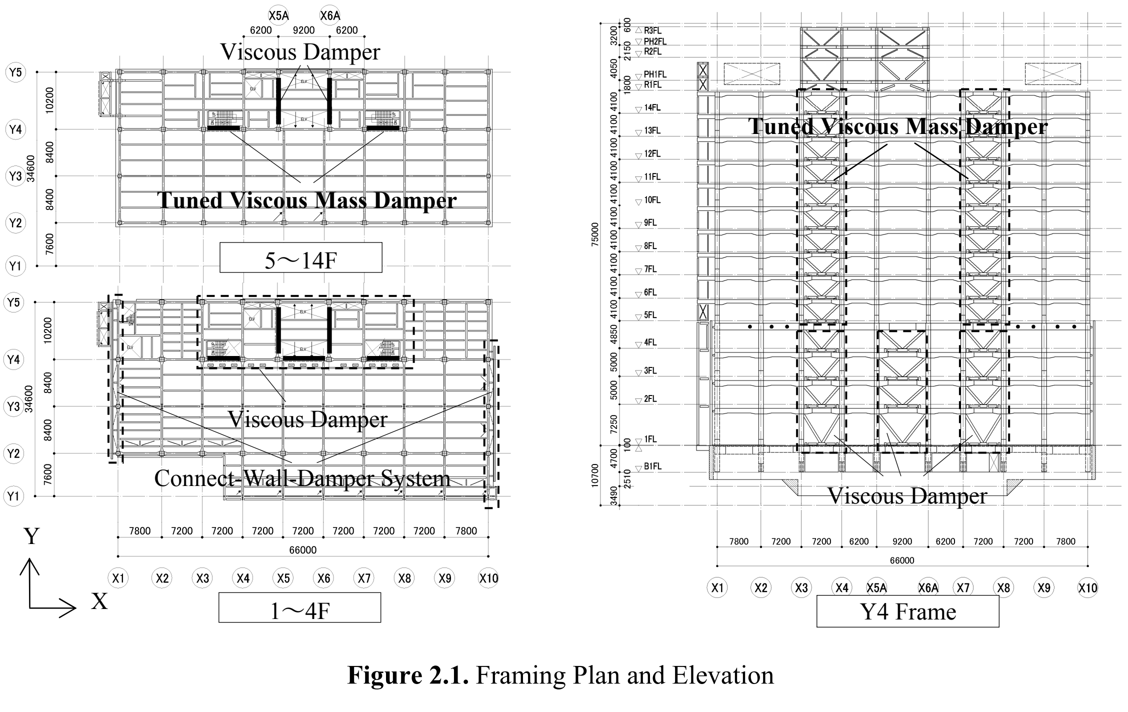

Figure 2.1. Framing Plan and Elevation

3. TUNED VISCOUS MASS DAMPER RESPONSE CONTROL SYSTEM

3.1. Outline of TVMD Response Control System

The TVMD response control system is composed of arranging viscous damping element and inertial mass element in parallel and connecting support spring element in series (Fig 1.1.), and can get efficient energy absorption effect because the motion of viscous damping element is expanded by tuning mass element and spring element of damper to those of structure to be controlled. Rotary damping tube with inertial mass (Fig 1.2.) has large mass as inertial mass element, and also has the function of viscous damping element. The TVMD system is formed by incorporating this damper to a building structure through a support member which has relevant stiffness like steel or rubber.

3.2. Optimum Response Control Design Method based on the Fixed Points Theory

In this section, a design method of this system (the optimum response control design method) which is based on the fixed points theory is presented (Saito et al. 2008). Here we concern about the multi-degree-of-freedom system with the TVMD system, m_{sk}, ${}_i m_{rk}$, ${}_i c_{dk}$, ${}_i k_{bk}$ represent *k*th story's mass of the primary structure, *k*th story's inertial mass, viscous damping coefficient and support member's stiffness of *i*th mode damper respectively. And x_{sk} and n represent *k*th story's relative displacement of the primary structure from the ground, and number of stories of the primary structure respectively. The optimum response control design method is as follows.

1) Give *k*th story's inertial mass of *i*th mode damper m_{sk} according to the target of response control.

2) Calculate the equivalent mass ${}_i\overline{M}$ and the equivalent mass between nodes ${}_i\overline{M}_r$ by eigenvalue problem analysis of the primary structure. Here, ${}_i u_{sk}$ and ${}_i\beta$ represent *k*th story's element of *i*th mode eigenvector and *i*th mode participation factor respectively.

$$ {}_i\overline{M} = \sum_{k=1}^{n}\left\{ m_{sk}\cdot\left({}_i\beta\cdot{}_i u_{sk}\right)^2\right\} \tag{3.1}$$

$$ {}_i\overline{M}_r = {}_i m_{r1}\cdot\left({}_i\beta\cdot{}_i u_{s1}\right)^2 + \sum_{k=2}^{n}\left[{}_i m_{rk}\cdot\left\{{}_i\beta\cdot\left({}_i u_{sk} - {}_i u_{s(k-1)}\right)\right\}^2\right] \tag{3.2}$$

3) Calculate mass ratio ${}_i\mu$.

$$ {}_i\mu = {}_i\overline{M}_r \big/ {}_i\overline{M} \tag{3.3}$$

4) Calculate optimum tuning frequency ratio ${}_i\beta_{opt}$ and optimum damping ratio ${}_i\varsigma_{opt}$.

$$ {}_i\beta_{opt} = \frac{1-\sqrt{1-4{}_i\mu}}{2{}_i\mu} \qquad {}_i\varsigma_{opt} = \frac{\sqrt{3(1-\sqrt{1-4{}_i\mu})}}{4} \tag{3.4, 3.5}$$

5) Get the support member stiffness ${}_i k_{bk}$ and viscous damping coefficient ${}_i c_{dk}$. Here, ${}_i\omega_n$ represents *i*th mode circular frequency of the primary structure.

$$ {}_i k_{bk} = {}_i m_{rk}\cdot\left({}_i\beta_{opt}\cdot{}_i\omega_n\right)^2 \qquad {}_i c_{dk} = 2\cdot{}_i\varsigma_{opt}\cdot{}_i m_{rk}\cdot{}_i\beta_{opt}\cdot{}_i\omega_n \tag{3.6, 3.7}$$

About the amount of m_{sk} in procedure 1), although it can be decided by trial run, some design methods which use numerical optimization have been also presented (Ikago, Sugimura, Saito, Inoue 2010, Ikago, Sugimura, Saito, Inoue 2011).

4. DESIGN OF TUNED VISCOUS MASS DAMPER

4.1. Ground Motion Acceleration for Design

Ground motion accelerations used in structural design are shown below (Table 4.1.). EL CENTRO-NS, TAFT-EW, HACHINOHE-NS are observed records and they are normalised to be 25cm/s and 50cm/s (Level 1 and Level 2 respectively) of their maximum velocity. KOKUJI-R,K,H are artificial earthquake accelerations used in structural design of some buildings in Japan. Fig 4.1. shows the velocity response spectra of these accelerations.

Table 4.1. Ground Motion Acceleration for Design

Ground Motion Acceleration for Design	Max of Acceleration (cm/s^2)	
	Level 1	Level 2
1 EL CENTRO-NS (1940)	255.4	510.8
2 TAFT-EW (1952)	248.4	496.8
3 HACHINOHE-NS (1968)	167.1	334.1
4 KOKUJI-R(Phase Angle:random)	66.3	331.7
5 KOKUJI-K(Phase Angle:JMA-KOBE)	71.2	355.9
6 KOKUJI-H(Phase Angle:HACNIHOHE-NS)	66.6	332.9

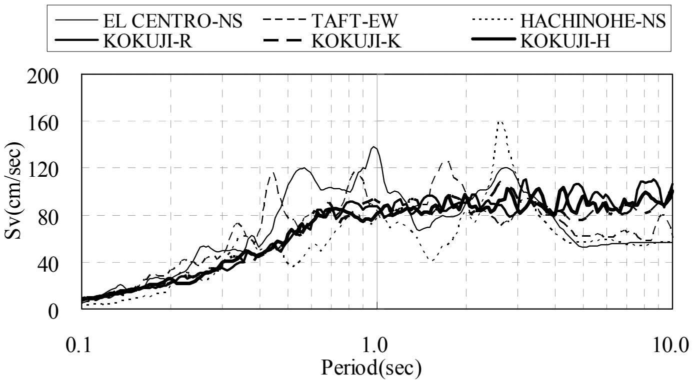

Figure 4.1. Velocity Response Spectra

4.2. Criterion in Structural Design

Table 4.2. shows the seismic criterion in structural design of this building. In this design, structural frames are supposed not to be damaged against Level 2 earthquake.

Table 4.2. Seismic Design Criterion

	Level 1	Level 2
Story Shear Force	≦Shear Force to Allowable Stress Design	≦Elastic Limit Strength
Inter-story Drift Angle	$R \leqq 1/250$	$R \leqq 1/125$
Ductility Factor	$\mu \leqq 1.0$	$\mu \leqq 1.0$

4.3. Design Parameter of Tuned Viscous Mass Damper

The design of the TVMD system is based on the optimum response control design method (see 3.2.). In this design, the TVMDs are tuned to the 1st mode of the primary structure. Inertial mass of damper is set to be 5,400ton. Table 4.3. shows the design parameters. The mass ratio ${}_1\mu$ presented by Eqn.3.3. becomes 0.071.

Table 4.3. Design Parameter of Tuned Viscous Mass Damper (each 1 damper)

Inertial Mass	Viscous Coefficient	Stiffness	Restricted Force
$5{,}400\times10^3$kg	7,300kN/(m/s)	68,600kN/m	1,200kN

4.4. Installation Method of the Tuned Viscous Mass Damper

The TVMD is constituted like Fig 4.2. to realize above parameters. As for support member, it is planned that a rubber member is to be a period adjustment member and installed through a steel brace. The material of the rubber member is a natural rubber (G6), and the form is sized at 400mm x 400mm, the thickness is 4mm, and 4 pieces are used in each damper. Stiffness of a sequential spring which consists of the rubber and the steel braces is designed to be the target stiffness shown in Table 4.3. Here, the controlling of the stiffness of the total system is very important, it's supposed to be easy to control it by the stiffness of the rubber member tended to be dominant to the total stiffness. On the other hand, inertial mass of 5,400 ton is realized by a steel weight which diameter is 600mm, length is 800mm, thickness is 50mm and actual mass is 560kg by mass amplifying effect.

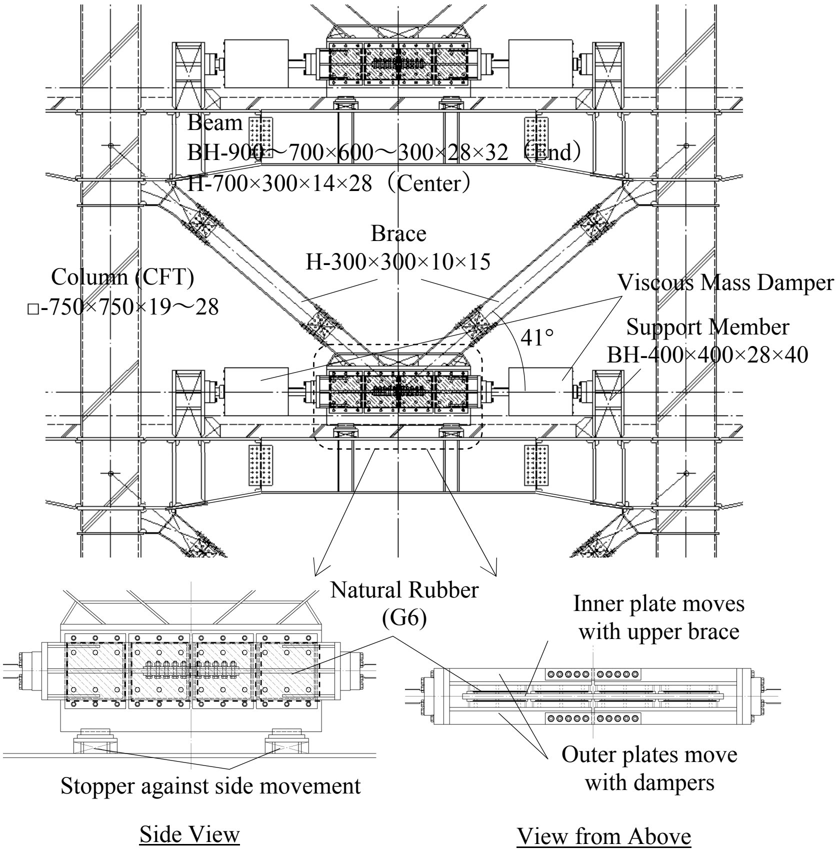

Figure 4.2. Installation Method of Damper

5. MODAL DAMPING AND FREQUENCY CHARACTERISTICS

5.1. Natural Period and Modal Damping

In this section, the change of the whole system by incorporating the TVMDs to the primary system is confirmed. The primary system is simply modelled to equivalent shear model, and nonlinear viscous damper is substituted to linear property in this study (Fig 5.1. and Table 5.1.). The inherent damping of the primary structure is set to be stiffness proportional and provided 0.02 damping ratio to the 1st mode. Table 5.2. and Table 5.3. present the natural periods and modal damping ratios by complex eigenvalue problem analysis respectively. The case without damper and the case with only the viscous damper at lower floors in the building are shown for comparison in addition to the case with all dampers. Although the number of whole system modes increases from 14 to 24 by incorporating the TVMDs, it can be seen that the modes whose periods are near each other arise from the 1st mode to the 11th mode. These modes correspond to the 1st mode of the other cases, and the 12 and higher modes of all damper cases correspond to the 2 and higher modes of other cases. On the other hand, it can also be seen that the modal damping ratios of the 1st and the 11th mode of all damper case become 14%, and they are larger than that of the other cases.

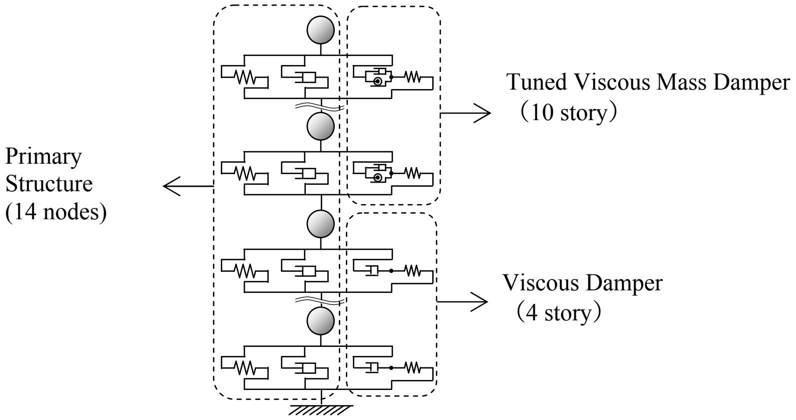

Figure 5.1. Study Model

Table 5.1. Parameter of the Primary Structure and Dampers

Story	Primary Structure			Damper		
	Mass ton(=×10^{3}kg)	Viscous Coefficient kN/(m/s)	Stiffness kN/m	Mass ton(=×10^{3}kg)	Viscous Coefficient kN/(m/s)	Stiffness kN/m
14	3747	16479	1272000	21600	29200	269510
13	1876	16997	1312000	21600	29200	269510
12	1661	17515	1352000	21600	29200	269510
11	1649	17917	1383000	21600	29200	269510
10	1682	18241	1408000	21600	29200	269510
9	1668	18772	1449000	21600	29200	269510
8	1687	19083	1473000	21600	29200	269510
7	1672	19692	1520000	21600	29200	269510
6	1695	21052	1625000	21600	29200	269510
5	1724	25120	1939000	21600	29200	269510
4	4222	24900	1922000	-	116660	1848500
3	3432	21363	1649000	-	116660	1848500
2	3468	22905	1768000	-	116660	1848500
1	3899	28553	2204000	-	116660	895500

Table 5.2. Natural Period

No Damper		Viscous Damper (Lower)		Viscous Damper (Lower)+ Tuned Viscous Mass Damper (Upper)	
Mode	Period(sec)	Mode	Period(sec)	Mode	Period(sec)
1st	2.03	1st	2.00	1st	2.20
				2nd	1.96
				3rd	1.96
				4th	1.95
				5th	1.95
				6th	1.94
				7th	1.94
				8th	1.93
				9th	1.93
				10th	1.90
				11th	1.69
2nd	0.79	2nd	0.75	12th	0.71
3rd	0.47	3rd	0.46	13th	0.42
4th	0.32	4th	0.31	14th	0.28
5th	0.27	5th	0.23	15th	0.22

Table 5.3. Modal Damping Ratio

No Damper		Viscous Damper (Lower)		Viscous Damper (Lower)+ Tuned Viscous Mass Damper (Upper)	
Mode	Damping Ratio	Mode	Damping Ratio	Mode	Damping Ratio
1st	0.02	1st	0.06	1st	0.14
				2nd	0.21
				3rd	0.21
				4th	0.21
				5th	0.21
				6th	0.21
				7th	0.21
				8th	0.21
				9th	0.21
				10th	0.21
				11th	0.14
2nd	0.05	2nd	0.12	12th	0.12
3rd	0.09	3rd	0.11	13th	0.10
4th	0.13	4th	0.14	14th	0.13
5th	0.15	5th	0.18	15th	0.18

5.2. Frequency Characteristics

In this section, the magnification factor against harmonic input is confirmed. Fig 5.2. presents the magnification factor of inter-story deformation of each story to the ground displacement.

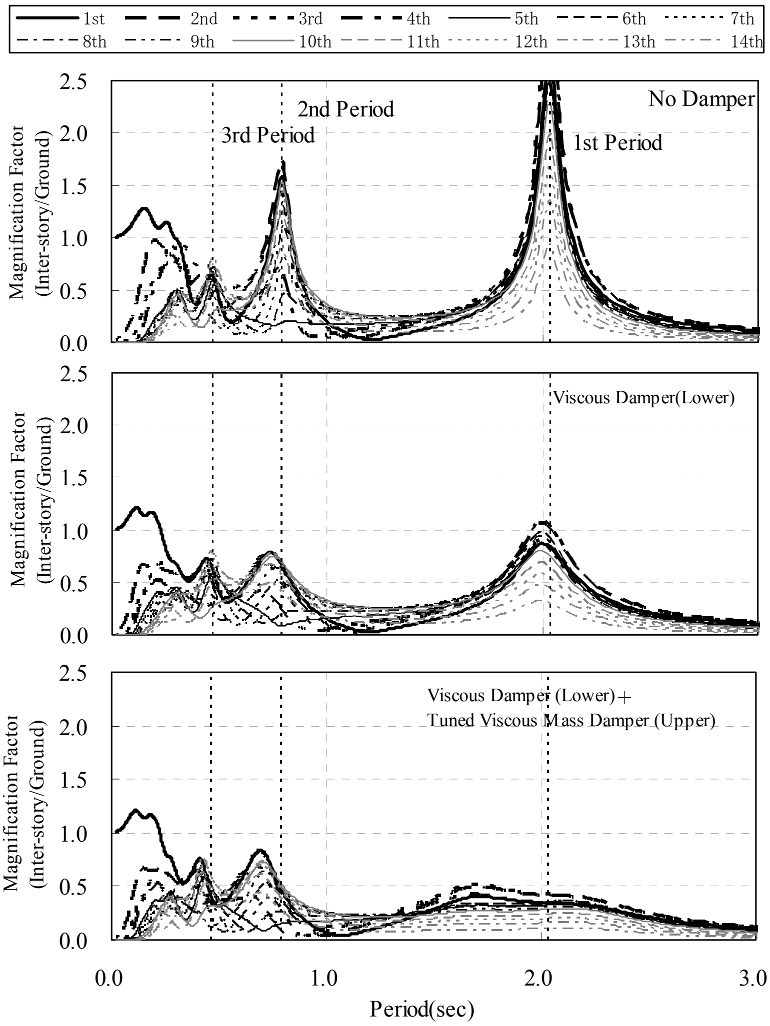

Figure 5.2. Magnification Factor of Displacement

It appears clearly that the magnification factor across wide range is reduced equally by incorporating the viscous dampers. On the other hand, the magnification factor of the tuned mode (=the 1st mode in this design) is reduced intensively and those of other modes are not almost changed when the TVMDs are incorporated. This means that the TVMD can raise the damping of arbitrary mode.

6. SEISMIC RESPONSE CONTROL EFFECT

6.1. Analysis Model

Fig 6.1. presents the dynamic analysis model for seismic response calculation. The viscous dampers are modelled by Maxwell Model. The TVMD dampers are modelled by 3-elements model and a spring element represents a rubber member.

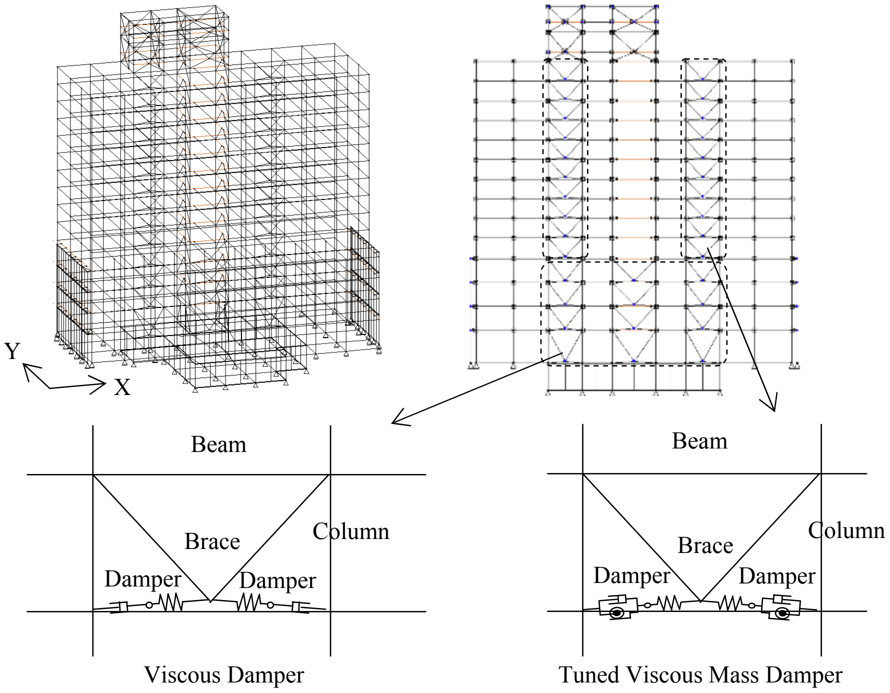

Figure 6.1. Dynamic Analysis Model

6.2. Maximum Response against Ground Motion

The maximum responses of this building against ground motion used in design are shown in Fig. 6.2. Each response satisfies the criterion in structural design according to the response control effect of both the TVMDs and the viscous dampers.

6.3. Advantage in Practical Design on the TVMD Seismic Response Control System

The TVMD has a problem that its damper force could increase compared with other viscous damper when both dampers have equal response control effect. To solve this problem, it's shown that the damper force can be reduced by installing the force restriction mechanism without reduction of response control effect (Kida et al. 2011). Fig 6.3. shows the comparison of maximum seismic response due to the existence of the force restriction mechanism against the TAFT-EW Level2 input. The force of restriction is set to be 1,200 kN, and it corresponds 0.5-1.0 times of maximum damper force when it's not restricted. Here, the case in which the TVMDs are exchanged with the viscous dampers incorporated in lower floor is shown for comparison. It can be seen that the Force-Restricted

TVMD can reduce the damper force with little reduction of response control effect, and the Force-Restricted TVMD can obtain equal response control effect with smaller damper force compared with the viscous damper. In this application example, the damper forces decrease about 0.7 times compared with traditional viscous damper. This can cause a reasonable design of frame structure.

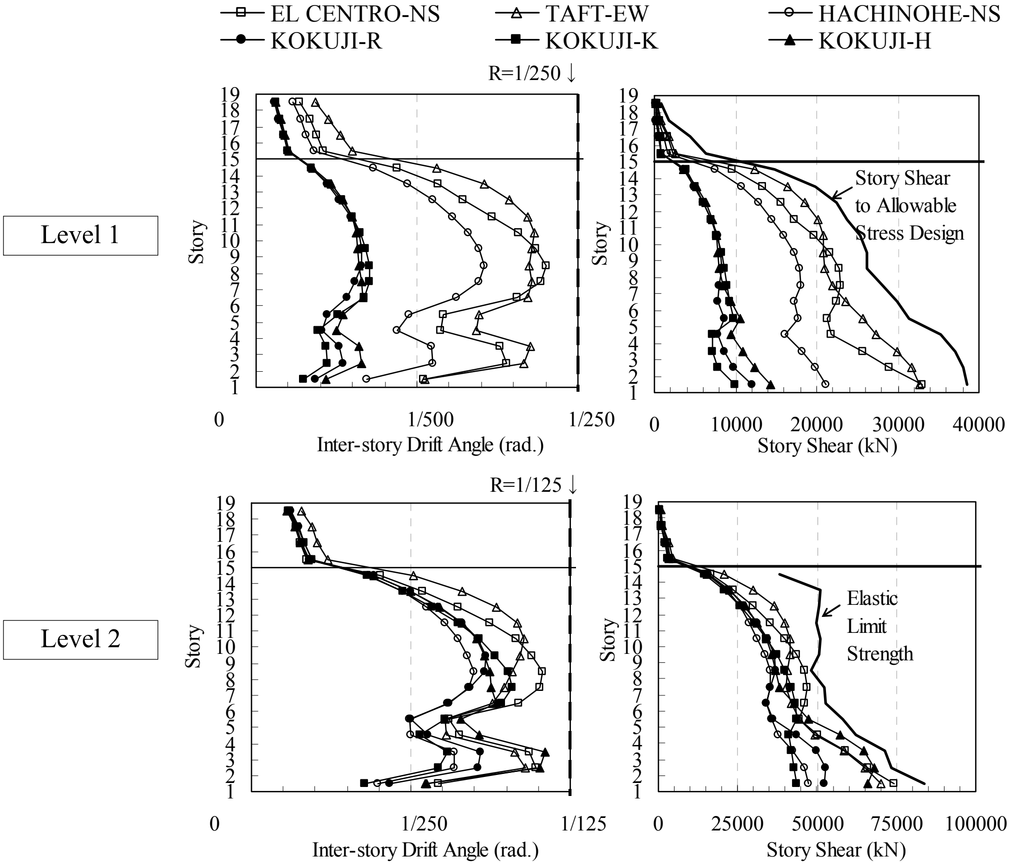

Figure 6.2. Maximum Seismic Response

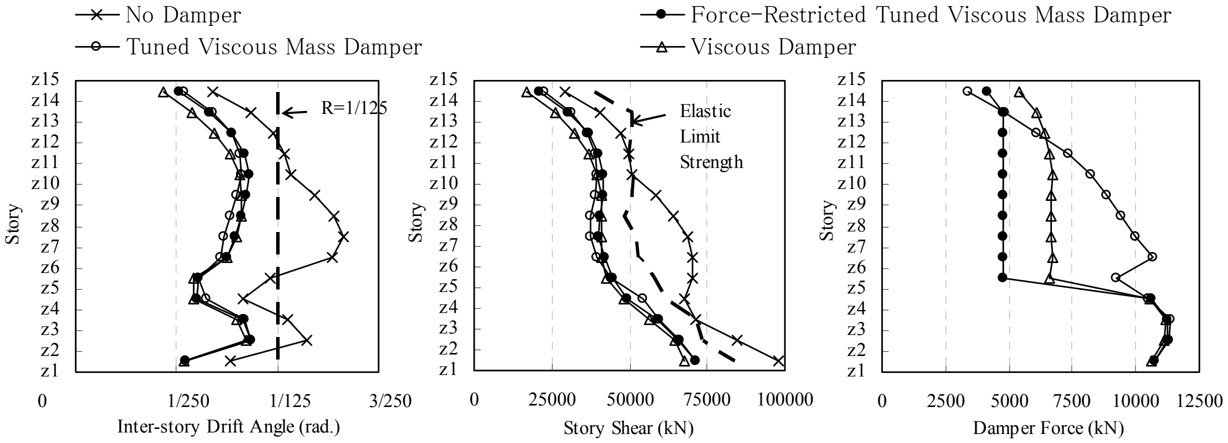

Figure 6.3. Comparison of Maximum Seismic Response due to Damper System Difference

7. CONCLUSIONS

This paper shows the application example of the newly developed TVMD to a steel building structure. First, a design method and an installation method of this system are shown, and next, the seismic response control effect of this system is presented by analysing natural period, modal damping ratio, frequency characteristics and seismic response. Lastly, an advantage of this system on a practical design is illustrated. The conclusions we obtained here are as follows.

(1) Very large mass effect can be obtained according to the TVMD system. In this application example, a mass ratio for the whole building becomes about 7% by incorporating dampers which holds 5,400ton mass effect.
(2)Damping of arbitrary mode within structure can be raised intensively according to the TVMD system. In this application example, damping of the 1st mode which is dominant to seismic response of building structure is raised effectively, and it becomes about the 14% damping ratio by complex eigenvalue problem analysis.
(3)It can be got sufficient seismic response control effect by combining the TVMD system which can raise damping of arbitrary mode with the traditional viscous dampers.
(4)The damper force of the TVMD can be decreased without reduction of response control effect by using force restriction mechanism of this system. In this application example, the damper forces decrease 0.7 times compared with traditional viscous damper. This can cause a reasonable design of frame structure.

REFERENCES

Furuhashi T., Ishimaru S. (2004). Mode Isolation By Inertial Mass Study on response control by inertial mass No.1. *Journal of Structural and Construction Engineering Architectural Institute of Japan.* **576**, 55-62. (in Japanese).

Isoda K., Hanzawa T., Tamura K. (2009). A Study on Response Characteristics of a SDOF Model with Rotating Inertia Mass Dampers. *Journal of Structural and Construction Engineering Architectural Institute of Japan.* **642**, 1469-1476. (in Japanese).

Saito K., Kurita S., Inoue N. (2007). Optimum Response Control of 1-DOF System Using Linear Viscous Damper with Inertial Mass and its Kelvin-type Modeling. *Journal of Structural Engineering*. **53B**, 53-66. (in Japanese).

Saito K., Sugimura Y., Nakaminami S., Kida H., Inoue N. (2008). Vibration Tests of 1-Story Response Control System Using Inertial Mass and Optimized Soft Spring and Viscous Element. *The 14th World Conference on Earthquake Engineering.* Paper ID 12-01-0128.

Ikago K., Saito K., Inoue N. (2012). Seismic Control of Single-degree-of-freedom Structure using Tuned Viscous Mass Damper. *Earthquake Engineering and Structural Dynamics.* **41:3**, 453-474

Kida H., Watanabe Y., Nakaminami S., Tanaka H., Sugimura Y., Saito K., Ikago K., Inoue N. (2011). Full-Scale Dynamic Tests of Tuned Viscous Mass Damper with Force Restriction Mechanism and Its Analytical Verification. *Journal of Structural and Construction Engineering Architectural Institute of Japan.* **665**, 1271-1280. (in Japanese).

The Building Center of Japan (2011). Complex Comunication Building incorporated with Efficient Seimic Response Control Systems. *The Building Letter Technical Report.* **547**, 1-11. (in Japanese).

Ikago K., Sugimura Y., Saito K., Inoue N. (2010). Optimum Seismic Response Control of Multiple Degree of Freedom Structures using Tuned Viscous Mass Dampers. *The Tenth International Conference on Computational Structures Technology.* Paper 164

Ikago K., Sugimura Y., Saito K., Inoue N. (2011). Seismic Displacement Control of Multiple-degree-of-freedom Structures using Tuned Viscous Mass Dampers, *The 8th International Conference on Structural Dynamics EURODYN.* 1800-1807.