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Vibration Control of Building under using Tuned Mass Damper

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Abstract—*This paper investigates the vibration control of multi-storied building using Tuned Mass Damper (TMD). Structural responses of high-rise buildings, under the action of seismic excitation have been studied. Response spectrum analysis and time history analysis are carried out using different load conditions based on the Indian standard code of practice IS: 1893-2002. In the present study 20 storied building has been model using MIDAS Gen software. A comparative study is carried out for the dynamic responses of building, with and without TMD. The result shows that there is significant reduction in displacement and acceleration response due to earthquake when TMD is installed on high-rise building. Comparative study of these results demonstrates that the used of TMD in building is effective in reducing the seismic vibrations.*

Keywords: *High-Rise building, Tuned Mass Damper, Response and Time History Analysis.*

1. INTRODUCTION

As the population increases, construction of high-rise buildings presents a practicable solution to the struggle associated with metropolitan society. Advances in construction technology and material science are making it possible to construct tremendously tall buildings. However, the safety of building structures and their contents as well as the comfort of occupants under external forces such as earthquakes and winds remains a major engineering concern. Conventional methods of design for strength alone do not guarantee that the structure will respond dynamically in such a way that the comfort and safety of the occupants is maintained, thus losing their importance and are becoming economically non-viable. Many researchers have made efforts to find some alternate method to control the structural response to manageable levels for economical design for earthquake. For buildings with modest height, implementation of passive, active, or hybrid control devices present a potential improvement in structural safety, performance of non-structural component, and human comfort, as these devices alter the dynamic characteristics of the structures to reduce structural response to external loads. One such controlling technique, which is being currently investigated, is the use of Tuned Mass Damper (TMD). TMD is a passive energy absorbing device consisting of a mass, spring and a viscous damper unit, when attached to a vibrating main structure, provides a frequency dependant hysteresis that increases the damping in the structure and hence aids in reducing vibration and keeping it within the desirable limit. TMD is popular because of its easy principle and several successful applications in real practice and has been found to be most successful device for controlling the structural responses for harmonic and wind excitations. Frahm [1] first proposed the basic form of TMD which did not possess any damping property by itself. So the effectiveness of the system was dependent upon the matching of its natural frequency and that of the excitation force. After that Ormondroyd and Den Hartog [2] introduced internal damping in TMD. The efficiency of TMD for controlling structural response is sensitive to its parameters i.e. mass, frequency, and damping ratio. TMD acts as a secondary vibrating system when connected to primary vibrating system. Optimum choices of damper parameters were not considered until Den Hartog [3] proposed closed form expressions of frequency ratio and damping ratio of the TMD for an undamped single degree of freedom system. Later damping in the main system was included through several researches performed by Bishop and Welboum [4], Snowdown [5], Falcon *et al.* [6]. Optimal design parameters were expressed in terms of damping coefficients and spring constants through minimization of performance index of structural vibrations are caused due to dynamic excitations. Villaverde and Koyama [7], and Villaverde and Martin [8] found that TMDs performed best when TMD is tuned to frequency close to natural frequency of structure. Vibration of structure makes TMD to vibrate in resonance, dissipating maximum vibration energy through damping in damper and also due to relative movement of damper with respect to the structure. The main advantages of TMD are they are inherently stable and guaranteed to work even during major earthquakes. In addition TMD is attractive as it dissipates a substantial amount of vibration energy of main structure without requiring any connection to ground.

The TMD is modeled as a mass with spring and damper, attached to SDOF structure, and thus the combined system together acts as two degrees of freedom system.

In the present paper, the helpfulness of TMD in controlling the seismic response of structures has been investigated. A 20^{th} storey building subjected to actual recorded earthquake ground motion and artificially generated ground motion is considered and comparative studies are carried out between the TMD installed structure and normal structure. It is observed that TMD is effective in controlling earthquake response, both for actual recorded and artificially generated earthquake ground motions.

2. EQUATION OF MOTION

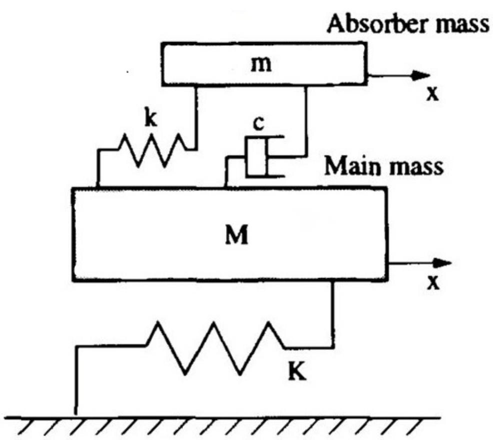

Fig. 1: SDOF system with single TMD

TMD structure interaction model is a single degree of freedom (SDOF) structure with TMD attached to it as shown in fig. 1 which is a two-degree of freedom system.

$$M\ddot{X}(t) + KX(t) + \left[C\{\dot{x}(t) - \dot{X}(t)\} + k_d\{x(t) - Xt = P(t) \qquad (1)$$

$$m\ddot{x}(t) + C_d\{\dot{x}(t) - \dot{X}(t)\} + k_d\{x(t) - X(t)\} = p(t) \qquad (2)$$

Where,

M = Mass of structure

m = Mass of TMD

K = Stiffness of structure

K_d = Stiffness of TMD

C_d = Damping of TMD

P (t) = Force acting on structure mass.

In case of base excitation with acceleration $\ddot{x}_g$ (t), P (t) =-M$\ddot{x}_g$ (t)

p (t) = Force acting on TMD mass.

$$p(t) = \begin{cases} \frac{m}{M}P(t)\ ;\ for\ base\ excitation \\ 0\ ;\ for\ main\ mass\ excitation \end{cases}$$

3. GOVERNING EQUATION FOR TMD PARAMETERS

Some parameters are required for effectiveness of TMD.
The parameters of are:

(a) Frequency ratio$\left(f = \frac{\omega_d}{\omega_s}\right)$; It is defined as the ratio of natural frequency of TMD to natural frequency of the structure.

(b) Mass ratio μ =$\left(\frac{m_d}{M}\right)$ and

(c) Damper damping ratio ξd = $\left(\frac{c_d}{2.\omega_d m_d}\right)$

Where,

M = Mass of the structure, m_d = mass of damper, c_d= damper damping coefficient, ω_d = Natural frequency of damper, ω_s = Natural frequency of structure.

The basis for Den Hartog method is to minimize the responses to sinusoidal loading which is for an undamped 2-DOF system result in the following parameters:

$$f = \frac{1}{1+\mu} \qquad (3)$$

$$\xi = \sqrt{\frac{3\mu}{8(1+\mu)}} \qquad (4)$$

After numerous studies on the applicability of TMDs for seismic applications were carried out by Villaverde [9], Villaverde and Koyama [7], and Villaverde and Martin [8] where it was found that TMD performed best when the first two complex modes of vibration of the combined structure and damper have approximately the same damping ratio as the average of the damping ratios of the structure and TMD. To achieved this, Villaverde [9] found that the TMD should be in resonance with the main structure (f =1) and its damping ratio be

$$\xi = \beta + \Phi\sqrt{\mu} \qquad (5)$$

Where,

β = damping ratio of structure,

μ = mass ratio of TMD mass to the mass of structure,

Φ = amplitude of the mode shape at the TMD location.

Most recently, Miyama [10] argued that TMD with a small mass less the 2% of first mode generalized mass are not effective in reducing the response of buildings to earthquake excitation. He suggested that most of the seismic energy should be absorbed by top storey so that the other storey would remain undamaged.

4. OPTIMUM TMD PARAMETERS

Even though present paper is focused on an MDOF structural system associated with single TMD on top, an approach has been developed to find the optimum parameters of TMD installed in roof floor level of a multi-storied building for minimum top deflection caused by lateral excitation.

For a MDOF structure, the mass ratio is computed as the ratio of the TMD mass to the generalized mass for the fundamental mode for a unit modal participation factor.

$$\mu = \frac{m}{\phi^T[M]\phi} \tag{6}$$

Where $[M]$ is the mass matrix and ϕ is the fundamental mode shape normalised to have a unit participation factor.

For the optimum TMD parameters, it was found that the tuning ratio for a MDOF TMD system is nearly equal to the tuning ratio for a 2-DOF TMD system for a mass ratio of $\mu\Phi$, where Φ is the amplitude of the first mode of vibration for a unit modal participation factor computed at the location of the TMD. The equation for the tuning ratio is obtained from the equation for the 2-DOF TMD system by replacing μ by $\mu\Phi$. Thus,

$$f_{opt} = \frac{1}{1+\mu\Phi} \tag{7}$$

The TMD damping ratio is also found to correspond approximately to the damping ratio computed for a 2-DOF TMD system multiplied by Φ. The equation for the damping ratio is therefore obtained by multiplying the equation for the 2-DOF TMD system by Φ, as defined:

$$\xi_{opt} = \Phi\left[\frac{\beta}{1+\mu} + \sqrt{\frac{\mu}{1+\mu}}\right] \tag{8}$$

For MDOF structures, the practical parameters of the optimal TMD stiffness and the optimal damping coefficient can be thus derived:

$$K_{d\ opt} = f_{d\ opt}^{\ 2}\,\Omega^2 m \tag{9}$$

$$C_{d\ opt} = 2\,\xi_d\, f_{d\ opt}\,\Omega\, m \tag{10}$$

5. NUMERICAL STUDIES

To show the effectiveness of TMD the optimum TMD parameters are computing, a 20 storey building with and without TMD were analysed using recent recorded earthquake data. The displacement and acceleration responses for the structure with and without TMD with different masses of TMD are present in table 1 below. It is observed that considering mass of TMD as 5% to 10% mass of main structure with zero damping ratios (β) results in a considerable reduction in displacements and accelerations.

Table 1: Displacement at Roof Level

floor No.	w/o TMD	FOR 2% TMD MASS	
		with TMD	% reduction
GF	0	0	0
1	0.006	0.005	6.2007536
2	0.015	0.014	5.7329213
3	0.025	0.024	6.0274763
4	0.036	0.034	6.2211037
5	0.046	0.044	6.1007957
6	0.057	0.053	6.2764300
7	0.067	0.063	6.1383893
8	0.077	0.072	6.0614386
9	0.086	0.081	5.9923626
10	0.095	0.090	6.0031490
11	0.104	0.098	6.1305140
12	0.112	0.105	6.2983927
13	0.119	0.112	6.5228593
14	0.127	0.118	6.8857642
15	0.133	0.124	7.2009878
16	0.139	0.129	7.5516986
17	0.145	0.134	7.8701400
18	0.150	0.138	8.1735097
19	0.154	0.142	8.3270733
20	0.157	0.145	8.4401929

floor No.	w/o TMD	FOR 5% TMD MASS	
		with TMD	% reduction
GF	0	0	0
1	0.006	0.004	28.01982
2	0.015	0.012	27.64194
3	0.025	0.020	28.28192
4	0.036	0.028	28.86506
5	0.046	0.036	29.07852
6	0.057	0.044	29.63801
7	0.067	0.051	29.77011
8	0.077	0.059	29.93133
9	0.086	0.066	30.07495
10	0.095	0.073	30.31447
11	0.104	0.079	30.71403
12	0.112	0.085	31.18699
13	0.119	0.091	31.75679
14	0.127	0.095	32.51869
15	0.133	0.100	33.22572
16	0.139	0.104	33.9414
17	0.145	0.108	34.52458
18	0.150	0.111	34.9518
19	0.154	0.114	35.04998
20	0.157	0.116	35.02066

floor No.	w/o TMD	FOR 5% TMD MASS	
		with TMD	% reduction
GF	0	0	0
1	0.006	0.004	32.733889
2	0.015	0.011	32.359260
3	0.025	0.019	33.015889
4	0.036	0.027	33.677039
5	0.046	0.034	34.085895
6	0.057	0.042	35.033228

7	0.067	0.049	35.728382
8	0.077	0.056	36.605736
9	0.086	0.062	37.552018
10	0.095	0.068	38.610990
11	0.104	0.074	39.824481
12	0.112	0.079	41.091037
13	0.119	0.084	42.441342
14	0.127	0.088	43.978612
15	0.133	0.091	45.425671
16	0.139	0.095	46.825605
17	0.145	0.098	47.990466
18	0.150	0.100	48.894197
19	0.154	0.103	49.388118
20	0.157	0.105	49.708268

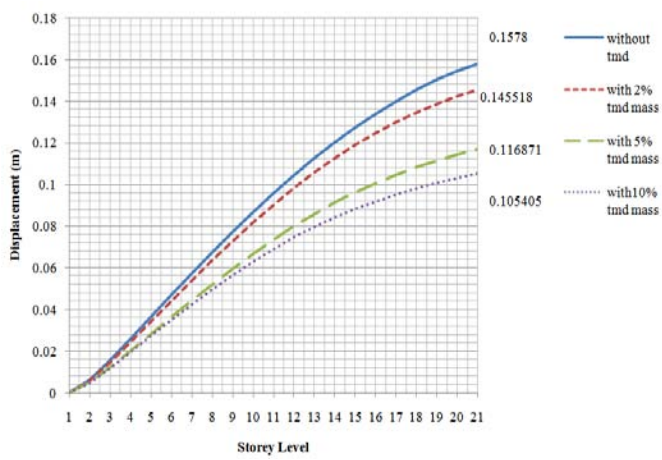

Fig. 2: Displacement Graph.

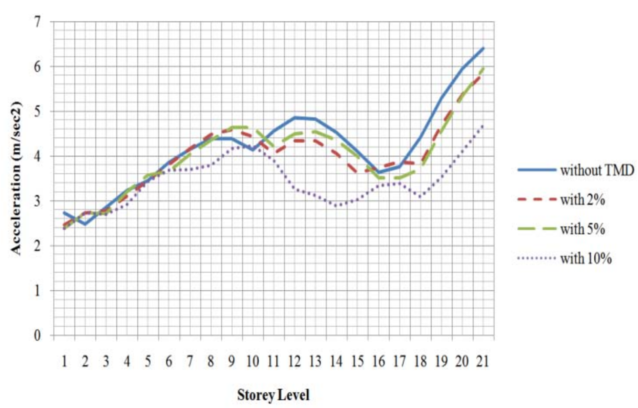

Fig. 3: Acceleration graph

The above table shows the percentage of response reduction of different floors of the building using TMD. It is observed that about 50% response reduction of the roof floor is achieved for 10% mass of TMD.

The graphs shown above are the displacement and acceleration responses for different storey of building, plotted considering with and without TMD, for several mass of TMD (I.e. 2%, 5% and 10%).

6. CONCLUSIONS

The general objective of this paper was to determine the reduction of response due to earthquake loading using optimum parameters of tuned mass damper. The results also show that in order for TMD to be effective, large mass ratio must be used. The top floor with appropriate stiffness and damping can act as a vibration absorber for the lower floors. The safety and functionality of top floors, however, may present problems since the top floor may experience large displacement. TMD have been proven to be effective in reducing the dynamic response of structures induced by seismic loads. TMD is most effective when the structural frequency is close to the central frequency of ground motion.

The results presented in this study suggest that the application of Tuned Mass Damper (TMD) with mass ratios between 2% and 10% is an appropriate measure to diminish the dynamic response of structures subjected to ordinary seismic ground motions.

7. MAIN NOTATIONS

M = Mass of structure,
m = Mass of TMD,
K = Stiffness of structure,
k_d = Stiffness of TMD,
C_d = Damping of TMD,
P (t) = Force acting on structure mass,
β = Damping ratio of structure,
μ = Mass ratio of TMD mass to the mass of structure,
Φ = Amplitude of the mode shape at the TMD location,
ξ_{opt} = Optimum TMD damping ratio,
f_{opt} = Optimum frequency ratio,
$K_{d\ opt}$ = Optimum stiffness of TMD,
$C_{d\ op}$ = Optimum damping of TMD,
Φ = Mode shape,
ϕ^T = Transposed of mode shape,
[M] = Mass matrix of the structure.

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