Effectiveness of Tuned Mass Dampers in Vibration Control of multi-storied buildings

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Abstract - *Due to the increase in need of tall structures, it is important to understand the need of vibration control in these structures as they are more vulnerable to unwanted vibration. One such vibration control device is Tuned Mass Damper (TMD). In this study a 40-storey building is considered and response spectrum analysis is carried out to study the response of the structure with and without TMD. Also the effect of TMD on the response is studied for uniform, non-uniform distribution of mass ratio and variation of damping ratio of damper and it is found that effectiveness of TMD increases with increase in mass ratio. Use of MTMD is much more effective than STMD of same mass ratio for vibration mitigation under earthquake.*

Key Words: **damping ratio, ETABS, mass distribution, mass ratio, MTMD, Response Spectrum Analysis, STMD, story displacement, Tuned Mass Damper, vibration control.**

1. INTRODUCTION

Vibration means the mechanical oscillation about an equilibrium point. The oscillation may be periodic or non-periodic.

With the rapid economic development and advanced technology, civil structures such as high-rise buildings, towers and long span bridges are designed with an additional flexibility, which lead to an increase in their susceptibility to external excitation. Therefore, these flexible structures are susceptible to be exposed to excessive levels of vibration under the actions of a strong wind or earthquake. To protect such civil structures from significant damage, the response reduction of civil structures during dynamic loads such as severe earthquakes and string winds has become an important topic in structural engineering.

A number of methods have been developed to reduce the structural response due to lateral excitations. A Tuned Mass Damper (TMD) is a passive damping system which utilizes a secondary mass attached to a main structure normally through spring and dashpot to reduce the dynamic response of the structure. It is widely used for vibration control in mechanical engineering systems. Now a days TMD theory has been adopted to reduce vibrations of tall buildings and other civil engineering structures. The secondary mass system is designed to have the natural frequency, which is depended on its mass and stiffness, tuned to that of the primary structure. When that particular frequency of the structure gets excited the TMD will resonate out of phase with the structural motion and reduces its response. 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. As a particular earthquake contains a large number of frequency content now a days Multiple Tuned Mass Dampers (MTMDs) has been used to control earthquake induced motion of high rise structure where more than one TMD is tuned to different unfavorable structural frequency.

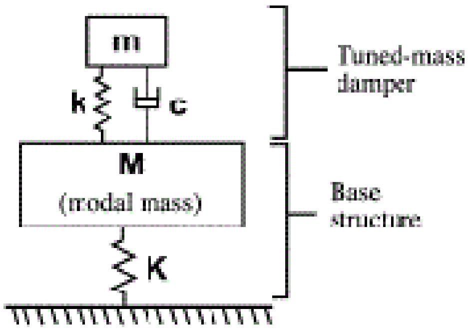

Fig -1: Schematic Diagram of a TMD

2. TUNED MASS DAMPER

A TMD is an inertial mass attached to the building location with maximum motion (generally near the top), through a properly tuned spring and damping element. Generally viscous and viscoelastic dampers are used. TMDs provide a frequency dependent hysteresis which increases damping in the frame structure attached to it in order to reduce its motion. The robustness is determined by their dynamic characteristics, stroke and the amount of added mass they employ. The additional damping introduced by the TMD is also dependent on the ratio of the damper mass to the effective mass of the building in a particular mode of vibration. TMDs weight is varied between 0.25% - 1.0% of the building’s weight in the fundamental mode (typically around one-third).

The frequency of a TMD is tuned to a particular structural frequency when that frequency is excited the TMD will resonate out of phase with frame motion and reduces its response. Often for better response control multiple-damper configurations (MDCs) which consist of several dampers placed in parallel with distributed natural frequencies around the control tuning frequency is used. For the same total mass, a multiple mass damper can significantly increase the equivalent damping introduced to the system.

Fig -2: Tuned Mass Damper in Taipei 101

3. AIM AND SCOPE OF THE STUDY

3.1 Objectives of the present study

The main objective of this dissertation is focused on the behavior of RC frame building with and without damper during earthquake.

The present work aims at the following objectives:

1. To perform response spectrum analysis of high rise (G+39) building frame with and without damper in ETABS software.
2. To determine the effect of Single Tuned Mass Damper (STMD) and Multiple Tuned Mass Damper (MTMD) on the dynamic response of structures under seismic excitations.
3. To study the response of the building in term of displacement.

3.2 Scope of the study

The present work aims at an objective demonstrating the effect of Tuned Mass Damper (TMD) techniques for symmetric high rise structures. The building studied in this section is a 40-storey Reinforced Concrete Special Moment Resisting Space Frames designed for gravity and seismic loads using linear analysis. The structure is evaluated in accordance with seismic code IS 1893:2002 under seismic zone V. Analysis is done with the help if ETABS software analysis engine.

4. METHODOLOGY

4.1 Principle of Tuned Mass Damper

When an earthquake occurs, the designed tuned mass dampers with a dashpot attached of heavy mass and tuned to the nearest frequency of the structure due to free vibration will move against the direction of the main structural vibrations caused by the lateral loads acting on the building and due to movement against the direction of the lateral force an inertia force will be acting on the structure because of which the TMD mitigates the response of the structure.

From the studies it was observed that a single tuned mass damper can attenuate the response of the structure only in the first mode having its frequency being tuned to the fundamental frequency of the structure.

In a high rise building if only single tuned mass dampers is used it can attenuate only first mode of vibrations but for several higher modes of a structure are primary and the anticipated response of vibration reduction cannot be achieved.

The researchers Li and Wang studied and presented a new method of using multiple tuned mass dampers in the structure to control the higher multiple modes of structure due to vibrations and obtained the required results for vibration reduction of the structure.

4.2 Determination of the optimum TMD

One TMD is effective in reducing dynamic response of only a single vibration mode of the structure. Although a structure has many vibration modes in reality, basic properties of TMD can be clearly discussed using a simplified 2-DOF model consisting of the main structure and the TMD system (Fig. 3).

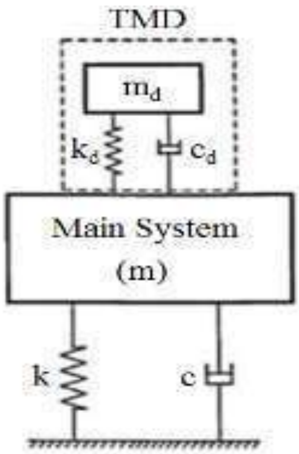

Fig -3: 2-DOF modeling of main structure and tuned mass damper system

Let us define the following parameters to be used in the following discussion.

Natural frequency of TMD, $\omega_d = \sqrt{\frac{k_d}{m_d}}$ (1)

Damping ratio of TMD, $\xi_d = \frac{c_d}{2 m_d \omega_d}$ (2)

Natural frequency of main structure, $\omega = \sqrt{\frac{k}{m}}$ (3)

Damping ratio of main structure, $\xi = \frac{c}{2m\omega}$ (4)

Mass ratio, $\mu = \frac{m_d}{m}$ (5)

Frequency (tuning) ratio, $\gamma = \frac{\omega_d}{\omega}$ (6)

When $\xi_d = 0$, a 2-DOF system shows 2 uncoupled vibration modes and when $\xi_d = \infty$ the 2-DOF system becomes a 1-DOF vibration system. Steady-state dynamic response subjected to harmonic excitation can be obtained analytically. It is usually called the resonant curve or dynamic magnification factor (DMF) curve plotted against angular frequency of the harmonic excitation. It is interesting to notice that DMF curves cross two fixed points independent of the damping ratio ξ_d. Den Hartog defined the optimum TMD by letting the two fixed points the same value and as high as possible in the DMF curve.

The physical meaning of this is to obtain flat DMF curve at resonant frequency, and consequently to suppress the dynamic response of the main structure most effectively. From this definition, the optimum frequency ratio γ_{opt} and the optimum damping ratio ξ_{dopt} of TMD are obtained by Den Hartog as function of mass ratio μ, i.e.

$$\gamma_{opt} = \frac{1}{1+\mu} \quad (7)$$

$$\xi_{dopt} = \frac{1}{2}\sqrt{\frac{3\mu/2}{1+3\mu}} \quad (8)$$

$$\Delta\xi_{eq} = \frac{1}{2}\sqrt{\frac{\mu/2}{1+\mu/2}} \quad (9)$$

Multiple Tuned Mass Dampers (MTMDs) consist of more than one TMD whose frequencies are distributed around the natural frequency of controlled mode of main structure. The natural frequencies of MTMD are distributed uniformly around their average natural frequency which is the same value of the fundamental natural frequency of the primary structure.

The natural frequency of the j^{th} TMD is expressed as:

$$\omega_j = \omega_T\left[1 + \left(j - \frac{n+1}{2}\right)\right]\frac{\beta}{n-1} \quad (10)$$

where, n is the total number of MTMDs and β is the non-dimensional frequency spacing of the MTMD, given as

$$\beta = \frac{\omega_n - \omega_1}{\omega_T} \quad (11)$$

If k_d is the constant stiffness of each TMD, then the mass of the j^{th} TMD is expressed as:

$$m_{dj} = \frac{k_d}{\omega_j^2} \quad (12)$$

The ratio of the total MTMD mass to the total mass of the main structure is defined as the mass ratio and is expresses as

$$\mu = \frac{\sum_{j=1}^{n} m_{dj}}{m} \quad (13)$$

where m denotes the total mass of the primary structure.

The ratio of average frequency of the MTMD to the fundamental frequency of main structure is defined as tuning ratio, expressed as

$$f = \frac{\omega_d}{\omega} \quad (14)$$

It is to be noted that as the stiffness and normalized damper force of all the TMD are constant and only mass is varying, the friction force adds up. Thus, the non-dimensional frequency spacing β, controls the distribution of the frequency of the TMD units.

4.3 Response Spectrum Analysis

A response spectrum is simply a plot of the peak or steady-state response (displacement, velocity or acceleration) of a series of oscillators of varying natural frequency that are forced into motion by the same base vibration or shock. The resulting plot can then be used to pick off the response of any linear system, given its natural frequency of oscillation. One such use is in assessing the peak response of buildings to earthquakes. The science of strong ground motion may use some values from the ground response spectrum (calculated from recordings of surface ground motion from seismographs) for correlation with seismic damage. If the input used in calculating a response spectrum is steady-state periodic, then the steady-state result is recorded. Damping must be present, or else the response will be infinite. Some level of damping is generally assumed, but a value will be obtained even with no damping.

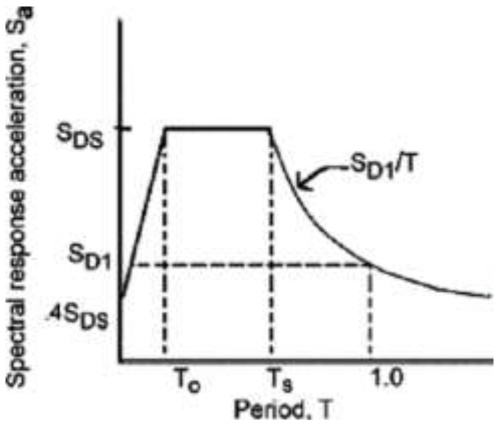

Fig -4: Response Spectrum Analysis

5. MODELING AND ANALYSIS

5.1 Model Definition

In this study we take a 40-storey RC building with 6 bays in X and Y direction and each bay with 5m spacing in the horizontal direction and also these models have uniform story height of 3m in vertical direction.

The geometrical parameters of the multi-story frame are as follows:

Type of building	- SMRF
Number of stories	- 40 stories
Floor height of each story	- 3m
Base supports	- Fixed
Structural type	- RCC Framed structure
Grade of concrete	- M30
Grade of steel	- Fe500
Size of columns	- 1200mm x 1200mm
Size of beams	- 600mm x 600mm
Depth of slab	- 150mm
Live load	- 3 kN/m^2
Floor finish	- 1 kN/m^2
Seismic zone	- Zone V
Importance factor	- 1.5
Reduction factor	- 5
Soil type	- 1

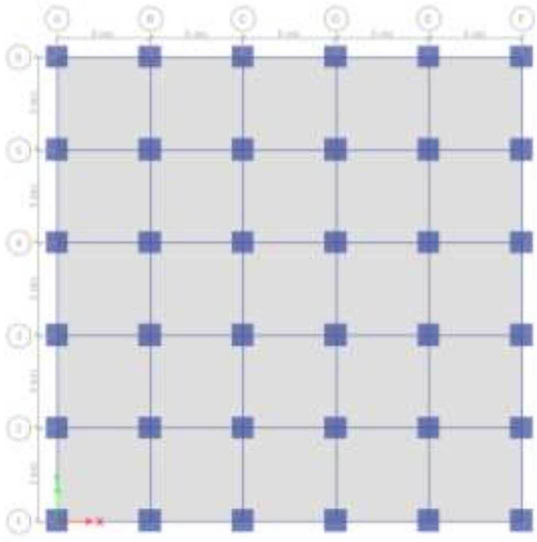

Fig -5: Plan of the model

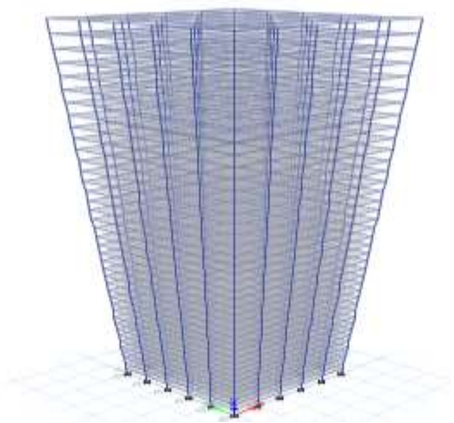

Fig -6: 3D model of 40 story RC frame without TMD

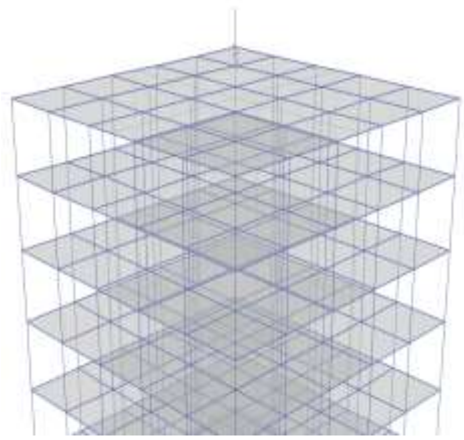

Fig -7: Enlarged view of location of 40 story RC frame with single TMD

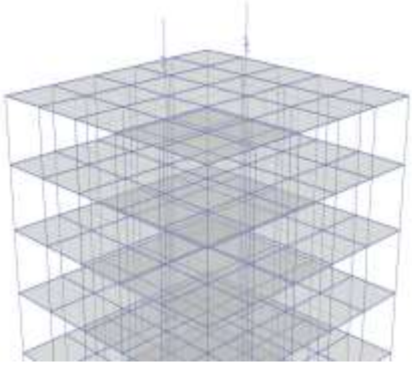

Fig -8: Enlarged view of location of 40 story frame with multiple TMD

6. RESULTS

A comparison study is done on the effectiveness of single tuned mass damper for vibration control by response spectrum analysis of the RC building. The response is calculated in term of displacement at the top floor with and without single TMD. The damping ratio of the building as well as damper is taken as 0.05 for every mode. In each case fundamental frequency of the building without TMD is tuned to the frequency of the damper. Different mass ratios of 0.02, 0.05 and 0.1 are taken in analysis.

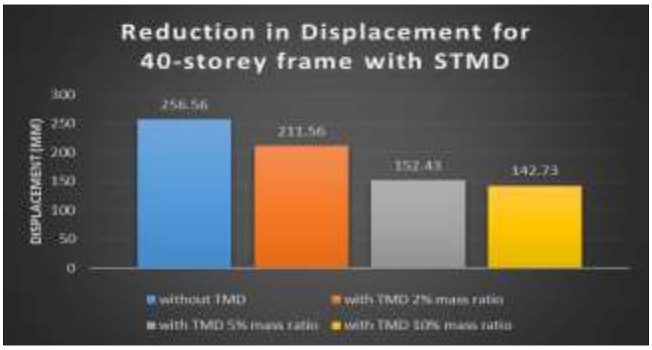

Chart -1: Comparison of maximum displacement of structure with & without STMD of varying mass ratios

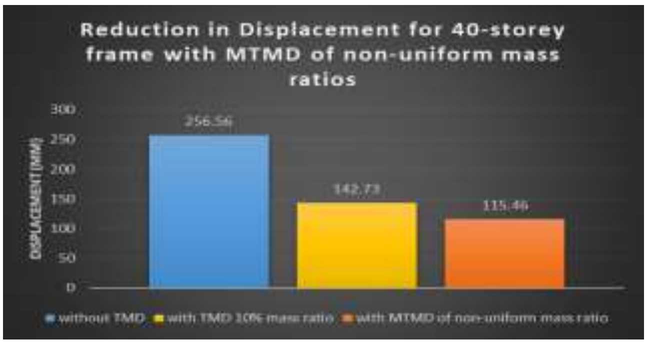

Chart -2: Comparison of maximum displacement of structure with & without MTMD of non-uniform mass ratios

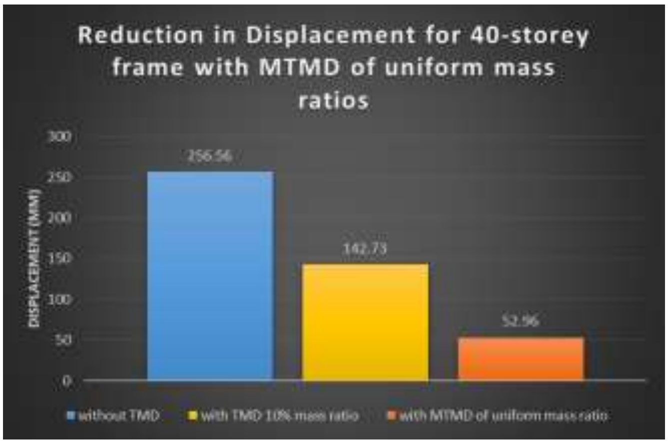

Chart -3: Comparison of maximum displacement of structure with & without MTMD of uniform mass ratios

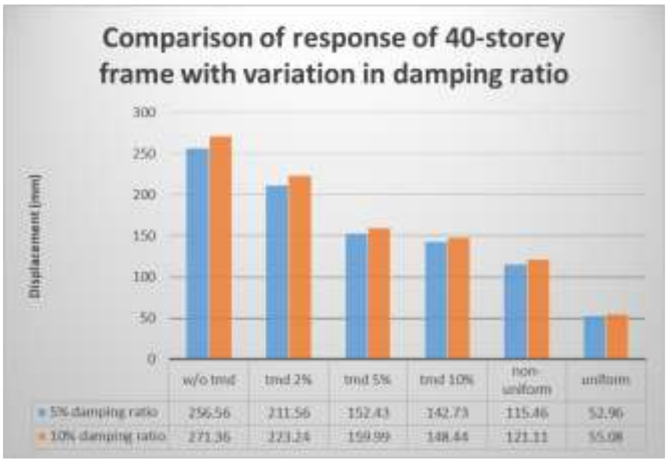

Chart -4: Comparison of maximum displacement of structure with & without TMD with varying damping ratios

7. CONCLUSIONS

On the basis of present study and reviewed literature the following conclusions can be drawn:

1. Response of the frame building reduces with the increase in mass ratio of the single TMD.
2. The MTMD with non-uniform distribution of mass ratio is more effective than single TMD of same mass ratio.
3. The MTMD with uniform distribution of mass ratio is most effective in vibration control in the present study.
4. The efficiency of TMD slightly increases with the increase in damping ratio.

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