

Earthquake Analysis of Tall Building with Tuned Mass Damper.

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Abstract: A Tuned mass damper (TMD) is a device consisting of a mass, and spring that 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. As tall buildings keep becoming taller, they become more susceptible to dynamic excitations such as wind and seismic excitation. For the structure safety and occupants comfort, the vibrations of the tall buildings are serious concerns for both engineers and architects. In order to mitigate the vibration, different approaches have been proposed, among which Tuned Mass Dampers (TMDs) are one of the most preferable and have been widely used in practice. Tall buildings and observation towers are occasionally vibrated under strong winds and become uncomfortable for occupants. Therefore, various types of dampers are being developed at present to reduce the vibration in those structures. However, there is no sure way to predict the wind-induced response of a structure with a damper system and to estimate the suppressing effects of dampers under earthquake loadings. Analysis of symmetrical moment resistance frame (MRF) 10th, 12th, 14th, 16th, 18th, and 21th storey three – dimensional model with tuned mass damper and without tuned mass damper by using software ETABS, moment resistance frames are column and girder plane frames with fixed or semi rigid connections. They can be constructed from concrete, steel or composite material. Moment resistance frames can be sufficient for a building up to 20 storey. A tuned mass damper (TMD) is placed on its top and through it to study its effects on structural response due to time history analysis with and without the tuned mass damper (TMD) in a ETABS. The result obtained from software analysis of 10th, 12th, 14th, 16th, 18th, and 21th storey building with and without tuned mass damper and compare result with each other.

Keywords - Tuned Mass Damper, Time history analysis, ETABS.

I. Introduction

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 strong winds has become an important topic in structural engineering. An earthquake is a natural phenomenon associated with violent shaking of the ground. They are vibrations of the earth's surface caused by sudden movements of earth crust mostly due to tectonic movements. Since earthquake forces are random in nature and unpredictable, the engineering tools needs to be sharpened for analyzing structures under the action of these forces. Earthquake loads are to be carefully modeled so as to assess the real behavior of structure with a clear understanding that damage is expected but it should be regulated. A different storey building such as 10th, 12th, 14th, 16th, 18th, and 21th storey building is selected which is subjected to dynamic loading earthquake. Under the increasing urban population density, scarcity of land and housing shortfalls, there is necessity of high-rise buildings.

1.1 Tuned Mass Damper

A tuned mass damper (TMD) is a device consisting of a mass, a spring, and a damper that 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 frequency is excited, the damper will resonate out of phase with the structural motion. Energy is dissipated by the damper inertia force acting on the structure. The Tuned Mass Damper (TMD) concept was first applied by Frahm in 1909 (Frahm, 1909) to reduce the rolling motion of ships as well as ship hull vibrations. A theory for the TMD was presented later in the paper by Ormondroyd and Den Hartog (1928), followed by a detailed discussion of optimal tuning and damping

parameters in Den Hartog’s book on mechanical vibrations (1940). The natural frequency of the TMD is tuned in resonance with the fundamental mode of the primary structure, so that a large amount of the structural vibrating energy is transferred to the TMD and then dissipated by the damping as the primary structure is subjected to external disturbances. Consequently, the safety and habitability of the structure are greatly enhanced. From the field vibration measurements, it has been proved that a TMD is an effective and feasible system to use in structural vibration control against high earthquake loads, as shown in Figure 1.1.

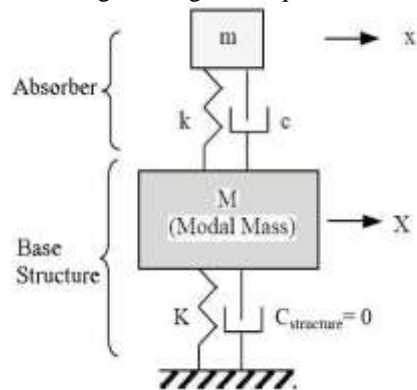


Fig. 1.1: A schematic representation of damped vibration absorber suggested by Den Hartog

1.1.1 Basic Principle

Consider the response of single-degree-of-freedom (SDOF) structural system subjected to a vibratory force $f(t)$ as shown in Figure 1.2.

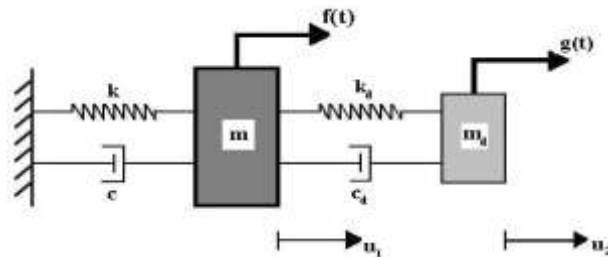


Fig. 1.2: Model of SDOF structure and TMD

Referring to Figure 1.2 the equations of motion are given as:

$$\begin{aligned}
 m\ddot{u}_1(t) + c\dot{u}_1(t) + ku_1(t) &= c_d[\dot{u}_2(t) - \dot{u}_1(t)] \\
 &+ k_d[u_2(t) - u_1(t)] + f(t), \\
 m_d[\ddot{u}_2(t) - \ddot{u}_1(t)] + c_d[\dot{u}_2(t) - \dot{u}_1(t)] \\
 &+ k_d[u_2(t) - u_1(t)] = -m_d\ddot{u}_1(t) + g(t),
 \end{aligned}
 \tag{1.1}$$

Where m is the main mass, m_d is the damper mass, k is the 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 is given as:

$$g(t) = \begin{cases} \frac{m_d}{m} \cdot f(t) & \text{for earthquake loading} \\ 0 & \text{for wind excitation} \end{cases}$$

To facilitate further discussions, additional notations are introduced here as follows:

μ is the damper mass to the main mass ratio, $\mu = m_d / m$, ω is the frequency of a harmonic excitation, ω_s is the natural frequency of the main mass, $\omega_s^2 = k / m$, ω_a is the natural frequency of the damper mass, $\omega_a^2 = k_d / m_d$, β is the ratio of excitation frequency to the main mass natural frequency, $\beta = \omega / \omega_s$, α is the frequency ratio, $\alpha = \omega_a / \omega_s$, ξ_a is the damping ratio of TMD and ξ_s is the damping ratio of the main mass. Equation (1.1) (1.2) can be used for structural response analysis. These equations are valid, only for single-degree-of-freedom (SDOF) structural systems. Since most building structures are multi-degree-of-freedom systems (MDOF), a more general form of the equations of motion for a structure-TMD system, TMD is installed on top of the structure, for earthquake loading has the vector-matrix form.

$$m_d[\ddot{u}_2(t) - \ddot{u}_1(t)] + c_d[\dot{u}_2(t) - \dot{u}_1(t)] + k_d[u_2(t) - u_1(t)] = -m_d \frac{\varphi^T M r}{\varphi^T M \varphi} g(t), \quad (1.3)$$

Where φ represents the mode shape vector. Under wind-type loading, force acting on damper mass equals zero while for earthquake-type excitations, $g(t)$ is the force acting on damper mass equals

$$g(t) = \left(\frac{\mu}{\Gamma} \right) \cdot f(t). \quad (1.4)$$

The participation factor (Γ) is expressed as,

$$\Gamma = \frac{\varphi^T M r}{\varphi^T M \varphi}. \quad (1.5)$$

1.2 Damper System

Critical components of the TMD are the dampers themselves. Several types of dampers have been considered for use in TMD's. However, many of these types of dampers are not compatible with TMD's for tall buildings because they are unable to meet all the stringent requirements necessary for use in these applications. Typical requirements for the dampers include the following:

1. The damper(s) must obey the proper damping law (as a function of velocity, position, or both) over the appropriate environmental extremes in order to provide the proper level of added damping to the structure without shifting the ratio of natural frequency of the tuned mass to the natural frequency of the building itself. Recall that optimal TMD designs require a frequency ratio of 1:1 for periodic inputs.

2. System friction must be mitigated in order to maintain a functional TMD regardless of the level of excitation to the structure.

3. The dampers must be of a maintenance free design for several reasons:

First and foremost, modern day tall buildings have a design life in the range of 50-100 years. Therefore, the TMD must also be designed for a long design life.

Secondly, it is generally unacceptable to shut down operation of the TMD for an extended period of time for maintenance. Since maintenance of TMD's will typically take a period of at least several days, the peak accelerations may exceed acceptable levels during this time.

4. The damper(s) must be able to operate during extreme conditions. For the extreme event, such as the 500 year design storm, the damper will need to self adjust without relying on an external driving actuator, thereby effectively increasing the level of damping in order to limit the motions of the mass during the event.

1.3 Objectives

1. Analysis of symmetrical moment resistance frame (MRF) 10th, 12th, 14th, 16th, 18th, and 21th storey three - dimensional model by using software ETABS.
2. To find the seismic response (storey drift, storey displacement and base shear) of a symmetrical MRF building with and without any damping device using ETABS.
3. A tuned mass damper (TMD) is placed on its top and through it to study its effects on Storey drift, storey displacement and base shear and analysis with and without the tuned mass damper (TMD) in ETAB.
4. The result obtained from software analysis of 10th, 12th, 14th, 16th, 18th, and 21th storey building with and without tuned mass damper and compare result with each other.

II. Tuned Mass Damper Methodology

The application of the Tuned Mass Damper (TMD) is an attractive option in reducing excessive floor vibrations. A TMD consists of a mass, spring, and dashpot, as shown in Figure 2.1, and is typically tuned to the natural frequency of the primary system. When large levels of motion occur, the TMD counteracts the movements of the structural system. The terms m_1 , k_1 , c_1 , X_1 represent the mass, stiffness, damping and displacement of the floor respectively, while m_2 , k_2 , c_2 , X_2 represent the mass, stiffness, damping and displacement of the TMD and $F(t)$ represents the excitation force. As the two masses move relative to each other, the passive damper is stretched and compressed, reducing the vibrations of the structure through increasing its effective damping. TMD systems are typically effective over a narrow frequency band and must be tuned to a particular natural frequency.

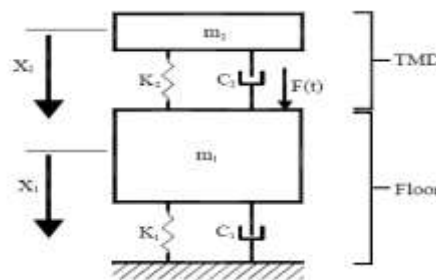


Fig. 2.1: Schematic Representation of a Two DOF System

Here, the subscript d refers to the tuned mass damper; as shown in Figure 2.2, the structure is idealized as a single degree of freedom system. Introduce the following notations.

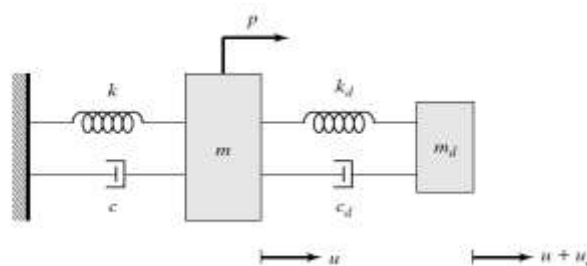


Fig. 2.2: SDOF-TMD system

$$\omega^2 = \frac{k}{m} \tag{2.1}$$

$$c = 2\xi\omega m \tag{2.2}$$

$$\omega_d^2 = \frac{k_d}{m_d} \quad (2.3)$$

and defining \bar{m} as the mass ratio,

$$\bar{m} = \frac{m_d}{m} \quad (2.4)$$

the governing equations of motion are

given by

$$(1 + \bar{m})\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = \frac{P}{m} - \bar{m}\ddot{u}_d \quad (2.5)$$

$$\ddot{u}_d + 2\xi_d\omega_d\dot{u}_d + \omega_d^2 u_d = -\ddot{u} \quad (2.6)$$

The purpose of adding the mass damper is to limit the motion of the structure when it is subjected to a particular excitation. The design of the mass damper involves specifying the mass M_d , stiffness K_d , and damping coefficient C_d .

2.1 Tuned Mass Damper Parameters

The natural frequency of the primary system can be divided into lower (f_1) and higher (f_2) frequency by attaching a spring mass tuned to the same fundamental natural frequency (f_n) of the primary system as shown in Figure 2.2. The most significant design variable of the damper is the mass ratio (μ) as defined in equation 2.5. When the mass ratio increases, the TMD becomes more effective and robust. In most applications the mass ratio is designed to be in the range of 1-10%. In the design of a TMD, the optimum natural frequency of the damper (f_d), and the optimum damping ratio of damper (ζ_{opt}) are given by equation (2.7) and (2.8) respectively.

$$f_d = \frac{f_n}{1 + \mu} \quad (2.7)$$

$$\zeta_{opt} = \sqrt{\frac{3\mu}{8(1 + \mu)^3}} \quad (2.8)$$

If there is zero damping then resonance occurs at the two un-damped resonant frequencies of the combined system (f_1 & f_2). The other extreme case was occurred when there is infinite damping, which has the effect of locking the spring (k_2). In this case the system has one degree of freedom with stiffness of (k_1) and a mass of ($m_1 + m_2$). Using an intermediate value of damping such as ζ_{opt} , somewhere between these extremes, it is possible to control the vibration of the primary system over a wider frequency range. The effectiveness of a single TMD was decreased significantly by the off-tuning or the off optimum damping in the TMD. The TMD damping ratio is also found to correspond approximately to the damping ratio computed for a SDOF system multiplied by Φ , i.e. $\zeta_{mdof}(\mu) = \Phi\zeta_{sdoof}(\mu)$ and damping is given by equation (2.10).

$$f = \frac{1}{1 + \mu\Phi} \left[1 - \beta \sqrt{\frac{\mu\Phi}{1 + \mu\Phi}} \right] \quad (2.9)$$

$$\zeta = \Phi \left[\frac{\beta}{1 + \mu} + \sqrt{\frac{\mu}{1 + \mu}} \right] \quad (2.10)$$

The above equation indicates that the best location for TMD is at the largest ζ , i.e. at the level where Φ and consequently the damping in the TMD and in the first two modes are maximums.

III. Structural Modeling and Analysis

Analysis of symmetrical moment resistance frame (MRF) 10th, 12th, 14th, 16th, 18th, and 21th three – dimensional concrete building is proposed to be analyzed using ETABS with Tuned Mass Damper (TMD) and

without any damping device. The performance of the building will be studied considering building with tuned mass damper and without tuned mass damper. To find out the seismic response (storey drift, storey displacement, and acceleration) of a symmetrical MRF building with and without any damping device using ETABS. Tuned Mass Dampers with varying mass ratio of 5% applied. Time-history analysis is carried out by applying the Bhuj (2001) intensity of earthquake, with specific dimensions. The structural configuration of the regular building is shown below Figure 3.2 and 3.1. All the building frames considered are 30m x 30m in plan area and 10th, 12th, 14th, 16th, 18th, and 21th. Height of the 10th storey building is 28.5m, 12th storey building height is 34.5m, 14th storey building height is 40.5m, 16th storey building height is 46.5m, 18th storey building height is 52.5m and 21th storey building height is 61.5m. Evidently, much progress has been extended in recent years in terms of the studies on the MTMD for mitigating oscillations of structures. However, in most studies on both the TMD and MTMD, it is assumed that a structure vibrates in only one direction or in multiple directions independently with its fundamental modal properties to design the TMD or the MTMD. The TMD attached to columns so it will affect the values of the displacements and base shear in each floor level in both direction X and Y (in plan) due to earthquake in direction of EQX and EQY as shown in Figure 3.1

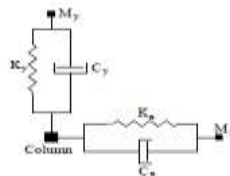


Fig. 3.1: Plan of TMD components in X and Y directions

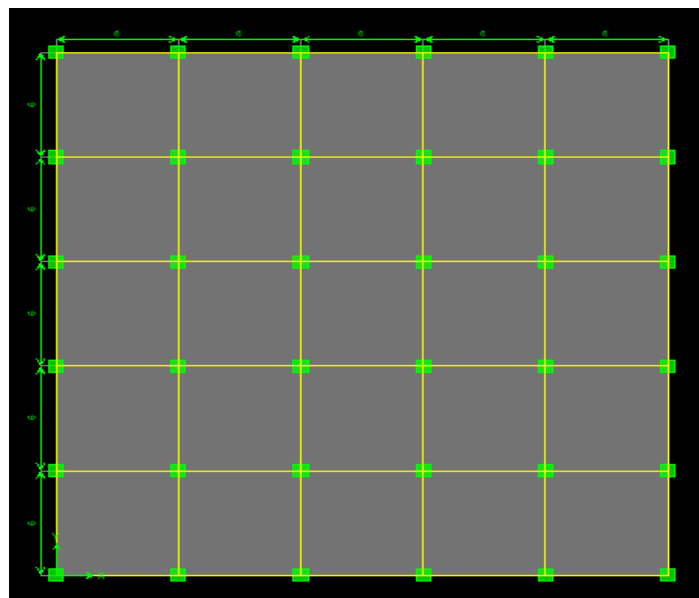


Fig. 3.2: Plan of building

To achieve systems of TMD were applied on the 10th, 12th, 14th, 16th, 18th, and 21th storey MRF with floor height 3m. Figure 4.5 illustrates the position of one TMD composed on top floor of the building (TMD attached to the column).

3.1 Assumption

- i. Column sizes from the first floor to the top are of the variable (get smaller) size.
- ii. All restrains that have been modelled are assumed to be fixed.
- iii. Only ground acceleration of X and Y directions are taken into account.

3.2 Material and Geometrical Properties

Density of RCC: 25 KN/m³

Tensile strength of steel: 500 N/mm²

Poisson ratio : 0.2

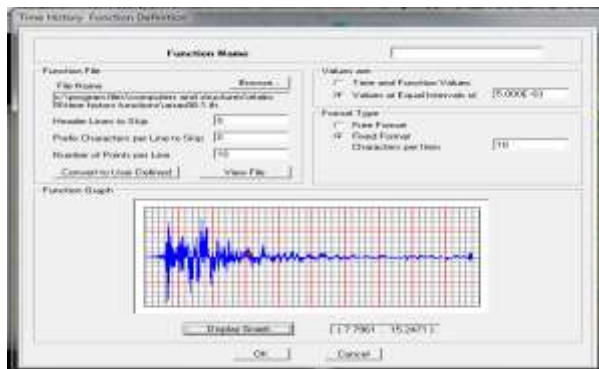


Fig. 3.3: Time history case data

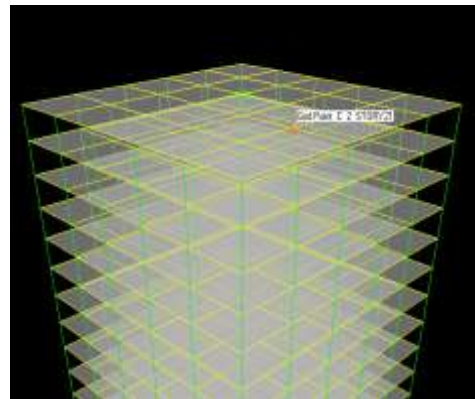


Fig. 3.4: Providing TMD at top floor

IV. Result and Discussion

4.1 Storey Displacement

Figure 4.1 shows the maximum displacement time histories of structures with and without TMD under the Bhuj earthquake. It demonstrates that the maximum displacement of the top storey without TMD is 35.4 mm and that of with TMD is 21.9 mm in an 10th storey structure. In comparison with an 10th storey structure, in a 12th storey structure, the maximum displacement of the top storey without TMD is 42.9 mm and that of with TMD is 27.3 mm. Whereas, in a 21 storey structure the maximum displacement of the top storey without TMD 76.8 mm and that of with TMD is 53.4 mm. Also the Top storey displacement values with and without TMD as well as the top storey displacement reductions were obtained after analysis.

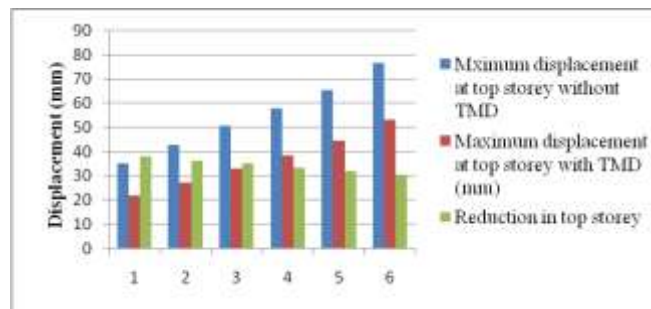


Fig. 4.1: Maximum storey displacement reduction with TMDs structure

4.2 Acceleration

The maximum acceleration time histories of the structures with and without TMD under bhuj earthquake. Figure it is demonstrated that, in a 10th storey structure, the maximum acceleration without TMD is 0.4216 g and maximum acceleration with TMD is 0.7395 g, as shown in Figure 4.2. As analytical result, a single TMD can only control the mode for which it designed. Therefore, the concept of Multi-Tuned Mass Damper (MTMD), i.e., having a separate TMD for other structural modes, appears to be a solution to the limited efficiency of TMD in mitigating seismic vibrations. The application of an active mass damper can also be considered as an alternative, to suppress the effects of higher modes of vibration for important high-rise structures.

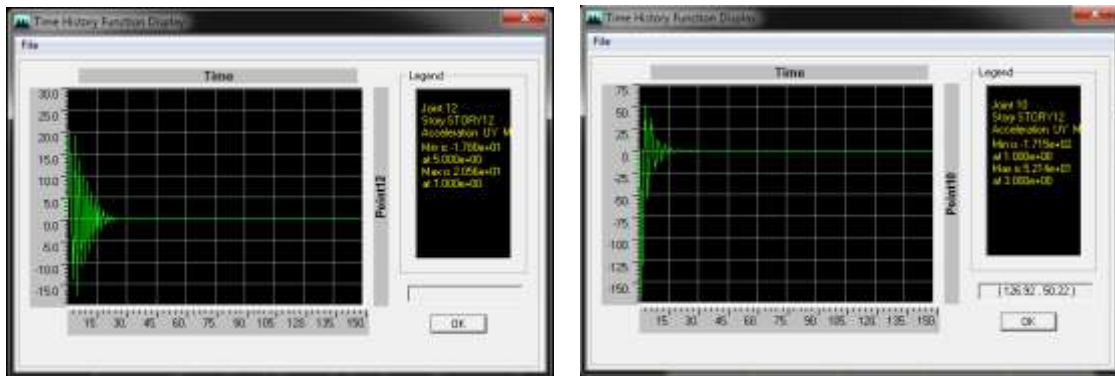
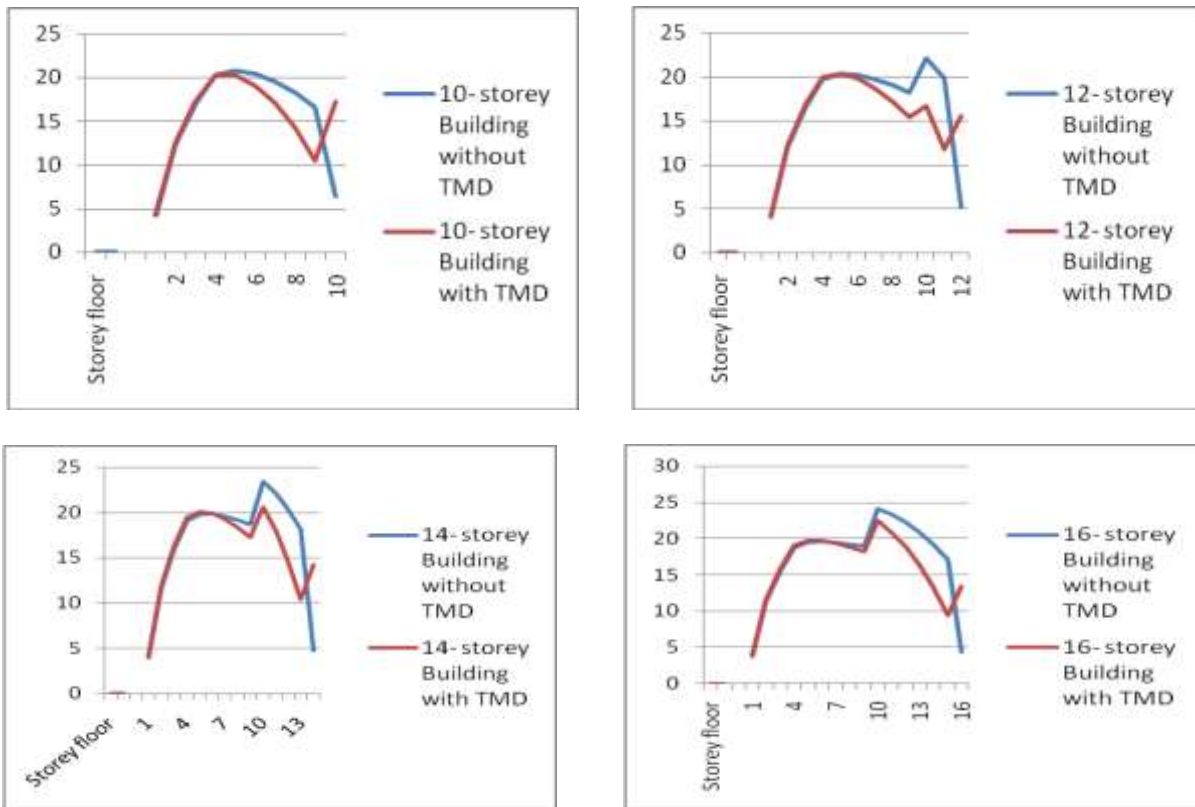


Fig. 4.3: Acceleration of 12th storey structures with and without TMD

4.3 Storey Drift

It is seen that the storey drift values are slightly high for the top floor while using TMDs 5% for X – direction excitation and Y-direction excitation respectively. In the case of a symmetrical MRF building the storey height is 3m and base storey height is 1.5m. According to the storey drift limitation given in *IS 1893 (Part I): 2002* each storey drifts must be limited to 0.004 times the storey height.



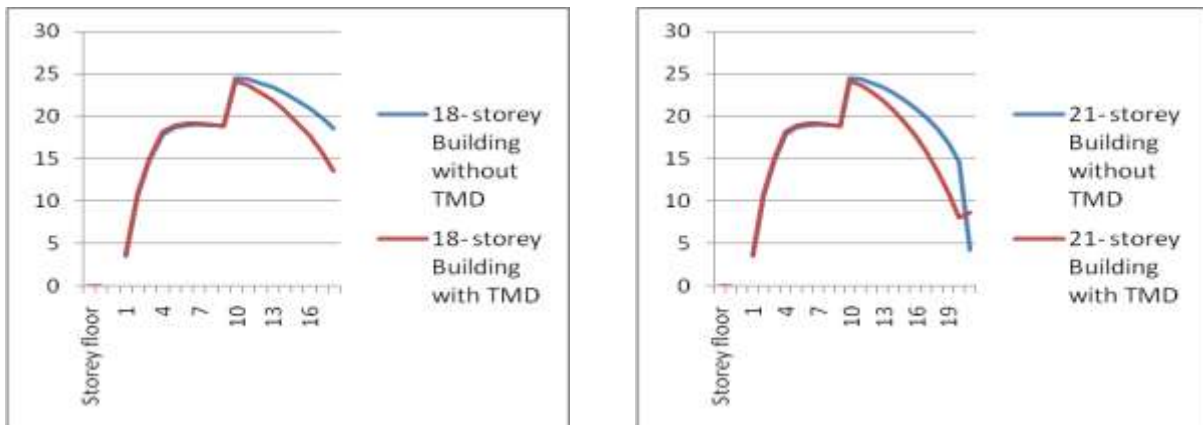


Fig. 4.4: Maximum storey drift of 10th, 12th, 14th, 16th, 18th, and 21th MRF building for X and Y excitation

4.4 Base shear

Then, from base shear plots that were obtained after analysis for MRF symmetrical building frame, buildings without TMD & with TMD,

Time History	Storey No.	Base shear (KN)	
		Building without TMD	Building with TMD
X,Y	10	2612.15	2670.07
X,Y	12	2511.07	2577.49
X,Y	14	2417.66	2489.56
X,Y	16	2355.58	2412.62
X,Y	18	2299.15	2365.02
X,Y	21	2234.38	2288.77

V. Conclusion

The seismic behaviour of 10th, 12th, 14th, 16th, 18th, and 21th storey building with tuned mass damper and without tuned mass damper was investigated. TMD is effective in reducing displacement and acceleration and, thereby, can be used for structures under earthquake. This study is aimed as tuned mass dampers in reducing structural (storey drift, storey displacement and base shear) of seismically excited 10th, 12th, 14th, 16th, 18th, and 21th storey building.

1. It has been found that the TMDs can be successfully used to control vibration of the structure.
2. For the regular building frame, 5% TMD is found to effectively reduce top storey displacement. The reduction of 10th storey building is 38.13, reduction of 12th top storey building is 36.36, reduction of 14th top storey building is 35.16, reduction of 16th top storey building is 33.34, reduction of 18th top storey building is 31.96, and reduction of 21th top storey building is 30.46. And base shear by about 2%.
3. Therefore, the TMD should be placed at top floor for best control of the first mode.
4. For the regular building, TMD with damping exponent (n) value 0.2 is found to be better than TMD with damping exponent value 0.5.
5. From analysis it can be seen that it is necessary to properly implement and construct a damper in any high rise building situated in earthquake prone areas.

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IS Codes

- IS 1893 (Part I): 2002, Indian Standard- Criteria for earthquake resistant design of structures, part 1 general provisions and buildings, Bureau of Indian Standards, New Delhi, June 2002.
- IS 875 : 1987, Indian Standard code of practice for design loads (other than earthquake) for buildings and structures.