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Vibration Control of Structures by Multiple Mass Dampers

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ABSTRACT

A system with multiple tuned mass dampers (MTMDs) consists of two lumped mass dampers. The first TMD is placed on the top of the structure and is tuned to the first natural frequency of the structure, while the second one is placed somewhere at the middle stories and is tuned to the second natural frequency of the structure. By controlling mass distribution along with other parameters, like damping ratio, frequency range and number of dampers, response of the main system can be controlled. In this research, to investigate how multiple mass dampers reduce seismic vibration of structures, time history data is checked. Multiple mass dampers (MTMDs) are distributed at each storey. For comparison, single mass damper (STMD) is installed at the top floor of the structure. Numerical study is performed to evaluate the effectiveness of MTMDs and the overall system performance. Time history data of three real earthquakes; namely, Kobe, Imperial Valley and Mammoth Lake earthquakes is considered in the present study. Displacement, acceleration, base shear and storey drift are obtained for the two configurations (structure with MTMDs and structure with STMD) for all earthquakes. Responses are also obtained for structure without damper system. From the results obtained, it is obvious that the MTMD configuration is more effective for controlling the seismic response of the primary system with comparison to STMD configuration.

KEYWORDS: Earthquake, Multiple tuned mass dampers, Single tuned mass damper, Time history.

INTRODUCTION

A tuned mass damper is a passive control device consisting of a lumped mass with a spring and a viscous damper attached properly to the main structure to reduce any undesirable vibration of the system. Recently, systems with multiple tuned mass dampers have been proposed. In recent years, the construction of lightly damped, flexible tall buildings by using high-strength materials in regions of seismic risk has created concern in the structural engineering community. In recognition of the serviceability issues, structural engineering researchers have created artificial passive vibration control devices. Tuned mass damper is the oldest passive vibration control device. In dynamic vibration control of structures, the tuned mass damper (TMD) has been installed as an effective passive control device to mitigate structural vibration. A TMD is attached to a main building structure in order to reduce any undesirable vibrations induced by earthquake loads. The natural frequency of the TMD is tuned in resonance with the fundamental mode of the building structure, so that a huge amount of the structural vibrating energy is transferred to the TMD and dissipated by damping as the building structure is subjected to earthquake loads.

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Multiple tuned mass dampers are more successful passive vibration control devices. In MTMD systems, MTMDs are tuned to several modes of structure vibration. In the present study, top storey displacement, acceleration, base shear and inter-storey drift of the buildings under study are obtained using MTMDs for different real earthquake time history data. The MTMDs are installed at each storey level to mitigate any undesirable vibration induced by earthquake load. The performance of MTMDs, spatially distributed in a primary structure, is investigated considering wind loads (Bergman et al., 989; Bergman et al., 1991). Most researchers have applied MTMDs for single-degree systems (Xu and Igusa, 1992; Igusa and Xu, 1994). It has been demonstrated that MTMDs with distributed natural frequencies are more effective than a single TMD. Effectiveness and robustness of MTMDs under dynamic load were studied (Yamaguchi and Harnpornchai, 1993; Kareem and Kline, 1995; Janjid, 1995). The present paper deals with the effectiveness and robustness of MTMDs in controlling structure vibration under real earthquake loads. It is revealed that MTMDs significantly reduce drift, acieration and force response of all types of buildings subjected to sinusoidal loads (Sakr, 2015). The design of MTMDs in an irregular building is presented. It was found that MTMDs are so much effective than STMDs (Levan and Daniel, 2013). It was found that dynamic response is reduced as a result of wind and earthquake excitation using a number of passive and active TMDs in tall buildings (Kowk and Samali, 1995). It was found that the optimal TMD parameters considerably reduce the response of structures for various types of seismic loading (Sadek et al., 1997). A numerical study is carried out to evaluate the effectiveness and robustness of MTMD system and the performance of structures in this study.

Description of STMD and MTMD Systems

The aim of designing an MTMD system is to tune damper parameters to the fundamental mode of vibration. This means that the natural frequency of a damper (or a group of dampers), ω_d, must be close to the natural frequency of the fundamental vibration mode of the structure (ω_d, ω_s). Moreover, the damping coefficient of the damper must be appropriately chosen (Zuo and Nayfeh, 2005) and c_j is obtained using equations developed by (Denhartog, 1947) for the SDOF damper.

The optimum parameters of such damper (or group of MTMDs) can be obtained by equations developed by Warburton (1982). The optimal frequency ratio is determined from:

$$(\frac{\omega_d}{\omega_s})^2 = \frac{2+\mu}{2(1+\mu)^2} \tag{1}$$

where:

$$m = \frac{\sum_{j=1}^{n} m_j}{m_s}, w_s^2 = \frac{k_s}{m_s}, w_d^2 = \frac{k_d}{m_d}, m_d \ \sum_{j=1}^{n} m_j \tag{2}$$

Motion Equation of Structure and MTMD System

The equation of motion of an MDOF system attached with MTMD and STMD (as shown in Fig. 2) can be expressed as:

$$\widetilde{M}\ddot{Y} + \tilde{C}\dot{Y} + \widetilde{K}Y = -\widetilde{M}\tilde{r}\ddot{Z}_b \tag{3}$$

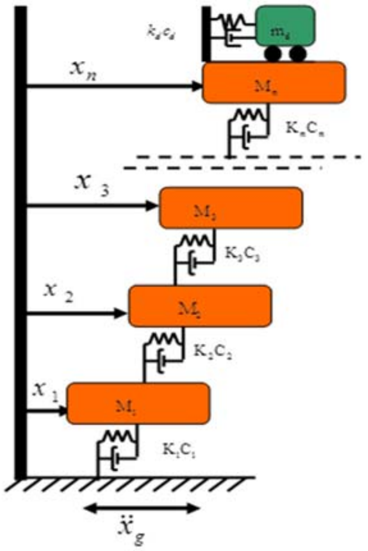

Figure (1): Structure-STMD system

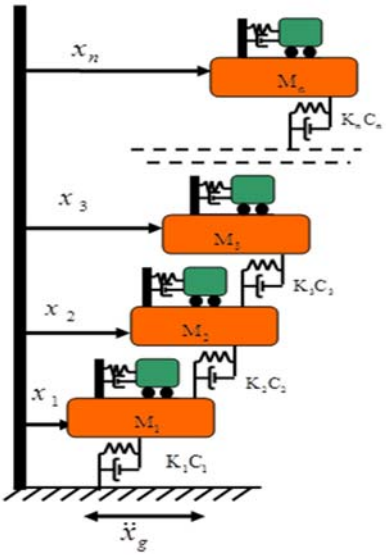

Figure (2): Structure-MTMD System

where: $Y = [x_s, x_1, x_2, \dots, x_n]^T$ is the relative displacement vector and $\bar{r} = [0\ I]^T$, where I is an $n \times 1$ unit vector.$\tilde{M}$, $\tilde{C}$ and $\tilde{K}$ represent the mass, damping and stiffness matrix of the combined system:

$$\tilde{M} = \begin{bmatrix} M_s & 0 \\ 0 & m \end{bmatrix} \tag{4}$$

where: $M_s$is the mass matrix of the structure and m is the matrix of dampers.

$$m = \text{diag}\,[m_1, m_2, \dots, m_n] \tag{5}$$

The stiffness matrix $\tilde{K}$ of the considered system can be written in the block form shown below:

$$\tilde{K} = \begin{bmatrix} k_s + k_d & k^* \\ k^{*T} & k \end{bmatrix} \tag{6}$$

where: k_s is the stiffness matrix of the structure and

$$k_d = \sum_{j=1}^{n} k_j \text{ and } k^* = [-k_1, -k_2, \dots, -k_n]$$

$$k = diag[k_1, k_2, \dots, k_n] \tag{7}$$

The damping matrix of the system $\tilde{C}$ is in a form similar to that of the stiffness matrix $\tilde{K}$. The specific blocks of this matrix are shown below:

$$\tilde{C} = \begin{bmatrix} c_s + c_d & c^* \\ c^{*T} & c \end{bmatrix} \tag{8}$$

where: c_s is the damping matrix of the structure and

$$c_d = \textstyle\sum_{j=1}^{n} c_j \text{ and } c^* = [-c_1, -c_2, \dots, -c_n] \tag{9}$$

$$c = \text{diag}[c_1, c_2, \dots, c_n]$$

$$\frac{c_j}{2\sqrt{m_j k_j}} = \sqrt{\frac{3\mu_j}{8(1+\mu_j)}} \quad , \xi_j = \frac{c_j}{2 m_j \omega_j} \tag{10}$$

Numerical Study

For a four-storey building with MTMD system, subjected to real earthquake, time history data analysis is carried out to study the performance of the proposed MTMD system. The MTMDs are distributed and installed at each storey. The building has the following mass and stiffness values:

$m_1 = m_2 = m_3 = 102.94´\ 10^3$ kg, $m_4 = 95.45´\ 10^3$ kg

$$k_1 = k_2 = k_3 = 243.53´\ 10^6 \text{N/m}$$
$$k_4 = 243.53´\ 10^6 \text{ N/m}$$

Unless mentioned otherwise, the following nominal values are assumed for the various parameters: damping ratio of structures $\xi_s = 5\%$, mass ratio $\mu = 5\%$. The fundamental natural frequency of the building is f_1 = 1.797264 Hz, which is tuned by STMD frequency and average frequency of MTMD system. The fundamental frequency of the building as well as STMD and MTMD frequencies are obtained by using MATLAB program. The analysis is performed using SAP 2000 software.

RESULTS AND DISCUSSION

The variation of structure displacement with time considering time history data of Kobe earthquake, Imperial Valley earthquake and Mammoth Lake earthquake using STMD, MTMDs and without dampers is shown in Figs. 3, 4 and 5 and in Table 1. It is observed that the MTMD system is more effective in reducing the displacement of the building. The maximum top storey displacement under Kobe earthquake is reduced 92.8% using MTMD and 31.15% using STMD. 91.6% and 26.02% reductions of top displacement are observed using MTMDs and STMD considering Imperial Valley earthquake. Similarly, it is observed that 92.7% and 30.97% reductions are achieved using MTMDs and STMD under Mammoth Lake earthquake. The above displacement reductions are observed within the duration of 10-15 s.

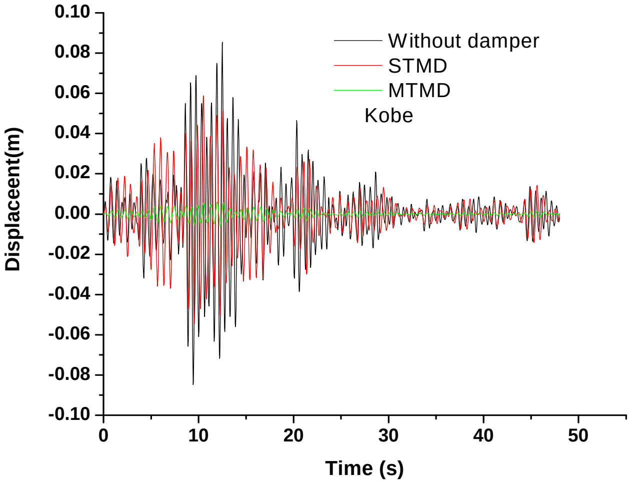

Figure (3): Variation of displacement of structures with time considering time history data of Kobe earthquake

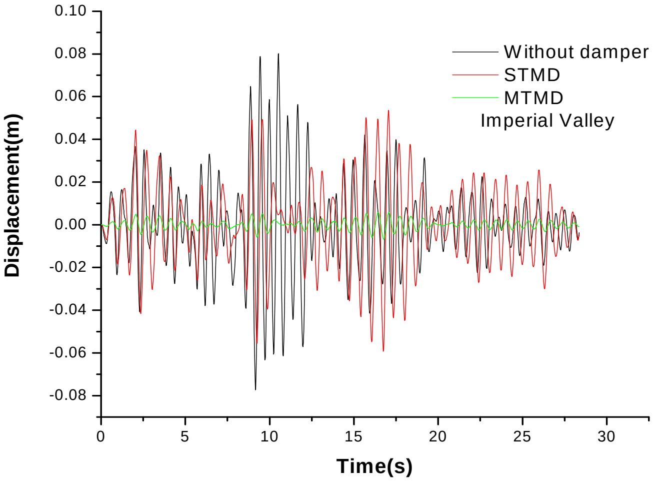

Figure (4): Variation of displacement of structures with time considering time history data of Imperial Valley earthquake

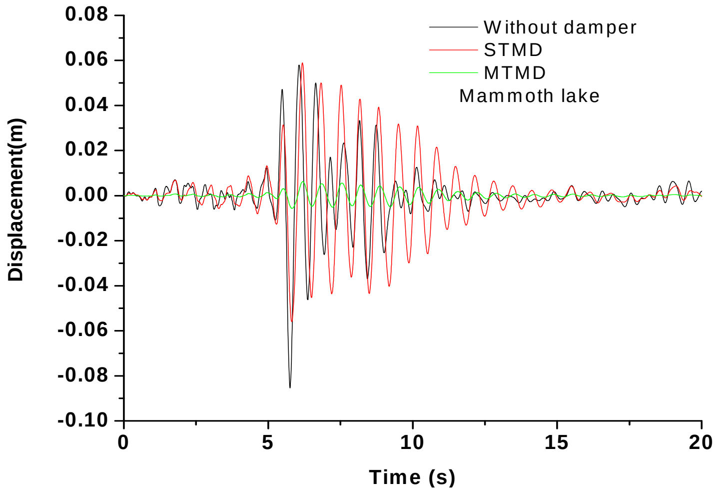

Figure (5): Variation of displacement of structures with time considering time history data of Mammoth Lake earthquake

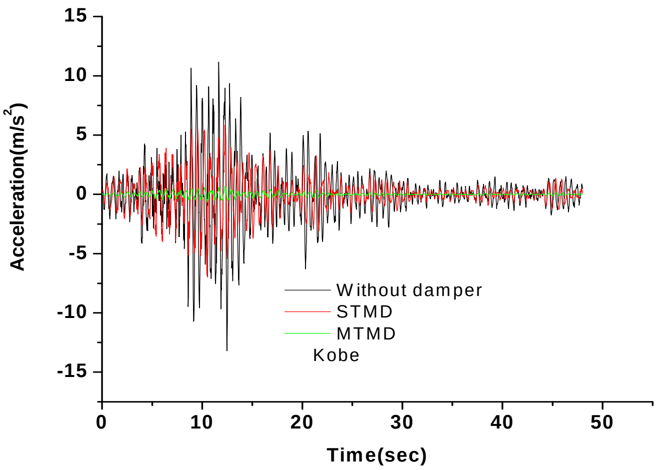

Figure (6): Variation of acceleration of structures with time considering time history data of Kobe earthquake

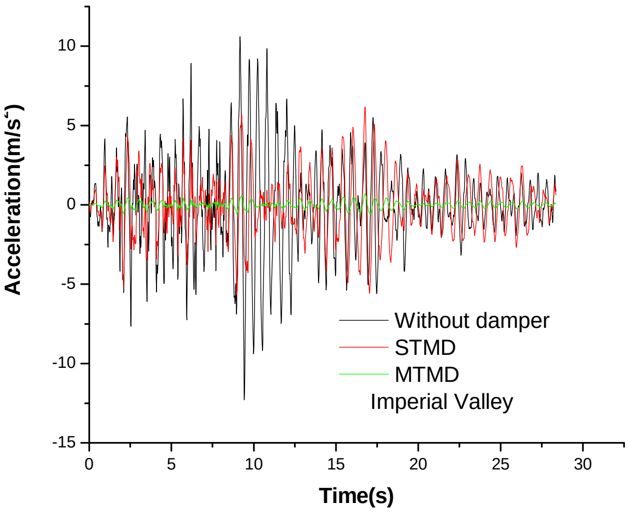

Figure (7): Variation of acceleration of structures with time considering time history data of Imperial Valley earthquake

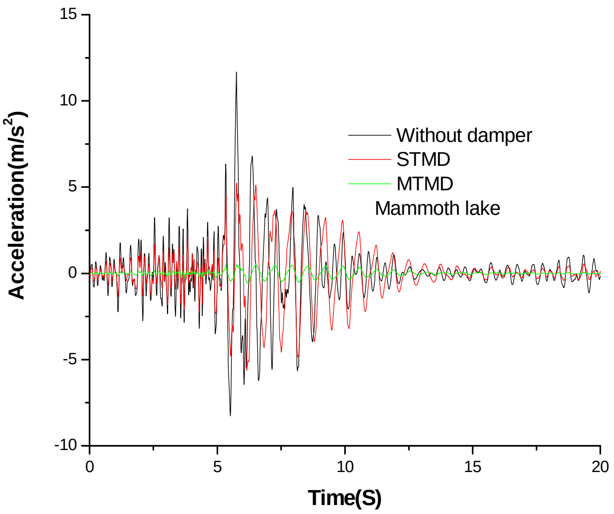

Figure (8): Variation of acceleration of structures with time considering time history data of Mammoth Lake earthquake

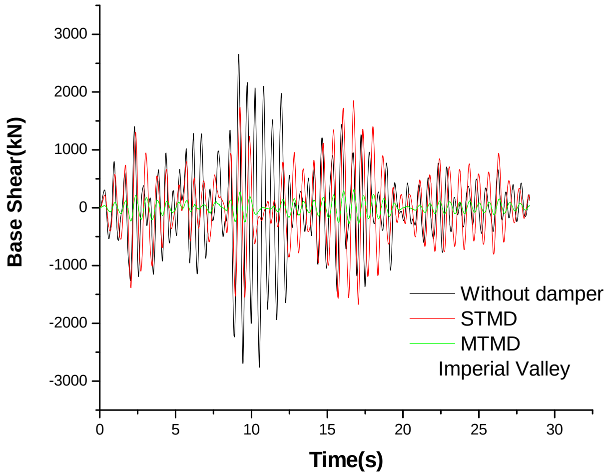

Figure (10): Variation of base shear of structures with time considering time history data of Imperial Valley earthquake

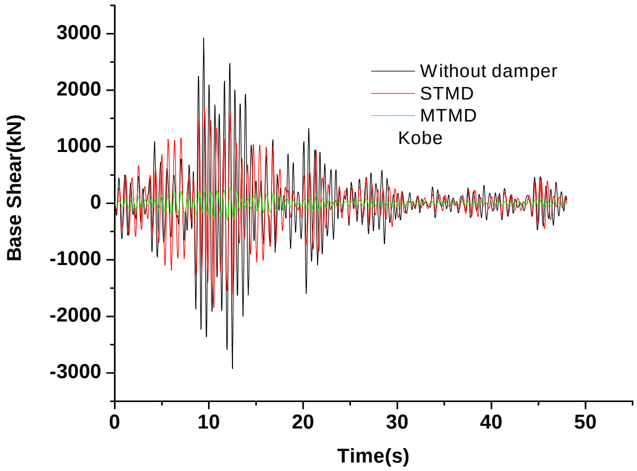

Figure (9): Variation of base shear of structures with time considering time history data of Kobe earthquake

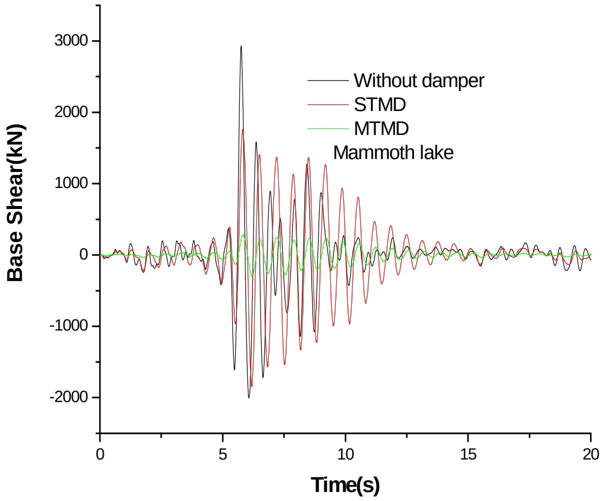

Figure (11): Variation of base shear of structures with time considering time history data of Mammoth Lake earthquake

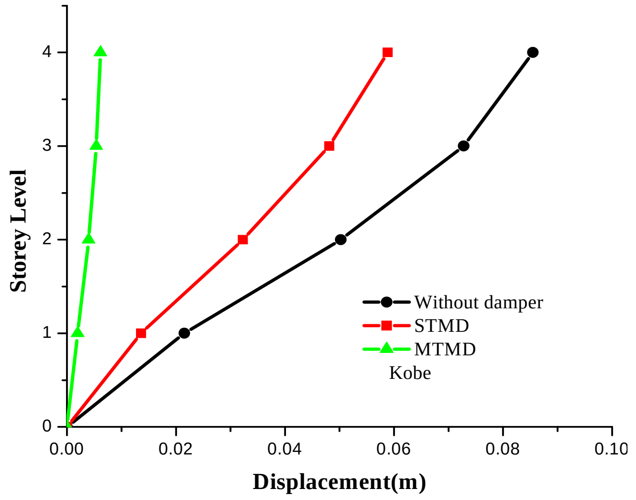

Figure (12): Variation of displacement of structures with storey level considering time history data of Kobe earthquake

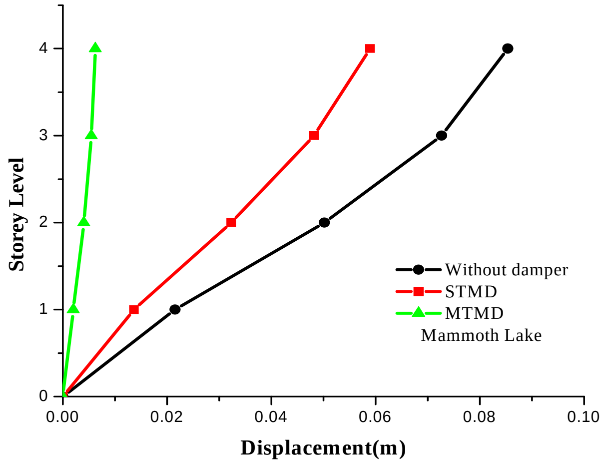

Figure (14): Variation of displacement of structures with storey level considering time history data of Mammoth Lake earthquake

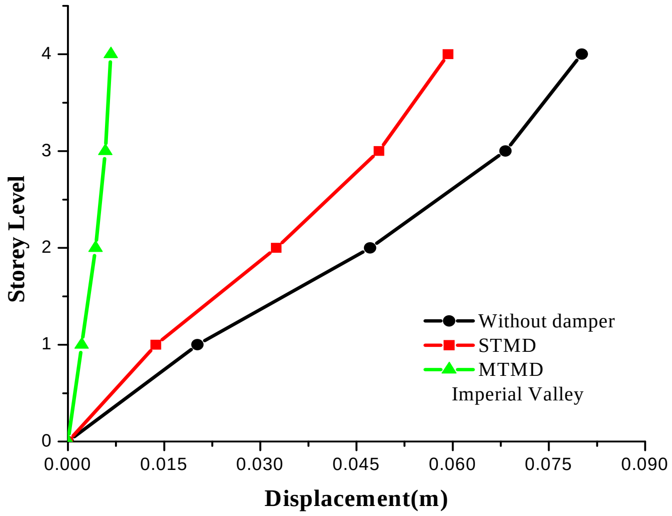

Figure (13): Variation of displacement of structures with storey level considering time history data of Imperial Valley earthquake

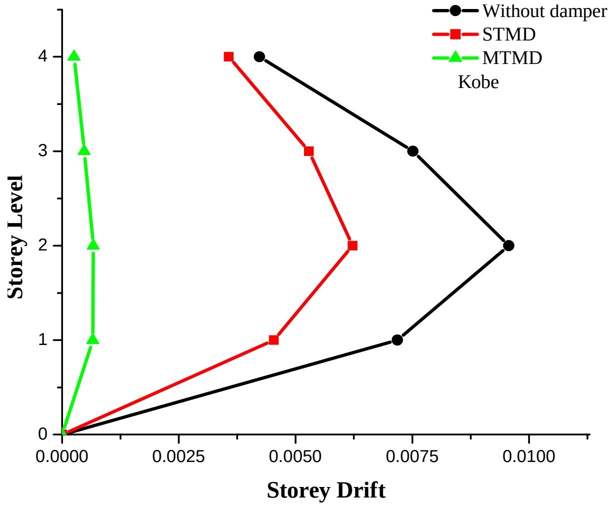

Figure (15): Variation of storey drift of structures with storey level considering time history data of Kobe earthquake

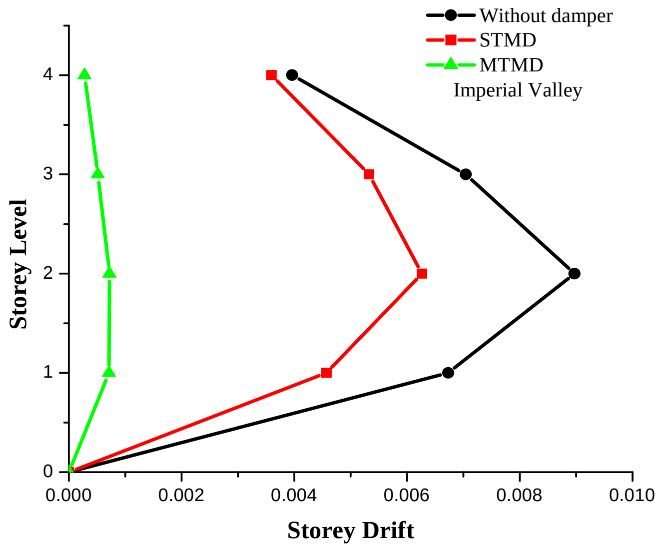

Figure (16): Variation of storey drift of structures with storey level considering time history data of Imperial Valley earthquake

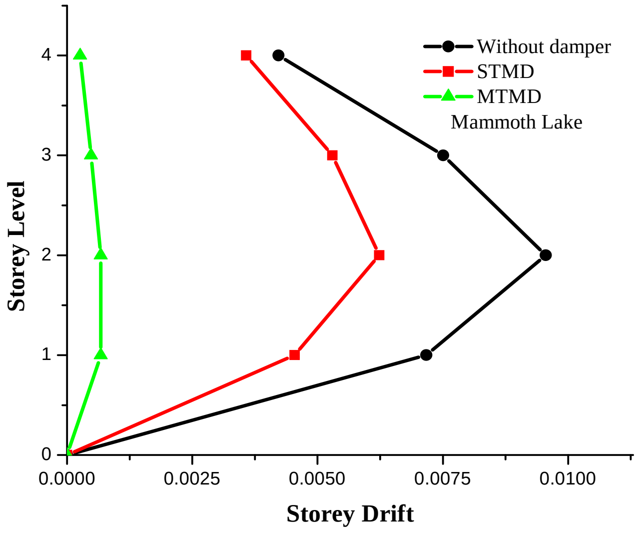

Figure (17): Variation of storey drift of structures with storey level considering time history data of mammoth lake earthquake

Table 1. Displacements of building using STMD, MTMDs and without dampers for different earthquakes

Displacement (m)				
Earthquake	**Floor Level**	**Without TMD**	**STMD**	**MTMDs**
Kobe	4	0.085483	0.058849	0.006166
	3	0.072801	0.048139	0.005395
	2	0.050253	0.032273	0.003976
	1	0.021544	0.013612	0.001975
Imperial Valley	4	0.080135	0.059277	0.006688
	3	0.068246	0.048489	0.005852
	2	0.047109	0.032508	0.004312
	1	0.020196	0.013711	0.002142
Mammoth Lake	4	0.085381	0.058931	0.006239
	3	0.072714	0.048206	0.005459
	2	0.050193	0.032318	0.004023
	1	0.021518	0.013631	0.001998

The variation of acceleration at the top storey of the building with time history data of Kobe earthquake, Imperial Valley earthquake and Mammoth Lake earthquake using STMD, MTMDs and without dampers is shown in Figs. 6, 7 and 8 and in Table 2. It is observed that the MTMD system is more effective in reducing the acceleration at the top storey of the building compared to STMD. The acceleration reductions at the top storey are observed to be 93.86%, 94.308% and 95.21% under Kobe, Imperial Valley and Mammoth Lake earthquakes, respectively using MTMDs. Similarly, 37.28%, 49.84% and 51.82% reductions of acceleration are recorded at the same storey using STMD. The duration of earthquake motion is considered within 10-15 s.

The base shear variation of the building with STMD, MTMDs and without dampers is shown in Figs. 9, 10 and 11 and in Table 3, for Kobe, Imperial Valley and Mammoth Lake earthquakes. Higher base shear reductions are observed considering MTMDs with comparison to STMD.

The variation of displacement at storey levels of structures considering time history data of Kobe, Imperial Valley and Mammoth Lake earthquakes using STMD, MTMDs and without damper are shown in Figs. 12, 13 and 14 and in Table 1. From these figures, it can be seen that MTMDs are more effective compared to STMD configuration considering 5% mass ratio and 5% damping ratio of structures.

The variations of storey drift are shown in Figs. 15-17. From these figures, it can be observed that MTMDs are more effective and robust in comparison to STMD configuration.

Table 2. Acceleration of building using STMD, MTMDs and without dampers for different earthquakes

Acceleration (m/s^2)				
Earthquake	**Floor Level**	**Without TMD**	**STMD**	**MTMDs**
Kobe	4	13.20116	7.00063	0.68505
	3	11.24261	5.72656	0.59938
	2	7.76059	3.8392	0.4417
	1	3.32703	1.61929	0.21941
Imperial Valley	4	12.30153	6.17018	0.70025
	3	10.47645	4.64463	0.61267
	2	7.23173	3.38377	0.4515
	1	3.1003	1.4272	0.22427
Mammoth Lake	4	11.67865	5.62623	0.55906
	3	9.94599	4.60229	0.48914
	2	6.86555	3.08547	0.36046
	1	2.94332	1.30138	0.17905

Table 3. Base shear of building using STMD, MTMDs and without dampers for different earthquakes

Earthquake	**Base shear (kN)**		
	without TMD	**STMD**	**MTMDs**
Kobe	2926.567	1849.496	296.055
Imperial Valley	2760.439	1851.716	310.868
Mammoth Lake	2930.325	1847.162	300.911

CONCLUSIONS

The performance of multiple tuned mass dampers (MTMDs) in mitigating seismic vibration of structures considering real time history data is investigated in this paper. For comparison, STMD is also installed at the top storey of the structure. It is observed that displacement reduction as a result of using MTMDs is higher compared to STMD for all real earthquake cases. Similarly, the % reductions of floor acceleration are also more for MTMD configuration with respect to STMD configuration for all real earthquake cases. Maximum reductions in base shear inter-storey drift are also found higher using MTMD configuration in all real earthquake cases. Based on the present study, it can be observed that the effectiveness and robustness of MTMD configuration are higher compared to STMD configuration, which is also valid for the overall system performance.

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