Mitigation of Response of Asymmetric Building using Passive Tuned Mass Damper

S.N. Khante, B.P.Nirwan

Abstract- In present scenario, most of the buildings are often constructed with irregularities such as soft storey, torsional irregularity, vertical and plan irregularity. Past earthquake studies shows that the most of the RC buildings having such irregularities were severely damaged under the seismic ground motion. Torsional effects may significantly modify the seismic response of buildings and cause collapse of structures. These effects occur due to different reasons, such as non uniform distribution of the mass, stiffness and strength and torsional components of the ground movement. The concept of structural control is now widely accepted and has been frequently implemented in construction. Among the numerous passive control methods available, tuned mass damper (TMD) is one of the simplest and most reliable system for reducing dynamic response of structure. The mechanism involved in mitigating the vibration consists in the transfer of the vibration energy to the TMD, which dissipates it by damping. In order to increase the efficiency of a TMD, it is necessary to define its optimum parameters. The response of asymmetric building with tuned mass damper to the selected ground motion is investigated with respect to the following parameters; eccentricity ratio of the superstructure (ex/d), ratio of uncoupled torsional to lateral frequencies of the superstructure (ω_θ/ω_x), uncoupled time period of the superstructure (T_x) and mass ratio (m_d/m_s). G+8 storey RCC asymmetric building is considered for analysis. Nonlinear time history analysis is carried out in SAP2000 software using El Centro earthquake record. The numerical results of the parametric study help in understanding the torsional behaviour of the building using passive tuned mass damper.

Keywords- Asymmetric building, Eccentricity ratio, Mass ratio, Non-linear Time History Analysis, Optimum Parameter of TMD, Passive tuned mass damper, Time period of superstructure, Torsional to lateral frequency ratio.

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1 INTRODUCTION

The seismic response of asymmetric buildings subjected to ground motions may be significantly modified due to the occurrence of torsional effects. As a result, the floors of the building not only translate laterally but also rotate along a vertical axis. This effect produces an uneven distribution of the lateral displacements at the same level (with an increase of the displacement at some points of the perimeter of the building), and a modification of the internal actions. The main reasons for the occurrence of torsional effects are two. First, lack of symmetry of the structural system due to a non-uniform distribution in plan of the stiffness, mass or strength. Second, asynchronic movement of the foundation of building due to characteristics of the seismic excitation. The asymmetric configuration of the building results in a coupling of the translational and rotational mode of vibration of the structures. An ideal multi-storey building designed to resist lateral loads due to earthquake would consist of only symmetric distribution of mass and stiffness in plan at every storey and a uniform distribution along height of the building. Such a building would respond only laterally and is considered as torsionally balanced building. But it is very difficult to achieve such a condition because of restrictions such as architectural requirements and functional needs. The issue of mitigating the response of structures due to seismic loads has drawn the interest of many researchers in recent years.
Tuned mass dampers (TMD) have been widely used for the vibration control in civil engineering structures. The concept of vibration control, using a mass damper, dates back to the year 1909, when Frahm invented a vibration control device called a dynamic vibration absorber. Since 1971, through intensive research and development in recent years, the TMD has been accepted as an effective vibration control device for both new and existing structures. The TMD is found to be a simple, effective, inexpensive and reliable means for suppressing undesirable vibrations of structures caused by seismic excitations. TMD is attached to a structure in order to reduce the dynamic response of the structure. The frequency of the damper is tuned to a particular structural frequency so that when that frequency is excited, the damper will resonate out of phase with the structural motion. Then the excess energy that is built up in the structure can be transferred to a secondary mass and is dissipated by the dashpot due to relative motion between them at a later time. Mass of the secondary system varies from 1-10% of the structural mass [3]. Lin *et al*. [1] illustrated the practical considerations and vibration control effectiveness of passive tuned mass dampers for irregular buildings, modelled as multi-storey torsionally coupled shear buildings, under bi-directional horizontal earthquake excitations. Zaharai and Ghannadi [2] presented the effectiveness of TMD in controlling building under earthquake excitation and investigated the practical consideration and vibration control efficiency of TMD for moment resisting frames. Mane and Murudi [3] investigated the influence of various ground motion parameter on seismic effectiveness of TMD. Den Hortog [4] derived closed form expression for optimum damper parameter assuming

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no damping in mass of structure to facilitate derivation. Soni *et al*. [5] presented the behaviour of asymmetric building isolated by the double variable frequency pendulum isolator (DVFPI). The DVFPI is an adoption of single variable frequency pendulum isolator (VFPI). The numerical results of the extensive parametric study help in understanding the torsional behaviour of the structure isolated with the double sliding surfaces as in the DVFPI. Khante and Nirwan[6] presented the seismic performance of asymmetric building using passive tuned mass damper and determine location of TMD on installed floor for effective performance.

2. BASIC PRINCIPLE

Consider the response of a single-degree-of-freedom (SDOF) structure-TMD system subjected to a vibratory force, f (t), as shown in figure 1. Referring to figure 2, the equations of motion are given as follows [2].

$$m.\ddot{u}(t) + c.\dot{u}(t) + k.u(t) = c_d.\dot{z}(t) + k_d.z(t) + f(t) \qquad (1)$$

$$m_d.\ddot{z}(t) + c_d.\dot{z}(t) + k_d.z(t) = -m_d.u(t) + g(t) \qquad (2)$$

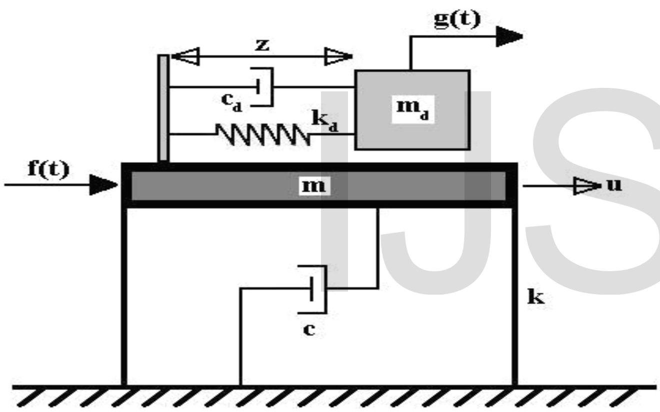

Fig. 1 Model of SDOF structure and TMD [3]

where u is the displacement of the SDOF system, z is the relative displacement between the SDOF system and the mass damper, m is the main mass, m_d is the damper mass, k is main spring stiffness, k_d is the absorber spring stiffness, c_d is the absorber damping, f (t) is the force acting on the main mass and g (t) is the force acting on the damper mass. Force acting on damper mass equals to zero for wind excitation and equals to μ.f (t) for earthquake loading. Summation of equation (1) and (2) leads to:

$$(m+m_d).\ddot{u}(t) + c.\dot{u}(t) + k.u(t) = f(t) + g(t) - m_d.\ddot{z}(t) \qquad (3)$$

From the equation 3, it is seen that the net merger effect of added small mass (m_d) on the structure, aside from a slight decrease in natural frequency and a slight increase in external force from f(t) to f(t)+g(t), in addition of a force term [$-m_d.\ddot{z}$(t)]. These equations for are valid only for SDOF structural system. Since most of building structure is MDOF structural system, a more general form of the equation of motion for a structure-TMD system is necessary. TMD is installed on top of the structure, for earthquake loading has the vector-matrix form:

$$m.\ddot{u}(t) + c.\dot{u}(t) + k.u(t) = c_d.\dot{z}(t) + k_d.z(t) + f(t) \qquad (4)$$

$$m_d.\ddot{z}(t) + c_d.\dot{z}(t) + k_d.z(t) = -m_d.\frac{\phi TMr}{\phi TM\phi} + g(t) \qquad (5)$$

Where ϕ represent the mode shape vector. Under wind type loading, force acting on damper mass equals to zero while for earthquake-type excitation, force on damper mass equals:

$$g(t) = \frac{u}{\Gamma}.f(t) \quad and \quad \Gamma = \frac{\phi TMr}{\phi TM\phi} \qquad (6)$$

To facilitate discussions, additional notations are introduced here as follows:
μ is damper mass to main mass ratio, $\mu = m_d/m_s$, ω is the frequency of a harmonic excitation, ω_s is the natural frequency of the main mass, ω_d is the natural frequency of the damper mass, β is the ratio of excitation frequency to main mass natural frequency, $\beta = \omega/\omega_s$, α is the frequency ratio, $\alpha = \omega_d/\omega_s$, ξ_d is the damping ratio of TMD and ξ_s is the damping ratio of the main mass.

3 BUILDING DISCRIPTION

The model of building is G+8 storeys RCC structure considered for the analysis. The building is asymmetric in plan as shown in figure 3. The building has bay width of 3m in X and Y direction with 3m storey height. Slab is modelled as rigid diaphragm. Building is eccentric with respect to mass and stiffness. Tuned mass damper is installed at top of building. Non-linear time history analysis is carried out in SAP2000 software using El Centro Earthquake records. CM (Centre of mass) is location where all mass of the system can be considered to be located. CR (Centre of rigidity) is the stiffness centroid within a floor diaphragm plan. When CM not coinciding with CR then eccentricity is created in structure i.e. distances between CM and CR. CM and CR are calculated by using ETABS software. Since building is eccentric with respect to mass and stiffness, the structure exhibits a torsional effect when excited in lateral X-direction.

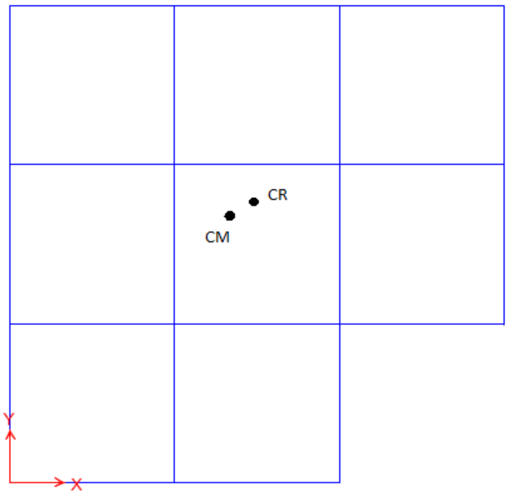

Fig. 3 Plan of building

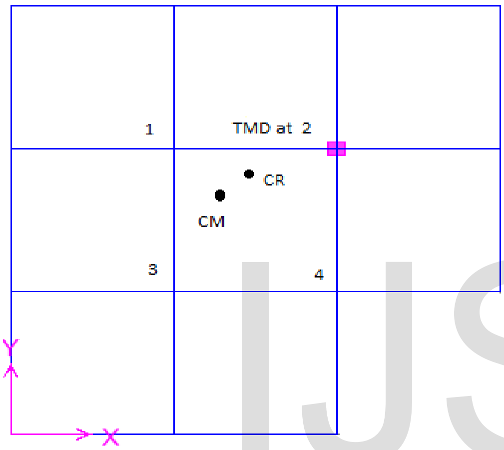

Fig. 4 Install location of TMD

The dynamic behaviour of the system under consideration to earthquake excitation can be described by following three degree of freedom. The two translational displacement u_{dx} and u_{dy} in orthogonal direction and rotation $u_{d\theta}$ about vertical axis of the centre of mass. Let k_{xi} and k_{yi}, i=1, 2…..N denote the lateral stiffnesses of the *i*th column in x and y-direction respectively, when N denote the number of column in each direction. The total lateral stiffness of the system in each direction, K_x, K_y is given by [6]

$$K_x = \sum_{i=1}^{N} k_{xi} \; ; \; K_y = \sum_{i=1}^{N} k_{yi} \qquad (7)$$

And the torsional stiffness defind about the centre of mass (CM) of the slab is

$$K_\theta = \sum_{i=1}^{N} (k_{xi} Y_i^2 + k_{yi} X_i^2) \qquad (8)$$

Where X_i and Y_i denotes the x and y- co-ordinate of the *i*th column with respect to the centre of mass of the slab the eccentricity between the CM (centre of mass) of the slab and the static centre of resistance (CR) of column is given by

$$e_x = \frac{1}{K_{yi}} \sum_{i=1}^{N} (k_{yi} X_i)$$
(9)

Corresponding to the translational and rotational modes, the three uncoupled modal frequency of the superstructure will be equal to

$$\omega_x = \sqrt{\frac{k_x}{m}}; \; \omega_y = \sqrt{\frac{k_y}{m}}; \; \omega_\theta = \sqrt{\frac{k_\theta}{m r2}}$$
(10)

Where, r is the radius of gyration of the slab about the vertical axis through the CM. The frequencies ω_x, ω_y, and ω_θ may be interpreted as the natural frequencies of the system if it is torsionally uncoupled but m, k_x, k_y and k_θ are the same as in the coupled system.
The numerical data for G+8 storeys RCC asymmetric building is as shown in Table 1.

TABLE 1
NUMERICAL DATA FOR BUILDING

Storey	G+8 Storey
Sizes of beam	0.23mx0.6m
Sizes of column	0.23m x 0.8m
Slab Thickness	0.125m
Live load on floor	2 kN/m²

4 OPTIMUM PARAMETER OF TMD

The optimum TMD parameter α and ξ as proposed by Den Hartog [5] are given in equation (11) and (12).

$$\alpha_{opt} = \frac{1}{1+\mu} \cdot \sqrt{\frac{(2-\mu)}{2}} \qquad (11)$$

$$\xi_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)}} \cdot \sqrt{\frac{2}{(2-\mu)}} \qquad (12)$$

Where μ is damper mass to main mass ratio, μ= m_d/m_s, α_{opt} is frequency ratio i.e ω_d/ω_s, ω_d is frequency of damper and ω_s is natural frequency of structure. ξ_{opt} is damping ratio of TMD. Optimum values of stiffness K_d and damping C_d of the TMD can be calculated as given in (13) and (14).

$$K_d = 4\,\pi^2\,\mu\,\alpha_{opt}^2\,\frac{ms}{Ts\,2} \qquad (13)$$

$$C_d = 4\,\pi\,\mu\,\xi_{opt}\,\alpha_{opt}\,\frac{ms}{Ts} \qquad (14)$$

It is established that [7] mass ratio μ=0.04 leads to maximum response reduction. Optimum parameter of TMD for mass ratio of 0.04 is as shown in Table 2.

TABLE 2
OPTIMUM PARAMETER OF TMD

Mass ratio (μ)	Frequency ratio (α)	Damping ratio (ξ)
0.04	0.95	0.121

5 PARAMETRIC STUDY

The response of asymmetric building using passive tuned mass damper to the selected ground motions is investigated with respect to the following non dimensional parameters: eccentricity ratio of the superstructure (ex/d), ratio of uncoupled torsional to lateral frequencies of the superstructure (ω_θ/ω_x), uncoupled time period of the superstructure (Tx), and mass ratio (m_d/m_s). Since these parameters predominantly influence the torsional coupling. Three response quantities, viz. peak displacement of slab, peak rotation of slab, peak base shear, in x-direction considered for the present study.

6 RESULT AND DISCUSSION

The response of asymmetric building with tuned mass damper for El Centro ground motion is investigated in terms of peak displacement, peak rotation and peak base shear.

6.1 Effect of eccentricity ratio (ex/d)

The superstructure stiffness eccentricity, ex/d is the most important parameter causing torsional coupling and torsional motions. Fig. 5 is plotted to show the effects of superstructure eccentricity on building with tuned mass damper.

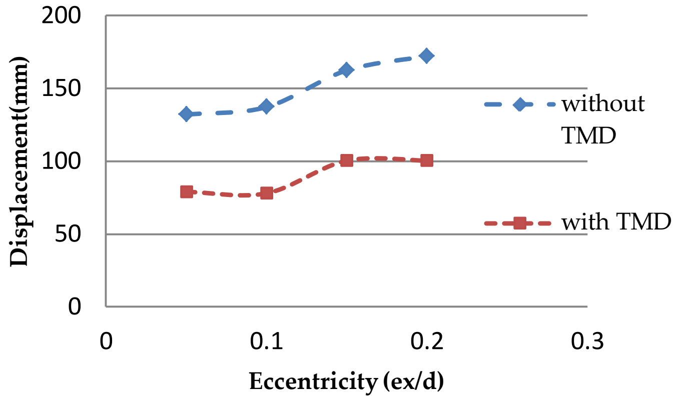

Fig.5 (a) Effect of eccentricity ratio (ex/d) on maximum displacement of asymmetric building with and without TMD

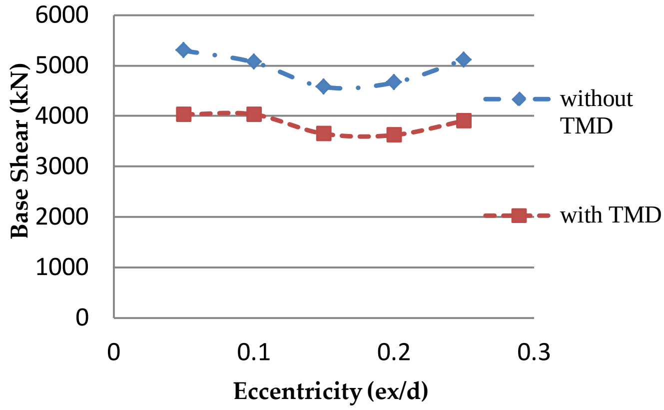

Fig.5 (b) Effect of eccentricity ratio (ex/d) on maximum base shear of asymmetric building with and without TMD

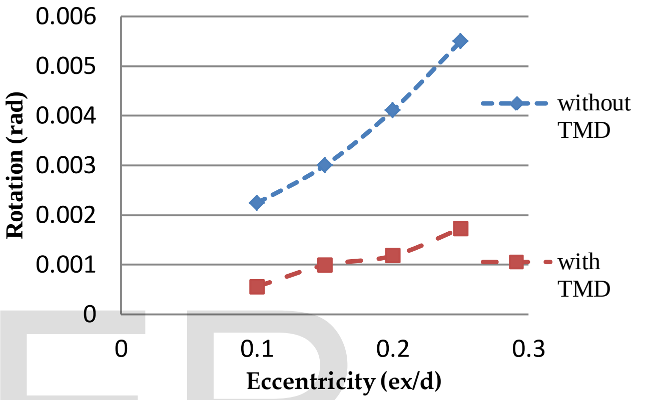

Fig.5 (c) Effect of eccentricity ratio (ex/d) on maximum rotation of asymmetric building with and without TMD

The superstructure eccentricity is varied from ex/d=0.1 to ex/d=0.25. From the fig. 5 (a), (b) and (c) it is observed that the eccentricity increases torsional responses i.e. peak slab rotation, peak slab displacement while the application of TMD reduces the torsional response. However the lateral responses i.e. peak base shear are not much influenced by superstructure eccentricity.

6.2. Effect of time period of superstructure (Tx)

The response of asymmetric building with tuned mass damper is plotted for different values of superstructure time period (Tx) as shown in fig. 6 (a), (b) and (c).

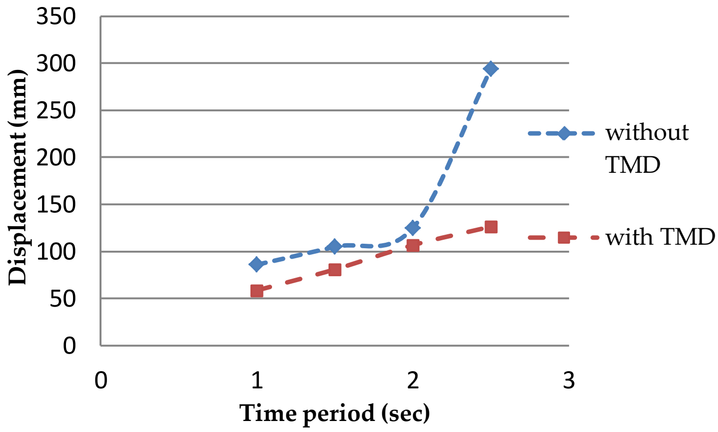

Fig. 6 (a) Effect of time period (Tx) on maximum displacement of asymmetric building with and without TMD

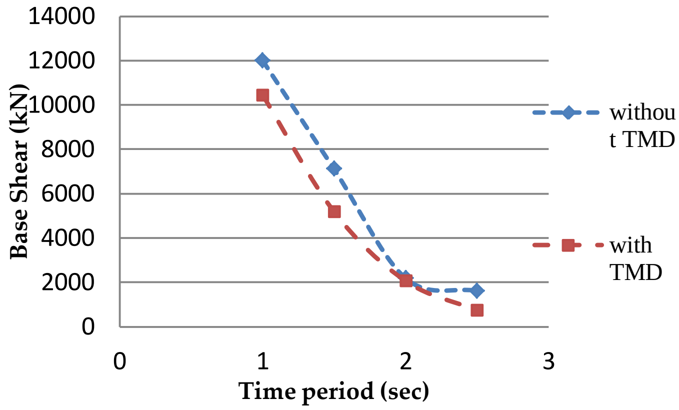

Fig. 6 (b) Effect of time period (Tx) on maximum base shear of asymmetric building with and without TMD

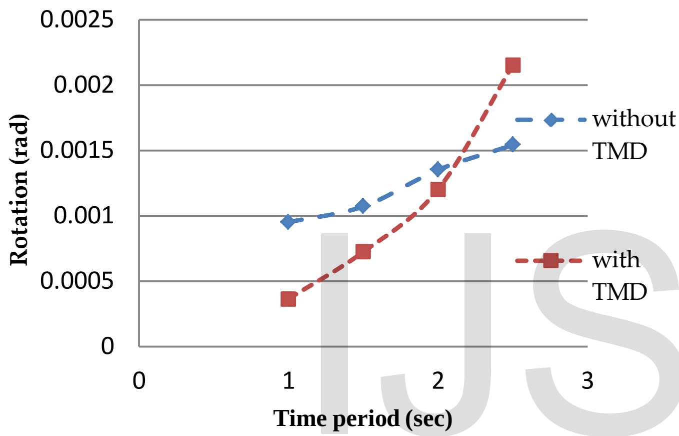

Fig. 6 (c) Effect of time period (Tx) on maximum rotation of asymmetric building with and without TMD

From fig. 6 (a), (b) and (c) it is observed that as increasing the time period (Tx), thereby making superstructure flexible in horizontal direction. All the torsional responses of building increase and lateral response decrease with and without TMD. The peak lateral displacement and peak rotation increases with increase in superstructure flexibility whereas peak base shear decreases as time period increases. Sudden rise in displacement is observed from time period 2 to 2.5 while with TMD response is very controlled and linear rise is noted. Steep change of slope in reduction of base shear is noted without TMD. With TMD the reduction in base shear steel continued for time period 2.5. For building with TMD with increasing time period from 2 to 2.5 sudden rise in slope is noted indicating sudden rise in rotation while without TMD with increase in time period slope is decreasing indicating reduction in rotation. Increase in rotation with TMD is due to TMD frequency is not exactly tuned with structural frequency.

6.3 Effect of mass ratio (m_d/m_s)

The fig. 7 (a), (b) and (c) depicts the influence of variation in mass ratio on the structural response.

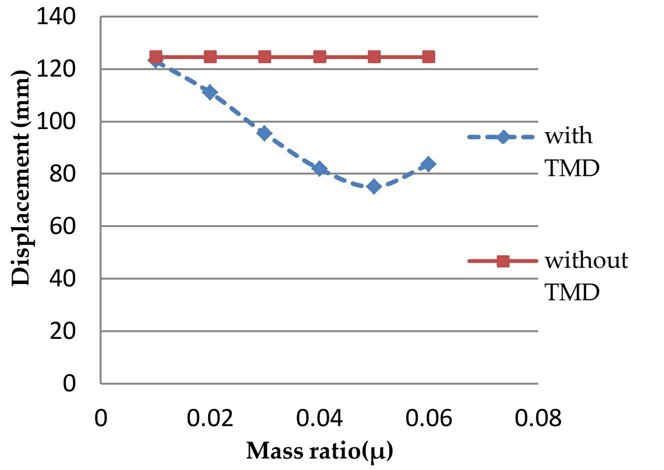

Fig. 7 (a) Effect of mass ratio (m_d/m_s) on the maximum displacement of the asymmetric building with and without TMD

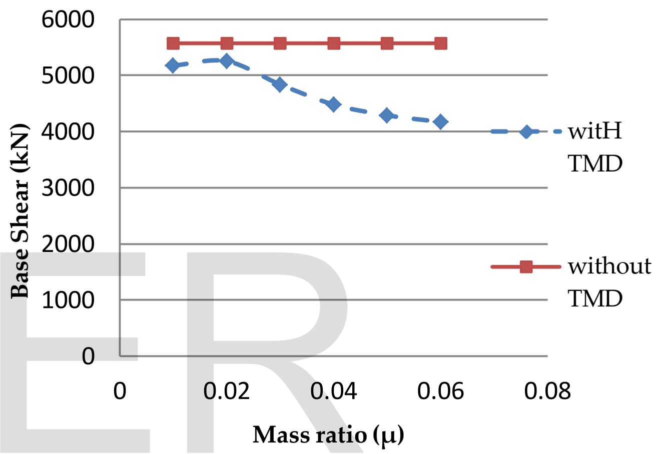

Fig. 7 (b) Effect of mass ratio (m_d/m_s) on the maximum base shear of the asymmetric building with and without TMD

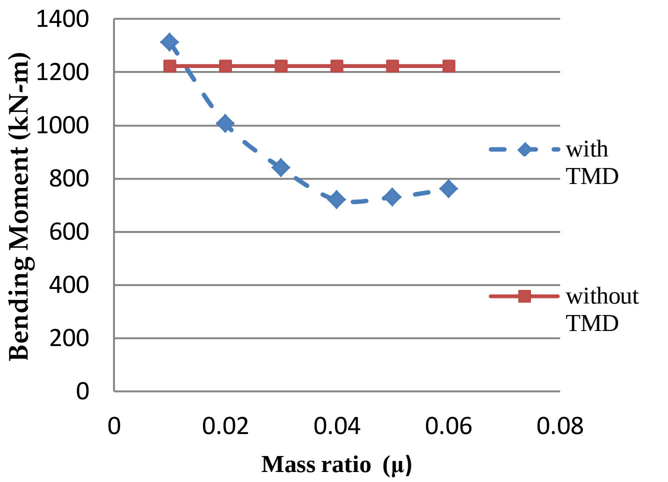

Fig. 7 (c) Effect of mass ratio (m_d/m_s) on the maximum bending moment of the asymmetric building with and without TMD

The base shear is highly influenced by variation of m_d/m_s. this is expected as the base shear is directly proportional the weight of the building. The peak displacement, peak bending moment and peak base shear decrease with increase in of mass ratio. Beyond mass ratio μ=0.05, peak

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displacement, peak bending moment show increasing trend. Decrease in peak base shear is due to opposite movement of mass of tuned mass damper relative to structural movement resulting lesser effective inertia force on building and consequently lesser maximum base shear. As the mass ratio increases the frequency (tuning) ratio of tuned mass damper are decreases, Hence effectiveness of TMD decreases resulting in increase in peak bending moment.

6.4 Effect of torsional to lateral frequency ratio of the superstructure (ω_θ/ω_x)

The ratio of uncoupled torsional to lateral frequency is an important parameter in behaviour of the asymmetric buildings that is, it highly influences the response of the system as shown in fig. 8 (a), (b) and (c).

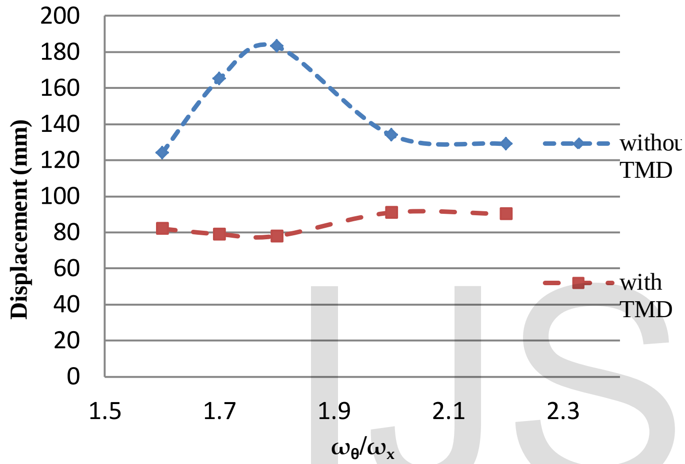

Fig. 8 (a) Effect of (ω_θ/ω_x) on the maximum displacement of the asymmetric building with and without TMD

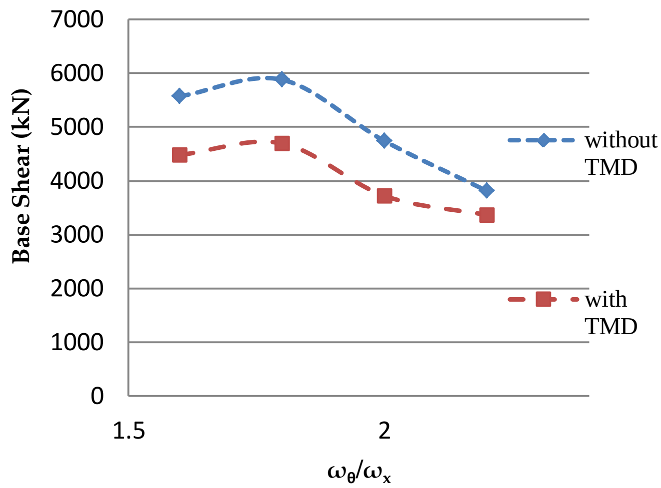

Fig. 8 (b) Effect of (ω_θ/ω_x) on the maximum base shear of the asymmetric building with and without TMD

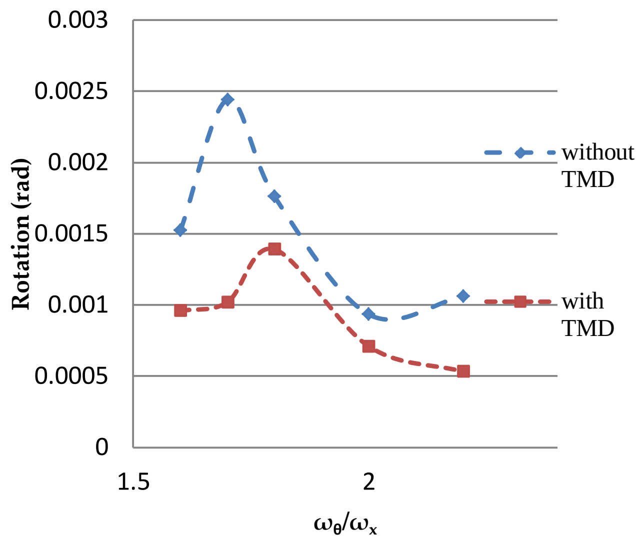

Fig. 8 (c) Effect of (ω_θ/ω_x) on the maximum rotation of the asymmetric building with and without TMD

From fig. 8 (a), (b) and (c) it is observed that with increase in ratio of (ω_θ/ω_x), peak displacement, peak rotation, peak base shear increases at the initial stage, later on it decreases as the system become stiffer. When above results are compared with results for superstructure eccentricity ratio, it is found that superstructure eccentricity ratio increases the torsional response quite rapidly than ratio of torsional to lateral frequency ratio. In general it is observed that use of TMD introduces reduction in response of building.

7 CONCLUSIONS

Based on the present study following conclusions are drawn:

TMD is reliable and practical alternative to enhance the earthquake resistance of existing and new structures. It is capable of providing the rigidity needed to satisfy structural drift limits. It is stable and has substantial energy absorption capability. Investigation of various non-dimensional parameters revealed that superstructure eccentricity increases torsional response such as peak rotation however peak base shear are not much influenced by superstructure eccentricity while with the application of TMD torsional response decreases. The superstructure flexibility magnifies torsional response and reduces lateral response of building with and without TMD. From results, it is observed that for higher values of torsional to lateral frequency ratio reduces torsional response such as rotation of building with and without TMD however the superstructure eccentricity increases torsional response quite rapidly than torsional to frequency ratio therefore superstructure eccentricity should be controlled. From results, it is noted that the peak displacement, peak bending moment peak base shear decreases with increasing mass ratio. Beyond mass ratio μ=0.05 peak displacement, peak bending moment show increasing trend.

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