Seismic Assessment of 10-Story Building Using Tuned Mass Damper

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ABSTRACT

In this paper, optimum parameters of Tuned Mass Dampers (TMD) are considered to control the responses of 10-story shear building under harmonic loading and 22 set of seismic records of FEMA-P695. The criterion used to obtain the optimum parameters is to select mass ratio, the frequency (tuning) and damping ratio that would result in smallest lateral displacements. State-space equations of motion are presented to compute the structural responses by developing a MATLAB file. A 10-story shear building is presented as a case study to assess the effects of TMDs on the multi-story structures. The results indicate that using TMD can reduce structural responses up to the average 20% under earthquake excitation and up to 90% under harmonic loadings. TMDs are not always effective under any type of ground motion; therefore, being aware of the given location is significant to design TMDs properly.

Keywords: tuned mass damper, passive control, seismic analysis, energy dissipation, tall buildings, state-space equations of motion

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1. INTRODUCTION

In structural engineering, there have been many methods for vibration control of the structural response under lateral loads, i.e. earthquake. All available approaches have been proposed to increase energy dissipation or ductility in order to control structural responses and minimize the structural damages under external forces. Without any additional energy dissipation devices in the structure, the response of any structure to earthquake excitation depends on size, shape, mass, and stiffness of the structure [1, 2] and needs to be cautious with considering various damping modeling techniques [3]. In general, categories of control strategies based on actuation device are passive control, active control, semi-active control, and hybrid control. In each category, there are many options available to be considered such as base isolation, friction dampers, visco-elastic dampers, tuned mass dampers, tuned liquid dampers as passive control; active mass dampers, active tendon system and active brace systems as active control; resettable dampers, electro-rheological dampers, and magneto-rheological dampers as semi-active control; and any combination of passive and active devices or passive and semi-active devices as hybrid control. Moreover, there are many works noticed on using shape memory alloys in any type of structures to reduce the structural response without residual strains [4-10].

In the case of passive energy dissipating, Tuned Mass Damper (TMD) is the most popular device due to its simple principle and several successful applications in high-rise constructions. The method is simply characterized by the use of a mass, a spring, and a viscous damper system calibrated to be in resonance with a particular mode of structural vibration. Therefore, three parameters need to be defined for designing TMDs as mass, damping and stiffness. Computing optimum values of these parameters investigated by many researchers [11-18]. In the literature, TMDs can significantly reduce the dynamic response of structures without any need for external power sources or sophisticated hardware. They are usually installed on the roofs of buildings and are more effective in wind-induced vibrations reduction than earthquake-induced vibrations. In seismic excitation, it is recommended to use more mass dampers for covering vast ranges of main frequencies of the structure due to the uncertainty behavior of earthquake prediction and dynamic features of the structure [19]. Naderpour et al. [20] investigated the structural control method of combining base isolation and non-traditional tuned mass dampers, and they found the largest reduction in structural responses in this combination rather than using just base isolation or TMDs.

Manchalwar and Bakre [21] studied a building with base isolated top floor as a TMD, and they found that base isolated TMD is quite effective as compared to building without TMD. In this project, TMDs are installed on the roof of the 10-story building, and structural responses are investigated using optimum values of TMD from Sadek et al. [14].

2. EQUATION OF MOTION

The equation of motion of the structural system under lateral loads may be written as:

$$\mathbf{M}\ddot{\mathbf{X}}(t) + \mathbf{C}\dot{\mathbf{X}}(t) + \mathbf{K}\mathbf{X}(t) = \mathbf{F}(t)$$

where $\mathbf{M}, \mathbf{C}, \mathbf{K}$ are mass, damping, and stiffness matrices of the structure.

Considering an N-story shear building with mass damper installed at the top floor gives mass, damping and stiffness matrices of the structure as:

$$\mathbf{M} = \text{diag} [m_1 \quad m_2 \quad \cdots \quad m_N \quad m_d]$$

$$\mathbf{C} = \begin{bmatrix} c_1 + c_2 & -c_2 & & & & \\ -c_2 & c_2 + c_3 & -c_3 & & & \\ & \ddots & \ddots & \ddots & & \\ & & -c_N & c_N + c_d & -c_d & \\ & & & -c_d & c_d & \end{bmatrix}$$

$$\mathbf{K} = \begin{bmatrix} k_1 + k_2 & -k_2 & & & & \\ -k_2 & k_2 + k_3 & -k_3 & & & \\ & \ddots & \ddots & \ddots & & \\ & & -k_N & k_N + k_d & -k_d & \\ & & & -k_d & k_d & \end{bmatrix}$$

$$\mathbf{X} = [x_1 \quad x_2 \quad \cdots \quad x_N \quad x_d]^T$$

$$\mathbf{F} = [f_1 \quad f_2 \quad \cdots \quad f_N \quad f_d]^T$$

where m_i, c_i, k_i, x_i, f_i are the mass, damping, stiffness, displacement, and applied external load at i -th floor ($i = 1, 2, \dots, N$), respectively; m_d, c_d, k_d are the mass, damping, and stiffness of the

damper; x_d is the displacement of damper relative to ground; and f_d is the external load applied at the absorber. A schematic model is shown in Figure 2.1.

Figure 2.1 Schematic model of MDOF system with TMD

By converting the equation of motion to state-space representation, the state-equations can be written as:

$$\dot{\mathbf{Z}}(t) = \mathbf{A}\mathbf{Z}(t) + \mathbf{B}\mathbf{F}(t)$$

where

$$\mathbf{Z}(t) = \begin{Bmatrix} \mathbf{X}(t) \\ \dot{\mathbf{X}}(t) \end{Bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} \mathbf{O}_{(N+1) \times (N+1)} & \mathbf{I}_{(N+1) \times (N+1)} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \mathbf{O}_{(N+1) \times (N+1)} \\ \mathbf{M}^{-1} \end{bmatrix}$$

$$\mathbf{F}(t) = -\mathbf{M}\{1\}_{(N+1) \times 1} \ddot{x}_g(t)$$

3. CASE STUDY

In this project, ten-story shear building with mass damper on the top of the floor is selected from Hadi and Arfiadi [15] which has the same mass (360 ton), stiffness (650e3 kN/m) and damping (6200 kN.s/m) in each story. The properties of mass damper are computed from the optimum relations found by Sadek et al. [14]. TMD mass ratio (μ) is the ratio of the TMD mass to the generalized mass for the fundamental mode for a unit modal participation factor.

$$\mu = \frac{m_d}{\phi_1^T \mathbf{M} \phi_1}$$

where ϕ_1 and $\mathbf{M}$ are the fundamental mode shape normalized to have a unit participation factor, and the mass matrix of the structure, respectively. As you will see further, the optimum value for the mass of the damper is computed to have the least maximum drift or displacement.

As per Sadek et al. [14], the optimum frequency (f_{opt}) and optimum damping ratio (ξ_{opt}) may be computed as:

$$f_{opt} = \frac{1}{1 + \mu\Phi} \left[1 - \beta \sqrt{\frac{\mu\Phi}{1 + \mu\Phi}} \right]$$

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

where f_{opt} is the ratio of the first natural frequency of TMD to the first natural frequency of the building ($= \omega_d / \omega$); β is the damping ratio of the building; and Φ is the amplitude of the first mode of vibration for a unit modal participation factor calculated at the location of TMD. In this project, the building damping ratio (β) is assumed as 0.02. The optimum values found for this building is presented in Table 1.

Table 1 Optimum TMD parameters for the given building for mass ratio of 0.06

Mass ratio (μ)	Damping ratio (β)	Tuning ratio (f)	TMD damping ratio (ξ)	Φ at the top story
0.06	0.02	0.9955	0.016	1.267

4. NUMERICAL STUDIES AND RESULTS

The described 10-story shear building is modeled in Matlab (R2019b), and the optimum values for the mass damper are computed and assign to the model. State-space representation for this model is applied to compute the structural responses from ODE45 function in Matlab. The results for controlled structure are compared with the uncontrolled one under 22 far-field record sets of earthquake [22] and sine-wave which are shown in table. The optimum mass ratio (considering 0.01 to 0.1) for TMD is found by minimizing the maximum displacement for each ground motion, and the structural response (displacement and drift) is compared with the uncontrolled building in Table 3.

As the results shown, using TMD at the top of the building has sometimes negative effects on the structure, and to have an optimum design for the TMD, different mass ratio would have better results; therefore, TMD design is so sensitive to the ground acceleration. Considering this approach for controlling the structural responses reduces an average of 20% on maximum drift and maximum displacement under ground motion. Using TMD in the buildings is so effective under harmonic loads that the responses may be reduced over 80% which is wonderful. To see structural responses visually, Figure 4.1 and Figure 4.2 show the responses under harmonic load (ID #23) and Manjil (ID #15) earthquake, respectively. Figure 4.3 represents the schematic deformation of the given building under harmonic load and Manjil earthquake for comparison.

Table 2 Summary of 22 far-field earthquake records [22] and harmonic load assigned to the building

ID No.	Earthquake			Station	Normali-zation factor	Normalized motions	
	M	Year	Name			PGA _{max} (g)	PGV _{max} (cm/s)
1	6.7	1994	Northridge	Beverly Hills	0.65	0.34	41
2	6.7	1994	Northridge	Canyon Country	0.83	0.40	38
3	7.1	1999	Duzce	Bolu	0.63	0.52	39
4	7.1	1999	Hector Mine	Hector	1.09	0.37	46
5	6.5	1979	Imperial Valley	Delta	1.31	0.46	43
6	6.5	1979	Imperial Valley	El Centro Array #11	1.01	0.39	43
7	6.9	1995	Kobe	Nishi-Akashi	1.03	0.53	39
8	6.9	1995	Kobe	Shin-Osaka	1.10	0.26	42
9	7.5	1999	Kocaeli	Duzce	0.69	0.25	41
10	7.5	1999	Kocaeli	Arcelik	1.36	0.30	54
11	7.3	1992	Landers	Yermo Fire Station	0.99	0.24	51
12	7.3	1992	Landers	Coolwater	1.15	0.48	49
13	6.9	1989	Loma Prieta	Capitola	1.09	0.58	38
14	6.9	1989	Loma Prieta	Gilroy Array #3	0.88	0.49	39
15	7.4	1990	Manjil	Abbar	0.79	0.40	43
16	6.5	1987	Superstition Hills	El Centro Imp. Co.	0.87	0.31	40
17	6.5	1987	Superstition Hills	Poe Road (temp)	1.17	0.53	42
18	7.0	1992	Cape Mendocino	Rio Dell Overpass	0.82	0.45	36
19	7.6	1999	Chi-Chi	CHY101	0.41	0.18	47
20	7.6	1999	Chi-Chi	TCU045	0.96	0.49	38
21	6.6	1971	San Fernando	LA-Hollywood Stor	2.10	0.44	40
22	6.5	1976	Friuli	Tolmezzo	1.44	0.50	44
23	Sine Wave			$0.05 \times diag(\mathbf{M}) \times g \sin(w_1 t)$			

Table 3 Optimum TMD parameters and structural response under each type of loading

ID No.	Optimum Damper Parameters			Controlled Building		Uncontrolled Building		Percent Reduction	
	m_d (ton)	k_d (kN/m)	ξ_d	Max Drift (cm)	Max Displacement (cm)	Max Drift (cm)	Max Displacement (cm)	Drift (%)	Displacement (%)
1	244	8021	0.37	3.31	19.82	3.29	22.21	-0.6	10.8
2	214	7188	0.35	1.59	9.57	3.36	20.06	52.7	52.3
3	244	8021	0.37	2.57	15.23	4.07	27.52	36.9	44.7
4	30	1195	0.15	2.06	14.03	2.76	16.83	25.4	16.6
5	61.05	2327	0.2	2.96	16.53	4.16	27.58	28.8	40.1
6	92	3402	0.24	1.65	7.23	1.44	8.94	-14.6	19.1
7	30	1195	0.15	2.40	12.71	2.17	12.28	-10.6	-3.5
8	30	1195	0.15	2.12	14.80	1.60	12.02	-32.5	-23.1
9	305	9568	0.41	1.73	11.50	2.76	16.89	37.3	31.9
10	30	1195	0.15	0.75	5.13	0.94	6.18	20.2	17.0
11	61.05	2327	0.2	1.42	9.23	1.80	12.27	21.1	24.8
12	30	1195	0.15	2.22	15.18	2.60	17.76	14.6	14.5
13	30	1195	0.15	2.82	14.79	3.64	17.24	22.5	14.2
14	152	5391	0.3	1.30	7.23	1.79	12.01	27.4	39.8
15	122	4422	0.27	1.37	7.57	1.77	10.69	22.6	29.2
16	30	1195	0.15	1.55	9.99	1.39	9.01	-11.5	-10.9
17	183	6312	0.33	2.13	13.27	2.31	14.56	7.8	8.9
18	214	7188	0.35	1.24	7.38	2.04	13.27	39.2	44.4
19	61.05	2327	0.2	1.67	10.56	2.44	15.98	31.6	33.9
20	153	5391	0.30	2.00	11.56	2.33	15.75	14.2	26.6
21	30	1195	0.15	2.79	17.58	2.88	19.30	3.1	8.9
22	122	4422	0.27	1.96	9.99	2.36	12.97	16.9	23.0
23	305	9568	0.41	0.77	4.20	5.63	37.64	86.3	88.8

Figure 4.1 Structural response of 10-story building under harmonic load

Figure 4.2 Structural response of 10-story building under Manjil earthquake

Figure 4.3 Maximum displacement for uncontrolled and controlled structure under (a) harmonic load, and (b) Manjil earthquake excitation.

5. CONCLUSION

In this project, structural response of 10-story shear building using tuned mass damper at the top of the building is investigated under harmonic and 22 set of earthquake records defined by the FEMA-P695. Optimum properties of TMD are computed under each type of loading. It is found that TMD can reduce structural responses up to the average 20% under earthquake loadings and up to 90% under harmonic loadings. Using TMDs is not always effective under different type of ground motions; thus, considering the ground motions related to the given location may help to design better and more effective dampers. As a suggestion for further research, to control the structural responses better, using more than one TMD may be useful and guarantee the reduction in structural responses.

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