Effectiveness of Tuned Mass Dampers in Mitigating Earthquake Ground Motions in Low and Medium Rise Buildings

Zixiang Zhou [1], Husam Najm[2], & Rosa Vasconez[3]

Abstract

Tuned mass dampers (TMD's) are passive energy devices used to reduce undesired vibrations in a number of structures or structural components such as industrial buildings, floor systems, and others. There have been few studies on the effectiveness of TMD's in reducing earthquake effects in low rise and medium rise buildings. This paper investigates the effectiveness of tuned mass dampers on the response of low rise and medium rise buildings under earthquake ground motions. Numerical integration methods were used to solve the systems of coupled equations of motion. Response parameters include roof displacements, base shears, and story drifts. Results from this analysis showed that the TMD can be effective in reducing drifts and base shears in low and medium rise buildings. The reduction was dependent on the TMD properties and location and optimum properties of the damper. A reduction of about 30% was observed in roof displacements for a mass ratio of 10% of the modal mass. A 25% reduction in base shear was also observed for certain cases despite the overall increase of mass of the system. However, this reduction should be interpreted taking into consideration the magnitude of drifts and base shears to justify the use of TMD's

Keywords: TMD, drift, mass ratio, damping, base shear, frequency ratio

1. Introduction

Flexible structures and structures with low inherent damping are susceptible to vibrations and higher displacements. In non-building structures, vibrations can lead to discomfort, larger displacements due to resonance, fatigue-related distress, erroneous readings in sensitive equipment, and others. In building structures, flexibility and low damping can cause discomfort, lead to excessive drifts, cracking, severe non-structural damage, and potential instability and collapse. There are many vibration mitigation techniques that can be used to enhance structural response and improve performance. They include: viscous dampers, friction dampers, visco elastic dampers, tuned mass dampers (TMD), tuned liquid dampers (TLD), yield plates, BFB braces, isolation bearings and others.

Tuned mass dampers (TMD's) are passive energy devices consisting of a mass, a spring, and a viscous damper attached to a vibrating system [Sadek et al, 1997] used to reduce these undesired effects which may result from machinery, wind loads, blast loads, and earthquake ground motions. They are mounted at certain location in the structure in order to maximize the reduction of its dynamic response. A tuned mass damper (TMD) can be described by three parameters:

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Mass ratio μ defined as the ratio of the mass of the damper to the mass of single degree of freedom (SDOF) system or the generalized mass for a given mode of vibration of a multiple degree of freedom (MDOF) system [Sadek et al, 1997**]**.

$$\mu = \frac{m_d}{m} \text{ or } \quad \mu = \frac{m_d}{\emptyset_1{}^T M \emptyset_1}$$

Frequency ratio *f* is defined as the ratio of the fundamental frequency of the damper to the natural frequency of a SDOF system or the frequency corresponding to the first mode of vibration for a MDOF system.

$$f = \frac{\omega_d}{\omega_n} = \frac{\omega_d}{\omega_1}$$

Where ω_d is the undamped natural frequency of the damper and ω_n and ω_1 is the undamped natural frequency of the SDOF and first mode of MDOF system respectively. The TMD damping ratio ξ_d defined as

$$\xi_d = \frac{c_d}{2 m_d \omega_d}$$

The TMD properties (mass, stiffness, and damping) are typically tuned to a resonant frequency of a particular mode. Energy is dissipated in the damper through inertia forces and damping. The effectiveness of a TMD in buildings depends on the ability of the TMD to increase the system damping to provide enough energy dissipation in the structure. This effectiveness depends on the following variables: 1) the mass ratio, 2) the damping ratio of the TMD; and 3) frequency or the tuning ratio. TMDs are typically placed at locations with highest displacements. TMDs can also be also used for individual floors or individual components; however, the use of multiple TMDs was not evaluated in this study.

1.1. Early Applications of TMD Systems

The concept of tuned mass damper can be traced back to 1909, when Frahm invented a dynamic vibration absorbing device [Rana et al, 1998] to control vibrations. Since then, researchers have done a lot of work in the passive control theory and application. Studies show that TMD devices are effective in reducing the response due to the harmonic [Hartog, 1985] or wind excitations [Luft, 1997, McNamara, 1977]. In early 1950's, the engineers in former Soviet Union applied percussive pendulum on the steel tower and chimney to reduce the structural vibration under wind load excitation.

In 1970's, engineers installed massive TMD devices in the 350 m high John Hancock Tower in Boston[ENR,1975] and the 300m high Citicorp Center in New York City [ENR,1977],and effectively reduced the wind-induced response. In 1980, a TMD was also successfully installed on the Sydney Tower in Australia to control the wind-induced vibration. In Japan, the first TMD device was installed on the Chiba Port Tower in 1980, and followed by the Funade Bridge in Osaka. In 2004, a 660 ton spherical TMD was installed in the Taipei 101 Tower in Taiwan, which is considered to be the largest damper in the world.

1.2. Previous Research on TMD Devices

Previous research by Gupta and Chandrasekaren [0] suggested that TMD may not be effective in reducing seismic loads because of the nature of their time history. Kanyia et al [981] reported that the TMD was not effective in reducing earthquake load effects. Sadek el al [1997] seems to indicate that there has not been a general agreement on the effectiveness of TMD systems in reducing structural response in buildings due to seismic loads. However, the research done by Wirsching and Yao [1973] showed the TMD devices can be effective in reducing building response to earthquake loads. They used a mass ratio of 50%, frequency ratio of 1 and a damping ration of 20%.

Miyama [992] found out that a TMD system with low mass ratios (< 2%) is not effective in reducing seismic load effects and suggested that the top story should be capable of dissipating enough seismic energy so that the other stories are not damaged or sustain minor damage. The work by Villaverde [1994] and Villaverde and Koyama [1993] showed that TMD systems tuned to the proper frequency ratio and damping can be effective in minimizing seismic load effects. This study used numerical techniques to evaluate the effects of TMD for various parameters on the response of a 4-story and 10 story buildings under earthquake ground motions. Observations of the response values such as displacements and base shear for the various parameters are used to identify optimum TMD properties.

2. Response of 2-DOF Structural System to a TMD

A two degree of freedom system with a tuned mass damper attached to top level was subjected to applied loads and ground accelerations as shown in Fig. 1. The governing equations of motions for the system are given in equations (1), (2), and (3). Equations (4) and (5) are matrix representations of equations (1) to (3). The system is a coupled system of differential equations.

$$m_1\ddot{u}_1 + c_1\dot{u}_1 + k_1u_1 - k_2(u_2 - u_1) - c_2(\dot{u}_2 - \dot{u}_1) = p_1 - m_1\ddot{u}_g \qquad (1)$$

$$m_2\ddot{u}_2 - c_2\dot{u}_1 + c_2\dot{u}_2 - k_2u_1 + k_2u_2 - k_d u_d - c_d\dot{u}_d = p_2 - m_2\ddot{u}_g \qquad (2)$$

$$m_d\ddot{u}_d + c_d\dot{u}_d + k_d u_d = -m_d(\ddot{u}_2 - \ddot{u}_g) \qquad (3)$$

This can be written in matrix format as follows:

$$M\ddot{u} + C\dot{u} + Ku = P - F + K_d u_d + C_d\dot{u}_d \qquad (4)$$

$$m_d\ddot{u}_d + c_d\dot{u}_d + k_d u_d = -m_d(\ddot{u}_2 - \ddot{u}_g) \qquad (5)$$

Where

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}; \quad C = \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix}; \quad K = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}$$

$$P = \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}; \quad F = \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = MI\ddot{u}_g; \quad K_d = \begin{bmatrix} 0 \\ k_d \end{bmatrix}; \quad C_d = \begin{bmatrix} 0 \\ c_d \end{bmatrix}$$
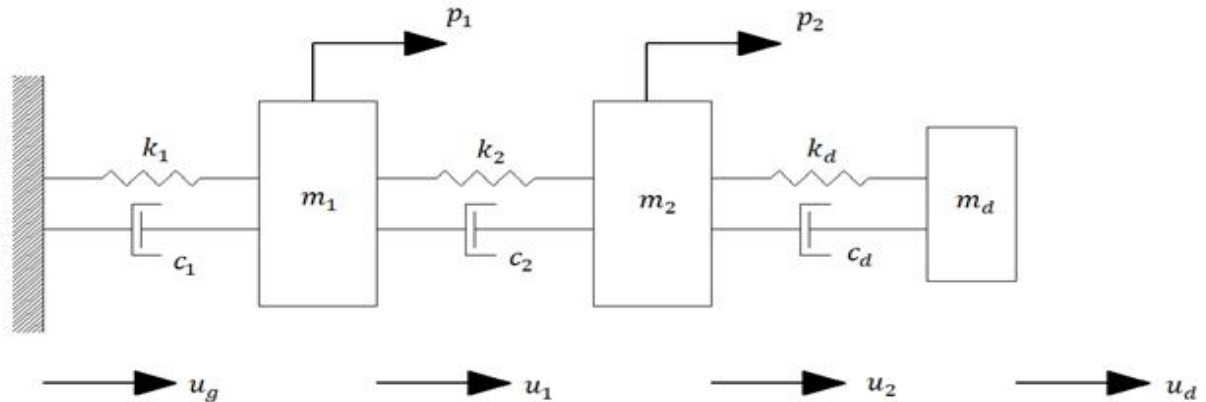

Fig. 1: 2-DOF System with TMD under ground motion excitation and applied loads.

The Newmark-β method [Gavin, 2011] was used to express the displacement and velocity of the primary mass and damper using the following recurrence relations:

$$u_{i+1} = u_i + \Delta \dot{u}_i + \Delta^2[\left(\tfrac{1}{2} - \beta\right)\ddot{u}_i + \beta \ddot{u}_{i+1}] \tag{6}$$

$$\dot{u}_{i+1} = \dot{u}_i + \Delta[(1 - \gamma)\ddot{u}_i + \gamma \ddot{u}_{i+1}] \tag{7}$$

$$u_{d+1} = u_d + \Delta \dot{u}_d + \Delta^2[\left(\tfrac{1}{2} - \beta\right)\ddot{u}_d + \beta \ddot{u}_{d+1}] \tag{8}$$

$$\dot{u}_{d+1} = \dot{u}_d + \Delta[(1 - \gamma)\ddot{u}_d + \gamma \ddot{u}_{d+1}] \tag{9}$$

Substitute u_{i+1}; $\dot{u}_{i+1}$ into (4) and u_{d+1}; $\dot{u}_{d+1}$ into (5)

$$[\boldsymbol{M} + \boldsymbol{C}\Delta\gamma + \boldsymbol{K}\Delta^2\beta]\ddot{u}_{i+1} + \left[\boldsymbol{C}\Delta(1 - \gamma) + \boldsymbol{K}\Delta^2\left(\tfrac{1}{2} - \beta\right)\right]\ddot{u}_i + [\boldsymbol{C} + \boldsymbol{K}\Delta]\dot{u}_i + \boldsymbol{K}u_i$$

$$= P_{i+1} - F_{i+1} + [K_d\Delta^2\beta + C_d\Delta\gamma]\ddot{u}_{d+1}$$

$$+ \left[K_d\Delta^2\left(\tfrac{1}{2} - \beta\right) + C_d\Delta(1 - \gamma)\right]\ddot{u}_d + [K_d\Delta + C_d]\dot{u}_d + K_d u_d \tag{10}$$

or

$$[m_d + c_d\Delta\gamma + k_d\Delta^2\beta]\ddot{u}_{d+1} + \left[c_d\Delta(1 - \gamma) + k_d\Delta^2\left(\tfrac{1}{2} - \beta\right)\right]\ddot{u}_d$$

$$+ [c_d + k_d\Delta]\dot{u}_d + k_d u_d = -m_d(\ddot{u}_2)_{i+1} - m_d u_{g\,i+1} \tag{11}$$

The following matrices, **H₁, H₂, H₃, H₄, H₅, H₆, H₇, and H₈** were defined to simplify the computations:

$$\boldsymbol{H_1} = \boldsymbol{M} + \boldsymbol{C}\Delta\gamma + \boldsymbol{K}\Delta^2\beta$$
$$\boldsymbol{H_2} = \boldsymbol{C}\Delta(1 - \gamma) + \boldsymbol{K}\Delta^2\left(\tfrac{1}{2} - \beta\right)$$
$$\boldsymbol{H_3} = \boldsymbol{C} + \boldsymbol{K}\Delta$$
$$\boldsymbol{H_4} = \boldsymbol{K}$$
$$\boldsymbol{H_5} = K_d\Delta^2\beta + C_d\Delta\gamma$$
$$\boldsymbol{H_6} = K_d\Delta^2\left(\tfrac{1}{2} - \beta\right) + C_d\Delta(1 - \gamma)$$
$$\boldsymbol{H_7} = K_d\Delta + C_d$$
$$\boldsymbol{H_8} = K_d$$

The matrices **H₁** thru **H₈** are all $n \times n$ matrices

The following scalar quantities B₁, B₂, B₃, B₄, and B₅ were also introduced to simplify the computations:

$$B_1 = m_d + c_d\Delta\gamma + k_d\Delta^2\beta$$
$$B_2 = c_d\Delta(1 - \gamma) + k_d\Delta^2\left(\tfrac{1}{2} - \beta\right)$$
$$B_3 = c_d + k_d\Delta$$
$$B_4 = k_d$$

$$B_5 = -m_d$$

Eqn. (10) and Eqn. **(11)** could be expressed in the following forms:

$$\boldsymbol{H_1}\ddot{u}_{i+1} + \boldsymbol{H_2}\ddot{u}_i + \boldsymbol{H_3}\dot{u}_i + \boldsymbol{H_4}u_i = \boldsymbol{P_{i+1}} - \boldsymbol{F_{i+1}} + \boldsymbol{H_5}\ddot{u}_{d+1} + \boldsymbol{H_6}\ddot{u}_d + \boldsymbol{H_7}\dot{u}_d + \boldsymbol{H_8}u_d \quad \textbf{(12)}$$

$$B_1\ddot{u}_{d+1} + B_2\ddot{u}_d + B_3\dot{u}_d + B_4u_d = B_5(\ddot{u}_2)_{i+1} - m_d u g_{i+1} \quad \textbf{(13)}$$

Let

$$\widetilde{\boldsymbol{H}} = \boldsymbol{P_{i+1}} - \boldsymbol{F_{i+1}} + \boldsymbol{H_6}\ddot{u}_d + \boldsymbol{H_7}\dot{u}_i + \boldsymbol{H_8}u_d - \boldsymbol{H_2}\ddot{u}_i - \boldsymbol{H_3}\dot{u}_i - \boldsymbol{H_4}u_i$$
$$\widetilde{B} = B_2\ddot{u}_d + B_3\dot{u}_d + B_4u_d + m_d u g_{i+1}$$

Eqn. (12) and Eqn. (13) could be expressed as:

$$\begin{cases} \boldsymbol{H_1}\ddot{u}_{i+1} - \boldsymbol{H_5}\ddot{u}_{d+1} = \widetilde{\boldsymbol{H}} \\ B_5(\ddot{u}_2)_{i+1} - B_1\ddot{u}_{d+1} = \widetilde{B} \end{cases} \quad \textbf{(14)}$$

The solution given in equations (15) and (16) determines the acceleration time history response of the 2-DOF system and the damper

$$\ddot{u}_{i+1} = \begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{Bmatrix}_{i+1} = \begin{bmatrix} H_1^{11} & H_1^{12} - C_2^1 \\ H_1^{21} & H_1^{22} - C_2^2 \end{bmatrix}^{-1} \begin{Bmatrix} C_1^1 \\ C_1^2 \end{Bmatrix} \quad \textbf{(15)}$$

$$\ddot{u}_{d+1} = \frac{B_5(\ddot{u}_2)_{i+1} - \widetilde{B}}{B_1} \quad \textbf{(16)}$$

Where

$$\boldsymbol{C_1} = \widetilde{\boldsymbol{H}} - \boldsymbol{H_5}\frac{\widetilde{B}}{B_1}; \quad \boldsymbol{C_2} = \boldsymbol{H_5}\frac{B_5}{B_1}$$

The above solution for the 2-DOF system with a TMD was extended to 4-story building with TMD and 10- story building with TMD. It was also extended to solve the cases where the TMD is placed at different levels in these structures. The flow chart in Fig. 2 shows the algorithm used for solving the system of equations which was based on the derivation above. A Matlab code was developed to solve the system of equations using numerical methods.
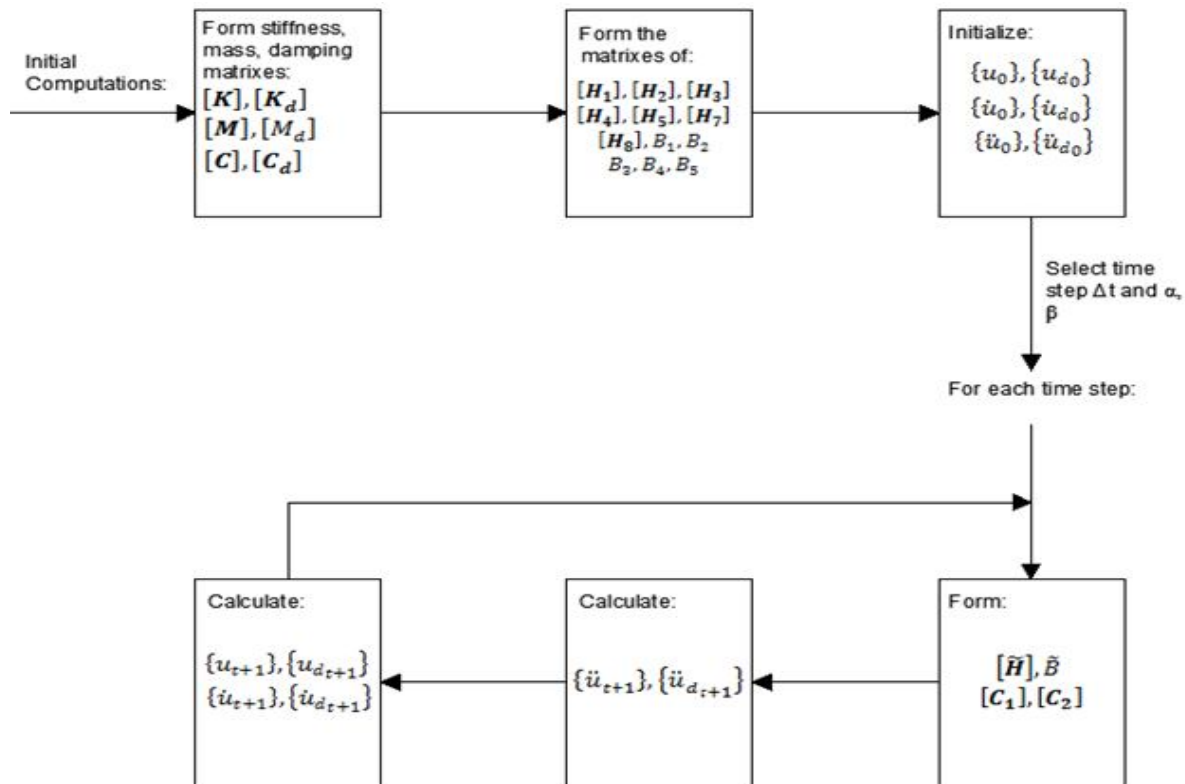
Fig. 2: Flow chart of the algorithms of the Matlab code.

3. Application of TMD to 4-Story and 10-Story Building Structures

In this study a single TMD was applied to a low rise and medium rise buildings. The TMD was placed at different levels in these buildings. The effects of TMD mass ratio, $\mu = m_d/\widetilde{M}_1$, TMD damping ratio, $\xi_d = c_d/(2\omega_d m_d)$, and TMD frequency ratio, $f = \omega_d/\omega_1$, were evaluated for different earthquake ground motions. The mass ratio μ was calculated as the ratio of the mass of the damper to the first mode mass of primary structure calculated as $\widetilde{M}_1 = \Phi_1^{-1} M \Phi_1$. The frequency ratio was calculated as the ratio of frequency of damper to the first mode frequency of primary structure. Fig. 3 shows the two structures evaluated in this study.

Fig. 3(a) shows a 4-story building structure with TMD at roof level and Fig. 3(b) shows a 10-story building structure with a TMD placed at roof level. The figures also shows the mass and stiffness properties of the building structures. Typical story height was 12ft (3.66 m) for both building structures. The parameters of the 4-story and 10-story building structures are tabulated in Table 1 and Table 2. Table 1 shows a fundamental period of vibration of 0.272 sec for mode 1 for the 4-story building. It also shows a modal mass for mode 1 equal to$6.6998 k \cdot s^2/in.$ Table 2 shows a fundamental period of 0.551sec for a 10-story building and a modal mass equal to$16.166 k \cdot s^2/in.$ A Matlab code was developed to carry out the mathematical calculations based on the equations given in section 1.2 for the response of a 2-DOF structure system with a TMD. The flow chart shown earlier in Fig. 2 shows the algorithm used in the Matlab code.
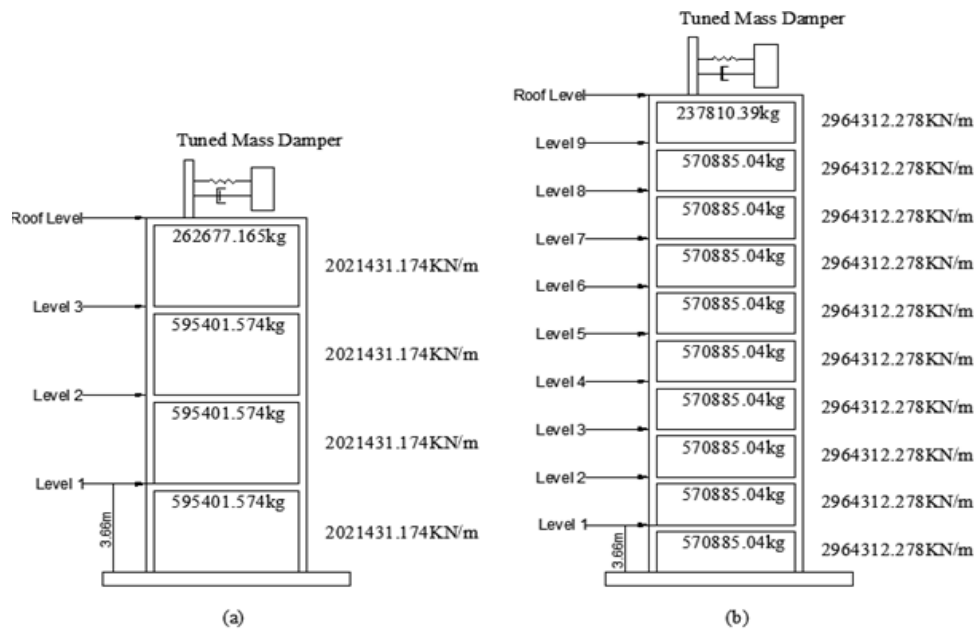
Fig. 3: Properties of the 4-story and 10-story buildings.

Table 1: Properties for 4-story building

Properties of Structure			
Natural Frequency (ω)	Natural Period(sec)	Orthogonal Modal Mass(kg)	Effective Modal Mass(kg)
23.0740	0.2723	1173256.3	1852276.8
65.7103	0.0956	1172818.5	163140.0
98.3501	0.0639	1170734.6	31626.3
116.3728	0.0540	801410.5	1838.7

Table 2: Properties for 10-story building

Properties of Structure			
Natural Frequency (ω)	Natural Period (sec)	Orthogonal Modal Mass(kg)	Effective Modal Mass(kg)
11.42	0.551	2830959	4569707
33.93	0.185	2833883	490856
55.61	0.113	2827124	164733
75.93	0.083	2842254	75143
94.38	0.067	2871674	38543
110.50	0.057	2868767	20401
123.90	0.051	2988320	10384
134.23	0.047	2720057	4605
141.21	0.045	2501527	1365
146.16	0.043	821811	17

3.1. Response of 4-Story Building Structure to TMD at Various Elevations

The 4-story building structure shown earlier in Fig. 3(a) was subjected to the El Centro ground motion. Two other ground motions (Lexington and Altadena) were also evaluated for comparisons. A single TMD was placed at the 4th level (roof level) and the 3rd level and the roof displacements and base shears were obtained for each TMD location. The effect of damping ratio of the first two modes of primary structure was also investigates. Two cases for damping ratios were selected: $\xi_1 = \xi_2 = 0.02$ and $\xi_1 = \xi_2 = 0.05$. Figure 4 shows the effect of the TMD mass ratio m on the roof displacements of the 4-story building. The building was subjected to the El Centro ground motion and the TMD was placed on the 4th level (roof level). The system damping of the primary structure was assumed to be 2%. The vertical axis in Figure 4 is the ratio of the roof displacement with the TMD in place to the original roof displacement (without the TMD). The horizontal axis is the TMD mass ratio μ defined earlier.
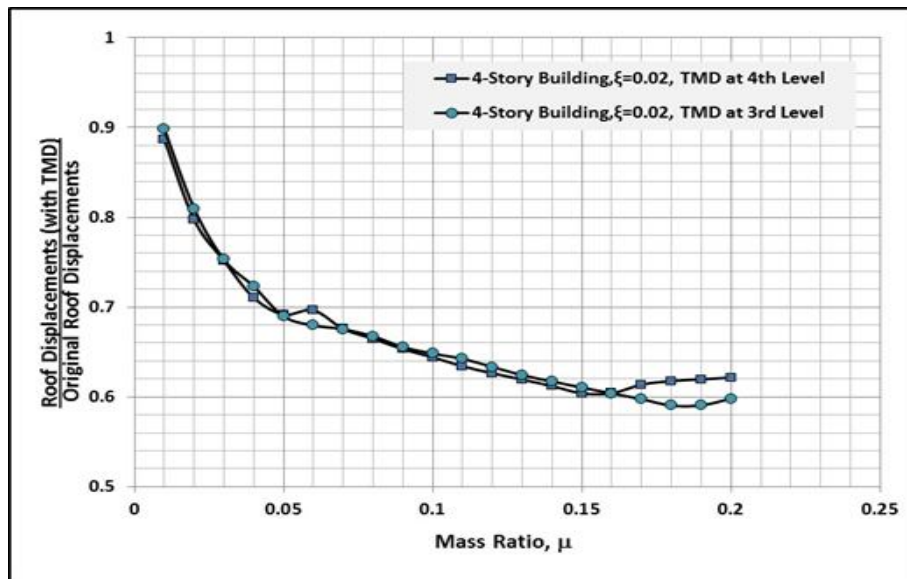

Fig. 4: Reduction in roof displacements with single TMD placed at 4th level and at 3rd level of 4-Story building damping with damping ratios $\zeta = 0.02$.

The plot in Fig. 4 shows the effect of mass ratio, μ, on the roof displacement obtained for the El Centro ground motion. The figure shows that the roof displacement decreases as the mass ratio, μ, increases. Figure 4 shows that for a mass ratio of 10% and damping ratio of 2% ($\mu = 0.1$ and $\xi_1 = \xi_2 = 0.02$), the roof displacement decreases to become 36% of the original displacement (without TMD). In other words, the reduction in roof displacement was about 36%. Similar reduction was observed when the TMD was placed at the 3rd level. Fig. 5 shows that when the damping ratio was 5% ($\xi_1 = \xi_2 = 0.05$), the reduction in roof displacements was about 30% due to the presence of the TMD.
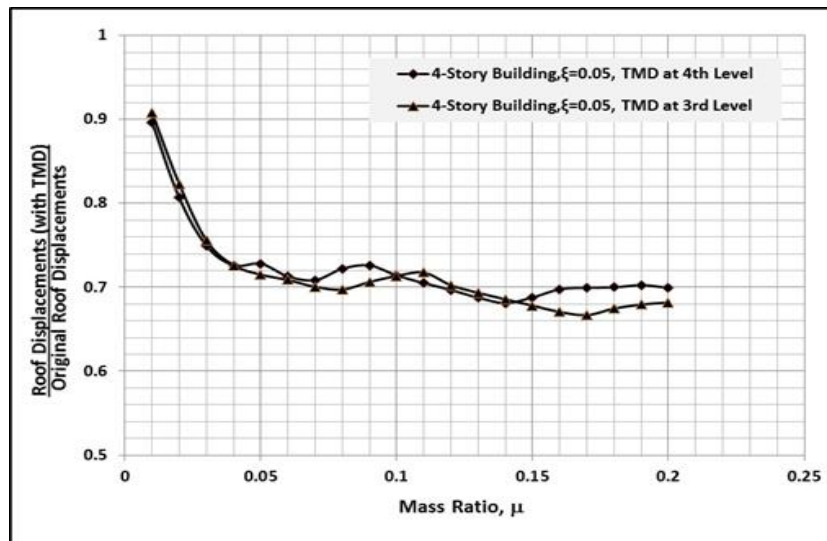
Fig. 5: Reduction in roof displacements with single TMD placed at 4th level and at 3rd level of 4-Story building damping with damping ratios ζ = 0.05.

Similar trend is found for the roof displacement for the other ground motions (Lexington and Altadena). Fig. 5 also shows that up to a mass ratio of 15% ((μ = 0.15), the reduction in roof displacement was similar for both locations of the TMD (3rd level or 4th level). However, for mass ratios between 15% and 25%, the reduction was higher when the TMD was at the 3rd level compared to the 4th level. The effect of the damping ratio of the primary structure on the roof displacement reduction is shown in Fig. 6. Fig. 6 shows that the reduction in roof displacements for a mass ratio of 10% (μ = 0.1) for ξ = 0.05 and ξ = 0.02 is 28% and 36%, respectively. For a mass ratio of 15% (μ = 0.15), these reductions were 31% and 40% respectively. This value indicated the effects of the TMD are more pronounced when the structure has lower damping ratios. However, the absolute roof displacement was still lower for the higher damping ratio. For example, the roof displacements were 0.858 in (21.8 mm), and 0.701 in (17.8 mm) for ξ = 0.02 and ξ = 0.05 respectively. With a TMD at 4th level and mass ratio is μ = 15%, the roof displacement were 0.518 in (13.2 mm), and 0.483 in (12.2 mm) for ξ = 0.02 and ξ = 0.05 respectively.
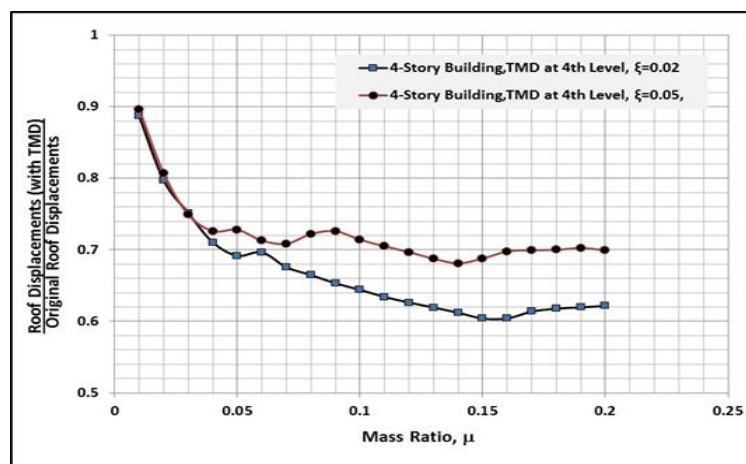

Fig. 6: Reduction in roof displacements with single TMD placed at 4th level of 4-Story building damping with damping ratios ζ = 0.02 and ζ = 0.05.

The effect of the TMD on the base shear for the 4-story building is shown in Figs. 7 and 8 for 2% and 5% respectively. Figs. 7 and 8 show the base shear decreases with the increase of mass ratio. It is also observed that the decrease is more pronounced with higher damping ratio. Both figures show that the base shear with TMD placed at 4th level is smaller than that when the TMD is placed at 3rd level for mass ratios less than 20% ($\mu < 0.2$). It is observed that the base shear for TMD placed at 4th level is similar to that when the TMD is placed at 3rd level when the damper mass is larger than 20% of the first mode modal mass $\widetilde{M}_1$ of the primary structure.
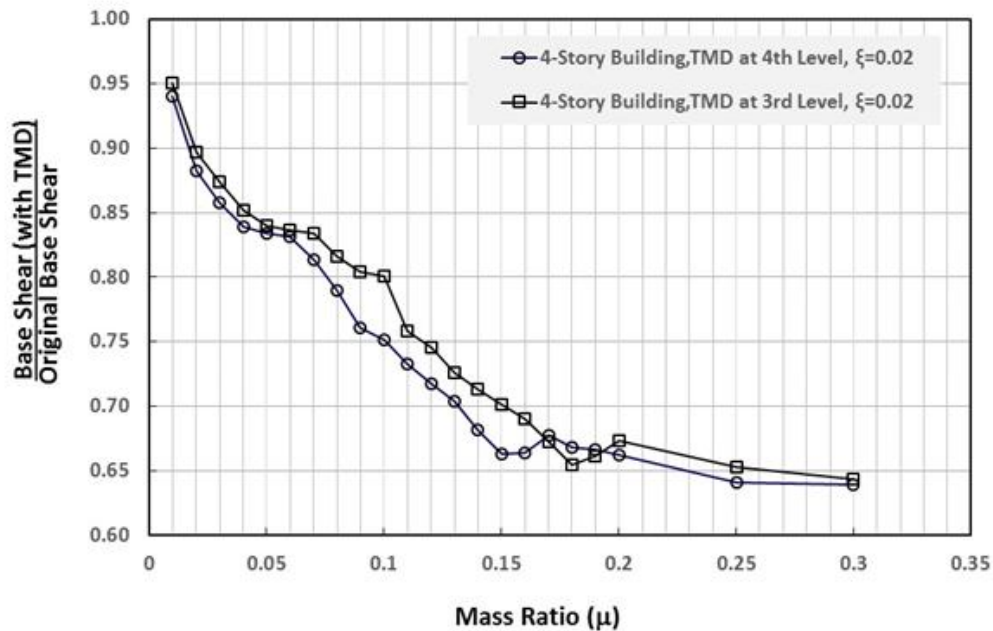
Fig. 7: Base shear reduction of 4-story structure for two locations of the TMD for damping coefficient of primary structure ζ =0.02.

While one would expect the base shear to increase with additional mass from the damper, the base shear of the system is still lower than the original base shear (without TMD) due the tuning effects of the damper in reducing the inertia forces. When the mass ratio is larger than 20%, there seems to be slight or no further reduction in the base shear. This may be attributed to the additional mass of the damper that contributes to higher inertia forces.

As expected, the base shear decreases with the increase of the damping ratio of the primary structure and the reduction in base shear was higher with higher damping. For example, for a mass ratio of 10% and a damping ratio of 2% ($\mu = 0.1$ and $\xi_1 = \xi_2 = 0.02$), the original elastic base shear was about 4,590 kips (20,415 kN) and the reduction was 25% when the TMD was placed at the 4th level as shown in Fig. 7. When the TMD was placed at the 3rd level the reduction in the base shear was about 20%. Fig. 8 shows that the reduction in the base shear for damping ratios of 5% and a mass ratio of 10% is 25% and 15% for the TMD at level 4 and level 3 respectively.
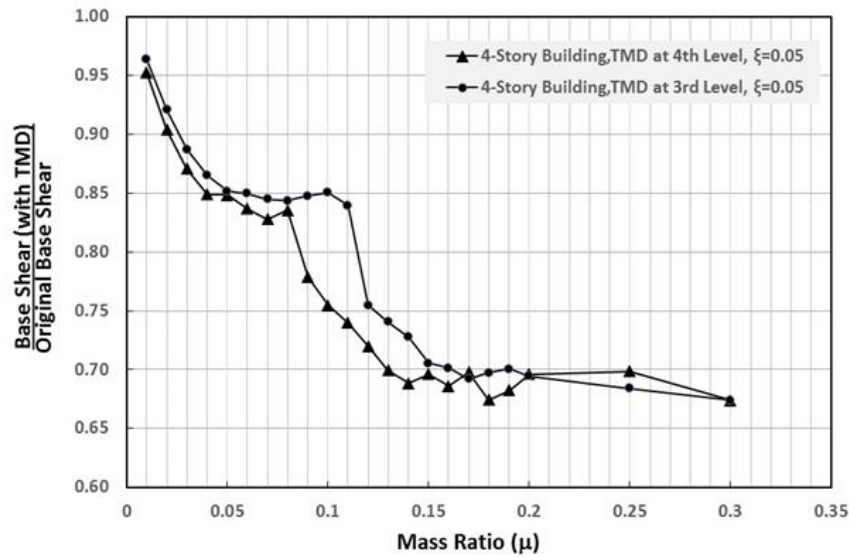
Fig. 8: Base shear reduction of 4-story structure for two locations of the TMD for damping coefficient of primary structure ζ =0.05.

With TMD attached at various levels, the base shear reduction when TMD placed at 4th level is higher than that when the TMD is placed at the 3rd level as shown in Figs. 7 and 8. The higher reduction with the TMD at level 4 may be attributed to the accelerations at the 4th level are lower than those with TMD placed at 3rd level. The optimal roof displacement reduction, base shear reduction, story drift, optimal damping ratio and optimal frequency ratio are obtained for the El Centro ground motion. The changes in roof displacement and base shears when the building-damper system was subjected to the Altadena and Lexington ground motion are shown in Figs. 9 and 10 respectively. Figs. 9 and 10 show different trends than those observed for the Elcentro ground motion. Fig. 9 shows that the TMD amplifies the roof displacements for the Altadena and the Lexington ground motions when the mass ratio is less than 15% and 25% respectively.
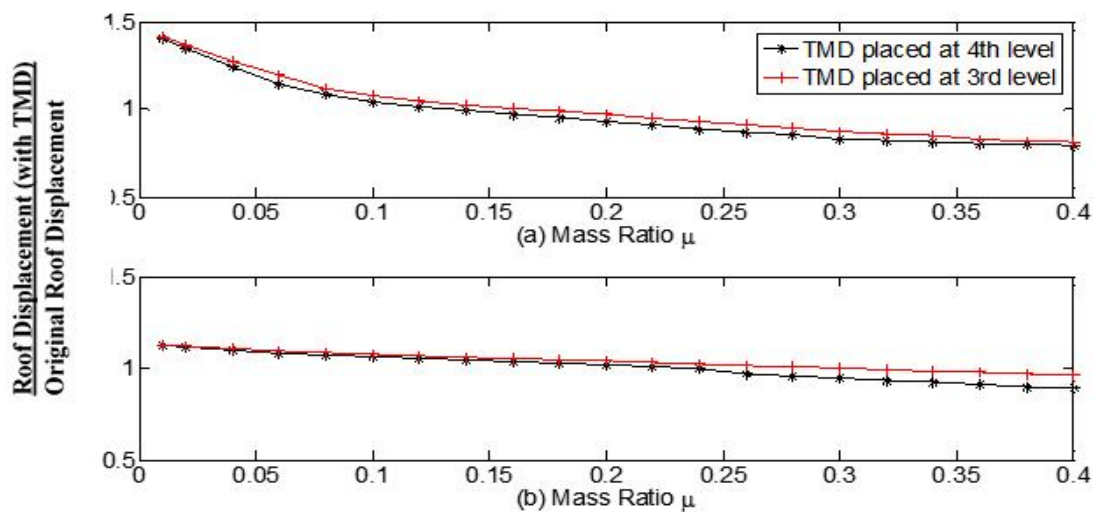

Fig. 9: Effect of damper on roof level displacement of 4-story structure with 2% damping ($\xi = 0.02$), (a) Altadena ground motion; (b) Lexington ground motion.
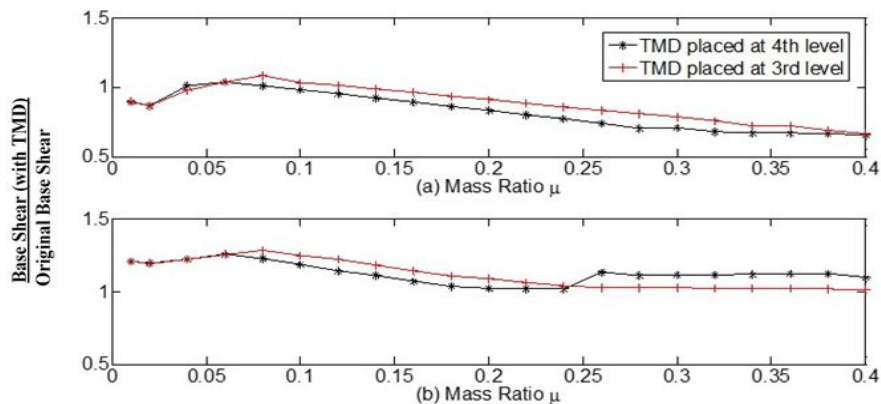
Fig. 10: Effect of damper on base shear of 4-story structure with 2% damping ($\xi = 0.02$) (a) Altadena ground motion; (b) Lexington ground motion.

The TMD also amplifies the base shear if the mass ratio is between 4% and 12% when subjected to the Altadena ground motion. For Lexington ground motion, the added TMD increases the base shear from 2% to 28% for the range of mass ratios shown in Fig. 10. These amplifications in roof displacements and base shears were not observed when the building structure with the TMD was subjected to the El Centro ground motion. These results show that optimum damper properties are dependent on the damper properties and earthquake time history and its characteristics and the TMD may not be well suited to certain structures and certain ground motions. The response of a building-damper system to near field and pulse velocity type time histories needs further evaluation. The effects of near-field ground motions were not evaluated in this study.

3.2. Response of 10-Story Building Structure to TMD at Various Elevations

The 10-story structure shown earlier in Fig. 1(b) is subjected to El Centro ground motion. A single TMD was placed at various levels along the height of the building. Three levels were chosen to evaluate the effect of TMD location: 1) roof level (10th level), 2) the 8th level, and 3) the 6th level. Response parameter such as rood displacements, base shear and story drifts were compared for each of the three levels for various mass ratios. The effect of the damping ratio of the first two modes, ξ_1 and ξ_2 of the primary structure and the ground motion characteristics were also analyzed similar to the 4-story building in Section 2.

Fig. 11 shows the reduction in roof displacements for various locations of the TMD in a 10-story building with 2% damping subjected to the Elcentro ground motion. The figure shows that when the TMD is placed at the roof level (10th level) and the 8th level, the reduction in roof displacement were similar with slightly more reduction with the TMD at the roof level. When the TMD location was lower (at 6th level) and a mass ratio $\mu = 0.1$, the reduction in roof displacement was about 43% compared to 48% for the higher locations. The effect of the damping ratio of the primary structure is shown in Fig 12. This is similar to the observations of the 4-story building. Fig. 12 shows that when the damping ratio is low (2%), the reduction in roof displacement is more pronounced compared to when the damping ratio is higher (5%).
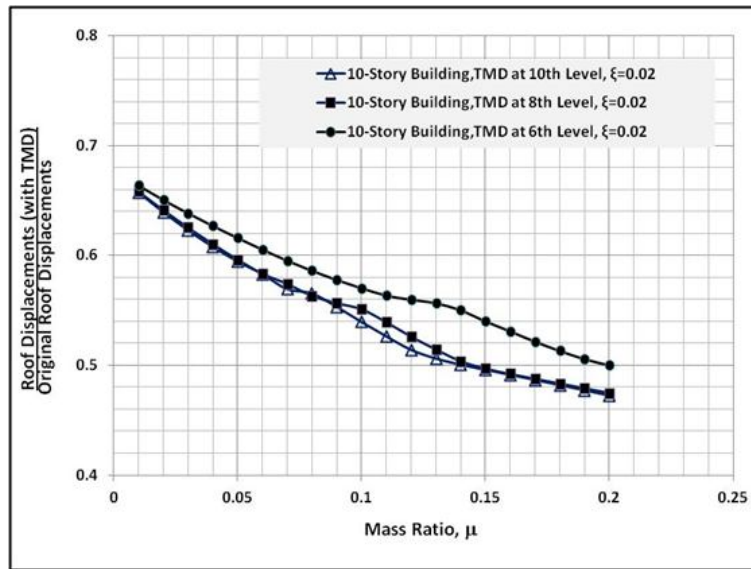
Fig. 11: Reduction in roof displacements with single TMD placed at various levels of 10-Story building with damping ratios $\zeta = 0.02$.
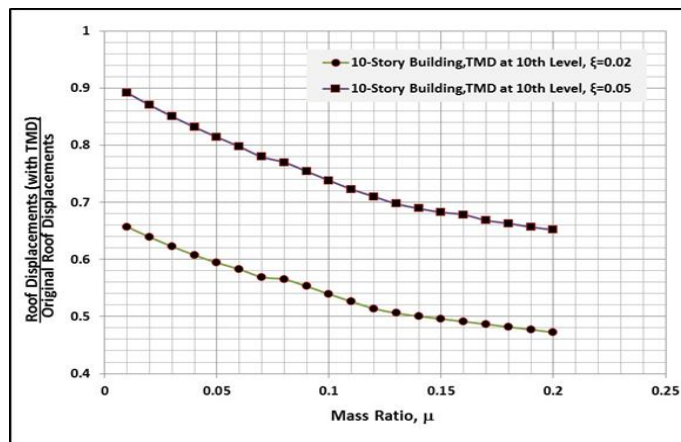

Fig. 12: Reduction in roof displacements with single TMD placed at 10th level of 10-Story building with damping ratios $\square$ = 0.02 and $\square$ = 0.05

Fig. 13 shows the reduction in base shears for various locations of the TMD. The figure shows that when the TMD is placed at the 8th level, the reduction in base shear was the lowest compared to other locations. Unlike the displacements, where when the TMD was at the 6th level the displacements were reduced the least, the base shear is reduced the least when the TMD is at the 8th level as shown in Fig. 13. However, for the mass ratio range between 5% and 10%, the reduction in base shear was more or less similar for all three locations. The effect of the damping ratio of the primary structure on the reduction of base shear is shown in Fig. 14. It is observed in Fig. 14 that when the damping ratio is lower ($\zeta = 2\%$), the reduction in base shear is more pronounced compared to when the damping ratio was higher ($\zeta = 5\%$). For example, for a mass ratio $\mu = 0.1$, the reduction in base shear for 2% damping was 18% compared to 14% for 5% damping ratio.
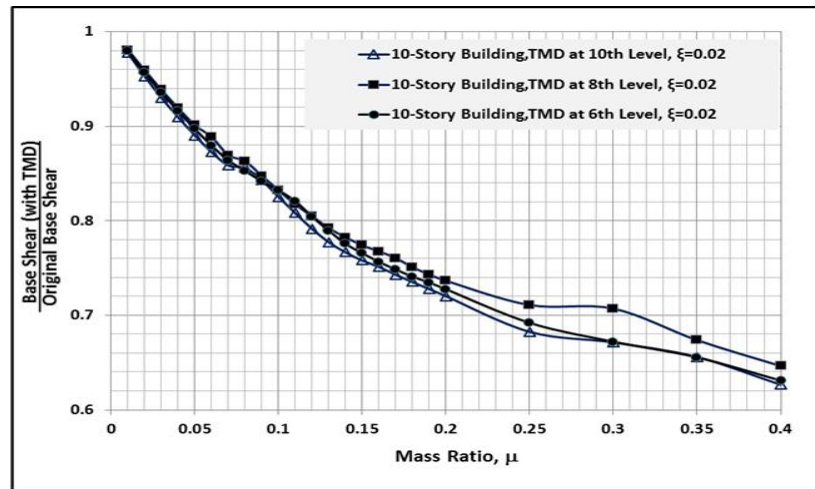
Fig. 13: Reduction in base shears with single TMD placed at various levels of 10-Story building with damping ratios ζ = 0.02.
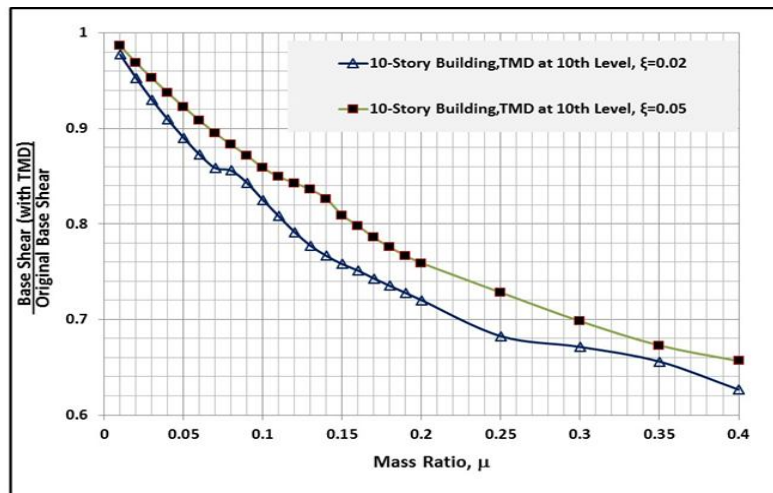

Fig. 14: Reduction in base shear with single TMD placed at 10th level of 10-Story building with damping ratios ζ = 0.02 and ζ = 0.05.

The effect of the TMD on roof displacements and base shear of low and medium rise buildings is shown in Figs. 15 and 16 respectively. In Fig. 15, the effect of the TMD placed at roof levels (4th level for the 4-story building and 10th level for the 10-story building) show similar trends in reducing roof displacements for mass ratios between 6% and 15%. Beyond 15% mass ratio, more reduction in the roof displacements for the 10-story building is observed while less reduction is observed for the 4-story building. Moreover the trend for the 10 story building is observed to be more or less linear reduction while that of the 4-story building has some nonlinearity for certain range of the mass ratio. Fig. 16 shows the effect of the TMD placed at roof levels (4th level for the 4-story building and 10th level for the 10-story building) on the reduction of base shears. The figure shows similar trends for the reduction however, the reduction is larger for the 4-story building compared to 10-story building.
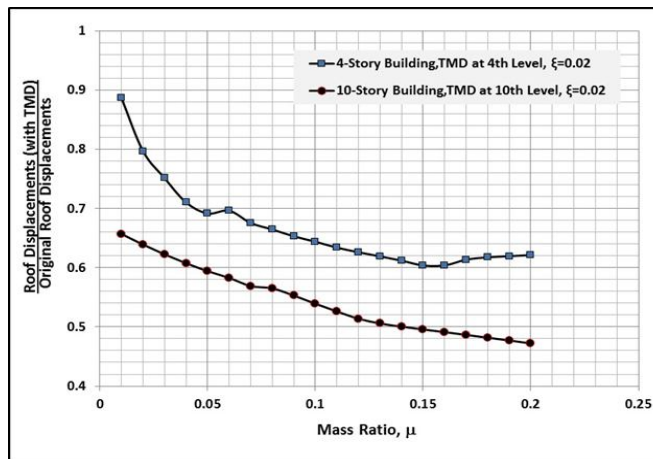
Fig. 15: Reduction in roof displacements with single TMD placed at roof levels of 4-Storyand 10-story buildings with damping ratio $\zeta = 0.02$.
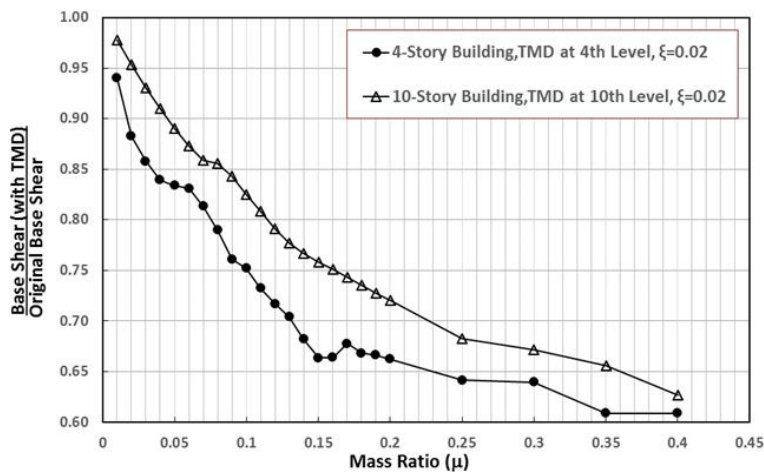

Fig. 16: Reduction in roof displacements with single TMD placed at roof levels of 4-Storyand 10-story buildings with damping ratio $\zeta = 0.02$.

For example, for a mass ratio of 10% ($\mu = 0.1$) the reduction in the base shear for the 4-story and the 10-story is 25% and 17% respectively. Beyond a mass ratio of 20%, the difference between the two reductions is less than 5%. It is also observed that the reduction curve for the 4-story seems to have a less defined slope compared to the 10-story reduction curves.

The 10-DOF building structure with a TMD was also subjected to two additional ground motion time histories: the Altadena and Lexington ground motion time histories. The impact of the TMD placed at different heights on the roof displacement and base shear was analyzed and the results are shown in Figs. 17 and 18 respectively. For the Altadena ground motion, the displacement and base shear reductions have similar trends to those observed for the El-Centro ground motions (Fig. 17 (a) versus Fig. 11 for displacements and Fig. 18(a) versus Fig. 13 for base shear), except that the reductions from Altadena seems to be less steep compared that from especially for mass ratios between 5% and 15%. The results from the Lexington ground motion however, shows different trends compared to El-Centro. While both Lexington and El-Centro time histories show reductions, the trends are different as can be seen in Fig. 17 (b) versus Fig. 13 and Fig. 18 (b) versus Fig. 13.
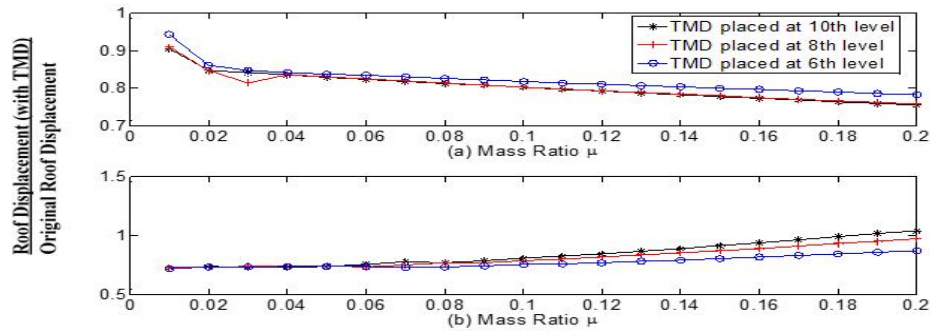
Fig. 17: Displacement reduction of roof level of 10-story structure with $\xi = 0.02$ (a) Altadena ground motion; (b) Lexington ground motion.
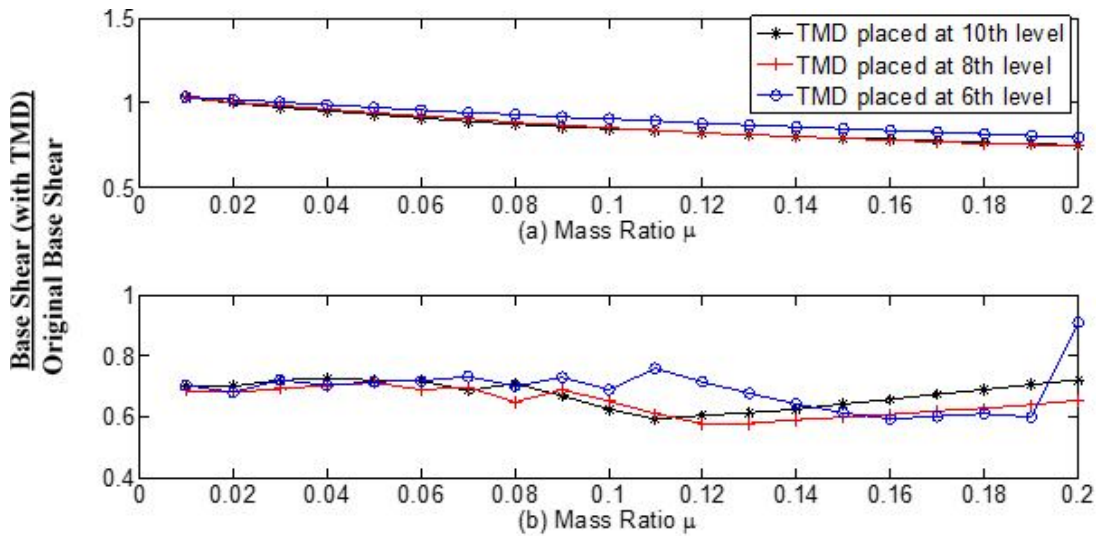

Fig. 18: Base shear reduction of roof level of 10-story structure with $\xi = 0.02$ (a) Altadena ground motion; (b) Lexington ground motion.

4.   Conclusion and Recommendations

A 4-story building and a 10-story building with tuned mass dampers were subjected to various ground motions to evaluate the effect of the TMD on reducing the roof displacement, base shear, and story drifts. Based on results from this study, the following conclusions can be presented:

1. The analytical investigation carried out in this study showed that TMD devices with optimum properties can be selected to reduce roof displacements and base shears in low rise and medium rise buildings subjected to earthquake ground motions.
2. While the reductions in displacements and base shears can be significant, these reductions should be analyzed and viewed relative to magnitudes of displacements and base shears under consideration. These reductions may not justify the use the TMD in low and medium earthquake zones compared to high seismic zones. For strong ground motions, the use of TMD may be a viable alternative compared to other alternatives.
3. The added TMD can be massive when the mass ratio is high. This will impose additional structural design requirements that should be addressed when design alternatives are being evaluated during preliminary design.

4. The reductions in roof displacements and base shear were higher for buildings with lower damping ratios compared to buildings with higher damping ratios. This is expected since the TMD increases the damping of the system and is more effective in structures with lower inherent damping.
5. The study showed that placing the TMD at higher levels was more effective in reducing displacements and base shear compared to lower levels. This was more pronounced in the low rise 4-story building compared to the 10-story building.
6. These results show that optimum damper properties to mitigate seismic forces are dependent on the earthquake time history and its characteristics as well as the damper properties; the TMD may not be well suited to mitigate the seismic response for certain ground motions as observed in this study. In such cases other mitigation measures should be considered.
7. The effect of multiple TMD's placed at various elevations and the effect of TMD on the response of higher modes as well as and the effects near field ground motions were not analyzed in this study.

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