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Technical Note

Optimum Seismic Design of Tuned Story Mass Damper Using Multi-Objective Genetic Algorithm

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ABSTRACT

A new system called Tuned Story Mass Damper (TSMD) is proposed and modified to enhance the seismic performance of mid-rise buildings. In TSMD systems, some part of a story's mass is utilized as Mass Damper, and an external passive damping device is used to provide the expected control force. For an 11-story structural model under seismic excitations, the equations of motion are solved in state space and two objective functions, the maximum displacement and maximum velocity of the top floor are considered to be minimized simultaneously. Using a fast and elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) approach, the optimum design parameters of the TSMD system, including mass, stiffness and damping as well as the best location of the TSMD system among the floors of the structure are obtained. The results show that considering the TSMD system on the fifth floor leads to the most reduction in displacement and velocity, not only for the roof, but also for the other floors as well. For the system under study, comparing with the non-controlled system, a reduction of about 31% on maximum displacement and 42% on maximum velocity of the top floor are obtained.

Keywords:
Optimization; Seismic response; Genetic Algorithm; Tuned Story Mass Damper

1. Introduction

Tuned mass damper (TMD) is one of the most reliable control devices that have been used to attenuate vibration of different structures subjected to dynamic loads. The main purpose of using TMDs is to transfer the vibration energy of the main structure to an auxiliary mass and damper, and to dissipate it there.

The main idea of using TMD was first proposed by Frahm [1] for damping the resonance vibrations, which arise in bodies subjected to certain periodic impacts, like ships and fixed bodies such as buildings when vehicles pass near them, or when machines are working within them. In seismic applications, several investigators have investigated the optimum TMD parameter. Sadek et al [2] reviewed the studies on the use of TMDs for seismic applications and proposed a method for selecting TMD parameters by providing equal and large damping ratios in the complex modes of vibration.

For structures with high damping ratios, TMDs with large mass ratios are required to significantly reduce the responses. In such cases, the use of roof equipment or addition of heavy blocks will not provide the necessary mass to provide sufficient damping in the predominant modes of vibration. The top floor itself, however, can provide the required mass [2]. This concept has been received an important interest by many civil engineering investigators.

Jagadish et al [3] studied two-story bilinear hysteretic structures to find the circumstances under which the top story of the structure could absorb a major portion of the energy input, thus reducing the response levels of the lower stories. This concept was named 'expandable top story', and the results showed that the ductility demand of the absorber story would be too much larger than what may normally expect.

Miyama [4] presented 'energy absorbing story' concept in which most of the total energy input due to the earthquakes was aimed to be absorbed in the top story of the multi-story frames leaving the other stories undamaged. Numerical results were shown that by tuning the strength and the inelastic stiffness of the top story, it is possible to get 80% energy absorption, even if the top mass weight is 5% of total mass.

Feng and Mita [5] proposed a vibration-control system for tall and super tall buildings, that take advantage of so-called 'mega-substructure configuration' in which substructures contained in the mega-structure serve as energy absorbers so that no additional mass is required for the intended vibration control as seen in the conventional mass damper systems. They derived optimum values of parameters such as the frequency and damping ratio of the substructure for a simplified model of mega-substructure.

Chey et al [6] proposed the idea of segregating the upper portion of multi-story buildings and isolating them as a tuned mass, and they utilized a passive viscous damper or a semi-active resettable device as an energy dissipation strategy. As a numerical study, they modeled a 12-story moment resistance frame as '10+2' stories and '8+4' stories frames and concluded that the proposed concept is very reliable for reducing the seismic response, and the larger mass ratio (8+4) had a better ability to reduce the overall seismic response of the structure.

Pourzeynali and Zarif [7] studied the suppression of the dynamic response of a base-isolated tall building, supported on elastomeric bearings. Moreover, in order to rectify the undesirable horizontal displacement of the lead-rubber bearings, they proposed a new method called 'Independent Story' that worked as a big TMD, without using any additional damping or stiffness devices except those of the structure itself. By considering the 6th story of a 10-story building as an "Independent Story" system and combining it with a base isolation system, they reached their desired goals and the effectiveness of the proposed system was proved.

Zahrai et al [8] designed a fuzzy controller for semi-active TMDs to decrease seismic vibration of the buildings. To reach a better performance, they used the upper stories of an 11-story building as mass damper. From their numerical studies, it was concluded that by adopting top story as mass damper and using fuzzy controller, the reduction of pick displacement is more than 35%, and by designing the two last stories as mass damper, the reduction will exceed 55%.

In this paper, the 'Tuned Story Mass Damper' (TSMD) system will be considered in order to control seismic vibration of medium rise buildings. Accordingly, either one full story of the building or even some part of it can be considered as TSMD system, where its location can also be on any floor. TSMD system takes advantage of a part of mass and stiffness of the floor, which is relied on as a tuned mass and will utilize a passive damping device. To enhance the performance of the TSMD system, its parameters including mass, stiffness and damping have been optimally designed using a fast and elitist non-dominated sorting genetic algorithm (NSGA-II) approach. Two objective functions, namely: maximum displacement and maximum velocity of the top floor of an 11-story building are considered to be simultaneously minimized. Moreover, in order to find the best placement of the TSMD system at the height of the structure, five possible states containing the placement of the system on 3rd, 5th, 7th, 9th and 11th stories of this building will be investigated.

2. Structural Model

In order to investigate the performance of the TSMD control system in reducing the seismic response of the building structures, the 11-story building of Reference No [8] is modeled as a 2-D shear-type frame with the assumption of masses lumped at floor levels, in which each floor has one lateral degree of freedom. The structural properties of this typical medium-rise building that is shown in

Figure (1) are provided in Table (1).

Now, the equation of motion of the structure under seismic loads will be considered as in Eq. (1):

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=[M]\{r\}\,\ddot{u}_g(t) \qquad (1)$$

where $[M]$, $[C]$, and $[K]$ are matrices of mass, damping and stiffness, respectively. $\{u\}$ is the displacement vector of structure, $\{r\}$ is the impact coefficient vector, and $\ddot{u}_g$ is the earthquake acceleration.

The mass matrix of this building is a diagonal matrix in which the mass of each story is stored on its diagonal. The stiffness matrix of the structure is developed based on the individual stiffness of each story, k_i, and is given in Eq. (2).

$$k_{ij}=\begin{cases} k_i+k_{i+1} & i=j\neq n \\ k_n & i=j=n \\ -k_i & i-j=1 \\ -k_{i+1} & j-i=1 \\ 0 & others \end{cases} \qquad (2)$$

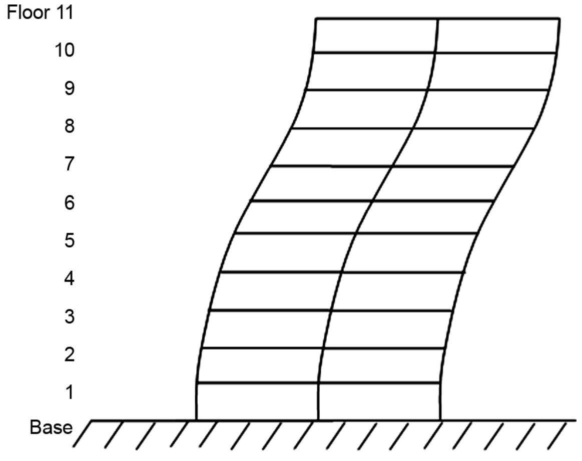

Figure 1. Two-dimensional view of the structure.

Table 1. Building's structural data.

Stories	Mass (ton)	Stiffness (MN/m)
1	215	468
2	201	468
3	201	468
4	200	450
5	201	450
6	201	450
7	201	450
8	203	437
9	203	437
10	203	437
11	176	312

The damping matrix of the building is also assumed to be proportional to the mass and stiffness matrices (Rayleigh method), given as Eq. (3):

$$[C]=a_0[M]+b_0[K] \qquad (3)$$

in which a_0 and b_0 are the proportionality coefficients which can be calculated using Eq. (4)

$$\begin{pmatrix} a_0 \\ b_0 \end{pmatrix}=\frac{\omega_n\omega_m}{\omega_n+\omega_m}\begin{bmatrix} \omega_n & -\omega_m \\ -\omega_n^{-1} & \omega_m^{-1} \end{bmatrix}\begin{Bmatrix} \xi_n \\ \xi_m \end{Bmatrix} \qquad (4)$$

where ω_n and ω_m are the structural modal frequencies of modes n and m, respectively; and ξ_n and ξ_m are the structural damping ratios for modes n and m. The modal damping ratio of the first two modes are assumed to be 5% of the critical value, and the proportionality coefficients are obtained as $a_0 = 0.4901$ and $b_0 = 0.0039$. Moreover, it should be noted that all vibration modes of the building are considered in the analysis, and modal frequencies and modal periods of this structure are given in Table (2).

Table 2. Dynamic properties of the structure.

Modes	Frequencies (rad/s)	Periods (s)
1	6.5641	0.9572
2	19.3359	0.3249
3	31.4358	0.1999
4	42.6332	0.1474
5	52.9356	0.1187
6	62.4987	0.1005
7	71.1572	0.0883
8	79.1068	0.0794
9	85.5849	0.0734
10	90.3704	0.0695
11	93.6721	0.0671

The equation of motion (Eq. 1) of this structure is solved in state space, where the state vector (Z) is considered as Eq. (5), in which $\{u\}$ is the displacement vector and $\{\dot{u}\}$ is the velocity vector of the structure's degrees of freedom.

$$Z=\begin{Bmatrix} \{u\} \\ \{\dot{u}\} \end{Bmatrix} \qquad (5)$$

The second order differential equation of motion of this building under seismic excitations is transferred to state space according to Eq. (6):

$$\overset{\bullet}{Z} = \begin{bmatrix} O_{n\times n} & I_{n\times n} \\ -[M]^{-1}[K] & -[M]^{-1}[C] \end{bmatrix} Z + \begin{bmatrix} O_{n\times n} \\ I_{n\times n} \end{bmatrix} \left(-\{r\}\,\ddot{u}_g(t)\right) \tag{6}$$

where I is identity matrix, O is zero matrix, and n is the number of degrees of freedom of structure.

To obtain the equation of motion of a structure equipped with TSMD system, it is enough to consider one additional degree of freedom for TSMD mass, and place the corresponding element in mass and stiffness matrices. Accordingly, equations of this system in common condition and the state space are as Eq. (7) and Eq. (8):

$$[M_T]\{\ddot{u}\} + [C_T]\{\dot{u}\} + [K_T]\{u\} = [M_T]\,\{r_T\}\,\ddot{u}_g(t) \tag{7}$$

$$\overset{\bullet}{Z}_T = \begin{bmatrix} O_{(n+1)\times(n+1)} & I_{(n+1)\times(n+1)} \\ -[M_T]^{-1}[K_T] & -[M_T]^{-1}[C_T] \end{bmatrix} Z_T + \begin{bmatrix} O_{(n+1)\times(n+1)} \\ I_{(n+1)\times(n+1)} \end{bmatrix} \left(-\{r_T\}\,\ddot{u}_g(t)\right) \tag{8}$$

where $[M_T], [C_T]$, and $[K_T]$ are extended matrices of mass, damping and stiffness of the structure equipped with TSMD, respectively.

In the present study, 14 worldwide strong ground motion accelerograms were used, which their relevant details are given in Table (3).

Necessary corrections are performed on the uncorrected accelerograms, including a band pass filtering of low and high frequency noises, as well as the instrumental and baseline corrections. All these corrected accelerograms, with an intense duration of more than 10 seconds have been normalized and scaled according to standard No. 2800 - 05 [9] and used in time history analyses.

3. Multi-Objective Optimization

In this study, a multi-objective optimization approach called NSGA-II [10] is used to simultaneously minimize the two objective functions, utilizing a computer program developed in MATLAB software. The flowchart of the algorithm used for solving this optimization problem is shown in Figure (2). This flowchart states that the population is initialized by random based on genetic algorithm. Once the population is initialized, the population is sorted based on non-domination into each front. The first front being completely non-dominant set in the current population and the second front being dominated by the individuals in the first front only and the front goes so on. All individuals in each front are assigned a rank (fitness) value based on the order of the front in which they belong to, such that the individuals in the first front are given a fitness value of 1 and individuals in the second are assigned a fitness value as 2 and so on. In addition, a new parameter called crowding distance is calculated for each individual. The crowding distance is a measure of how close an individual is to its neighbors. Large average crowding distance will result in better diversity in the population. Parents are selected from the population by using binary tournament selection based on the rank and crowding distance.

Table 3. Earthquake accelerograms considered in the present study.

No.	Earthquake	Date	Duration (s)	Mechanism	Vs30 (m/s)	Magnitude (Ms)	Station
1	Bam	2003	35	Strike slip	504.85	6.6	Baft
2	Tabas	1978	39	Reverse	377.56	7.35	Bajestan
3	Manjil	1990	54	Strike slip	723.95	7.37	Ab-bar
4	Chichi	1999	90	Reverse Oblique	492.26	7.62	CHY041
5	Imperial Valley	1979	64	Strike slip	471.53	6.53	Cerro Prieto
6	Northridge	1994	40	Reverse	501.75	6.69	Anacapa Island
7	San Fernando	1971	27	Reverse	385.69	6.61	Buena Vista-Taft
8	Kocaeli	1999	30	Strike slip	523	7.51	Arcelik
9	Landers	1992	50	Strike slip	382.93	7.28	Amboy
10	Borrego	1968	60	Strike slip	415.13	6.63	Pasadena - CIT
11	El Centro	1940	31	-	-	6.9	PeknoldVerion
12	Kobe	1995	54	Strike slip	609	6.9	Chihaya
13	Loma Prieta	1989	40	Reverse Oblique	391.91	6.93	APEEL 10 - Skyline
14	Coalinga	1983	65	Reverse	522.74	6.37	Parkfield-Cholame 2E

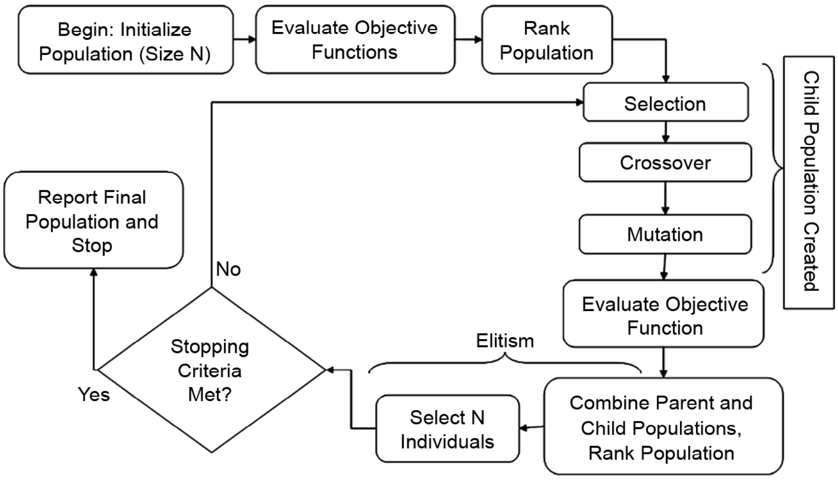

Figure 2. The flowchart of NSGA-II.

An individual is selected based on the lesser rank or greater crowding distance than the others [11].

It should be noted that crowding distance is compared only if the rank of both individuals are the same. The parents which have been selected will work as the new initial population for the next iteration, and this process will be continued until the termination condition of the algorithm is obtained.

The genetic algorithm is used to create the child population. Here, arithmetic crossover and Gaussian mutation will be used as genetic operators. Crossover is the main operator of producing the next generation, and tries to combine the best parameters of the selected parents. Mutation is a small change in a member of the population and will bring genetic diversity into the population. The main aim of mutation is to create members that had not been existed and may help to provide a better solution.

For evaluation of the proposed TSMD control system, maximum displacement and maximum velocity of the top floor are considered as objective functions to be simultaneously minimized. Furthermore, the mass, stiffness and the required damping of TSMD are decision variables to be evaluated through the multi-objective optimization. These objective functions can be expressed as Eq. (9):

$$F_1 = \frac{D_r^c(t)}{D_r^{uc}(t)}$$
$$F_2 = \frac{V_r^c(t)}{V_r^{uc}(t)} \tag{9}$$

where $D_r^c(t), D_r^{uc}(t), V_r^c(t),$ and $V_r^{uc}(t)$ are the maximum displacement and the maximum velocity of the top floor of the building in controlled and uncontrolled cases, respectively.

4. Numerical Study

In order to find the best location of TSMD among the floors of the structure, five different cases are investigated. These cases include positioning TSMD as part of the mass and stiffness of the eleventh, ninth, seventh, fifth and third stories of the eleven-story building. By doing the optimization process for each of these cases, the optimal solutions category that is called Pareto front are obtained. These Pareto fronts represent the ability of the TSMD control system in fulfilling the objective functions and reducing the seismic response of the structure; therefore, by comparing them, the best location of TSMD system at the height of the structure will be determined.

This optimal design procedure has been conducted for 14 major worldwide earthquakes mentioned in Table (3) and the results have been compared. For instance, Figures (3) and (4) depicted five optimal Pareto fronts of the Borrego and El Centro earthquakes. Finally, the comparison of the optimal Pareto fronts generates from the 14 earthquakes show that the location of the TSMD system on the fifth floor of the eleven-story building is the best placement in order to obtain the maximum reduction in the seismic response of the structure.

The next aim of the optimal design procedure of this study is to find the best design values of the TSMD parameters. Each optimal Pareto front has

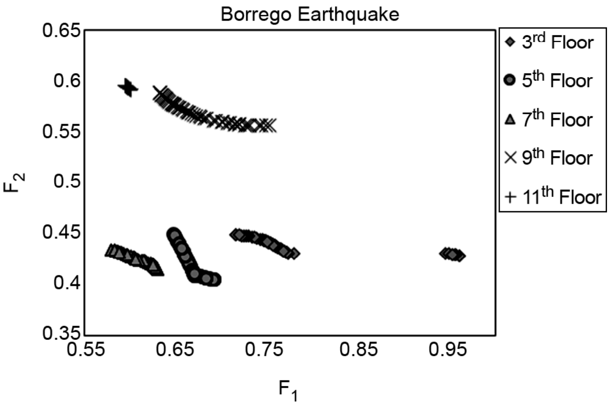

Figure 3. Optimal Pareto fronts of the Borrego earthquake.

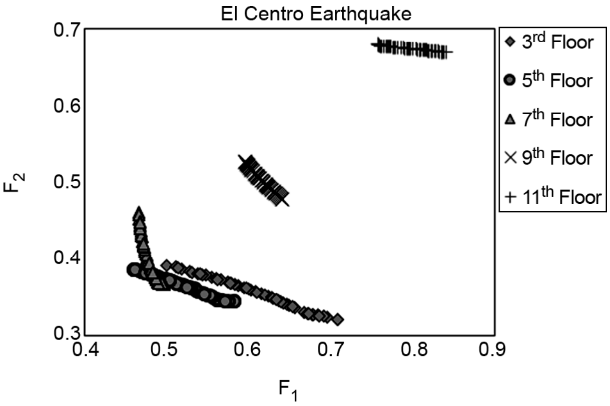

Figure 4. Optimal Pareto fronts of the El Centro earthquake.

50 members with different values for each of the parameters and different abilities in fulfilling the objective functions. Furthermore, the final decision should be made based on 14 earthquakes. Thus, there are 700 possible situations that the best one should be chosen as the optimum design of the TSMD parameters. To do this, three averaging methods as follows are used:

1) Arithmetic Mean: it is the sum of the values of each parameter divided by the number of values that participate in the decision making process.
2) Weighted Mean: the reduction ratio of the controlled and uncontrolled displacement of the roof (1-F1) is taken as a weighting coefficient for the value of the related parameter, then the sum of the obtained values will be divided by the sum of the weighting coefficients.
3) Arithmetic Mean plus standard deviation: here the calculated arithmetic mean will be added by one standard deviation to take into account the effects of the values that are not near the mean value, but have a better ability in fulfilling the objective functions.

The results of optimal values of the TSMD design parameters calculated by applying these three methods are shown in Table (4).

In order to make the final decision for the TSMD parameters among these three methods, the building equipped with TSMD on its 5th floor employing these design parameters is analyzed under the excitation of all 14 mentioned earthquakes, and the values of maximum reduction of displacement (1-F1) and maximum reduction of velocity (1-F2) of the roof of the structure are calculated and presented in Table (5).

Table 4. TSMD design parameters obtained from the three proposed methods.

Method	Mass (ton)	Stiffness (kN/m)	Damping (MN.s/m)
Arithmetic Mean	79.77	19253.8	3.5719
Weighted Mean	79.06	18064.3	3.4764
Arithmetic Mean Plus Standard Deviation	115.07	29722.4	5.2627

By comparing the results given in Table (5), it can be concluded that the third averaging method is the most appropriate method for determining the TSMD design parameters. In this method, maximum displacement of the roof is reduced by 31% and the maximum velocity of the roof is reduced by 42%. According to the results, it can be said that the final designed TSMD that located on the 5th floor has a mass equal to 5.25% of the total mass of the structure, the stiffness equal to 0.61% of the total stiffness of the structure and put to use 5.263 MN.s/m external damping.

In order to verify the effectiveness of the designed system and to have a comparison with similar recent studies, Table (6) is presented. Since the characteristics of each of the mentioned research, including buildings under study, damping ratio, the accelerograms used and the nature of the control system used is different, it is needed to explain more about the compared results in Table (6).

Chey et al [6] analyzed their 2-dimensional 12-story model under 30 earthquake excitations. The damping ratio of the building was considered to be 5 percent, and in the first phase the two last stories and in the second phase the last four stories were utilized as tuned mass.

Pourzeynali and Zarif [7] optimized the base isolation system parameters of a 10-story structure that its sixth floor was acting like a big TMD, with

Table 5. The TSMD design parameters obtained from the three proposed methods, and their ability to reduce the seismic response of the structure for various earthquakes.

Earthquake	Arithmetic Mean		Weighted Mean		Arithmetic Mean Plus Standard Deviation	
	$(1-F_1)$ %	$(1-F_2)$ %	$(1-F_1)$ %	$(1-F_2)$ %	$(1-F_1)$ %	$(1-F_2)$ %
Bam	-5	52	-7	52	13	42
Tabas	-1	45	-3	46	16	39
Manjil	32	56	32	58	38	47
Chichi	48	3	48	3	47	9
Imperial Valley	17	14	9	4	19	11
Northridge	60	70	60	57	52	55
San Fernando	-14	42	-15	41	0	41
Kocaeli	14	47	12	47	23	43
Landers	29	61	27	61	42	54
Borrego	16	52	13	50	34	58
El Centro	39	59	40	59	40	58
Kobe	56	64	56	64	57	64
Loma Prieta	-1	38	-3	40	23	30
Coalinga	25	53	25	55	30	35
Average	**22.5**	**47**	**21**	**45.5**	**31**	**42**

Table 6. Comparative results of the present study with recent related studies.

Survey	Number of Stories	Location of the System	Mass (ton)	Stiffness (kN/m)	Damping (MN.s/m)	Roof Displacement Reduction	Roof Velocity Reduction
Present Study	11	Some part of 5th floor	115	29.73	5.263	31%	42%
Chey et al [6]	12	Last Two Floors	311	2.935	1.252	29%	-
Chey et al [6]	12	Last Four Floors	625	5.293	3.085	33%	-
Pourzeynali and Zarif [7]	10	6th Floor	252	714	-	27%	-
Zahrai et al [8]	11	Top Floor	176	1.8135	7.14	19%	-
Zahrai et al [8]	11	Last Two Floors	379	2.0185	8.37	42%	-

the view to minimize the top floor and base isolator displacements at the same time. The damping ratio of the building was 2 percent and the model was analyzed under the force of 18 accelerograms.

Zahrai et al [8] analyzed an 11-story building that was also investigated in the current study, under the excitations of the Chichi and Tabas earthquakes in two passive and semi-active control modes. The damping ratio of the building was 1 percent, and in the first stage the last floor and in the second stage the last two floors were utilized as tuned story mass. Here we mentioned the mean results of the two earthquakes in passive mode.

It should be mentioned that, in the present research, the main structural damping ratio considered to be 5 percent, and the investigations were performed under the effect of 14 accelerograms. In addition to top floor displacement, the results have shown that the seismic response of all floors was reduced.

The time histories of the controlled and uncontrolled responses of the building's top floor for Borrego earthquake and El Centro earthquake are shown in Figures (5) to (8), which indicate the performance of the optimally designed TSMD in reducing seismic responses. However, not only the proposed TSMD system is designed to reduce the top story seismic responses, but also succeeded in reducing the other stories responses. These reductions are more evident in the higher stories and those with larger uncontrolled responses. The values of the controlled and uncontrolled maximum responses of the building stories are shown in Figures (9) to (12).

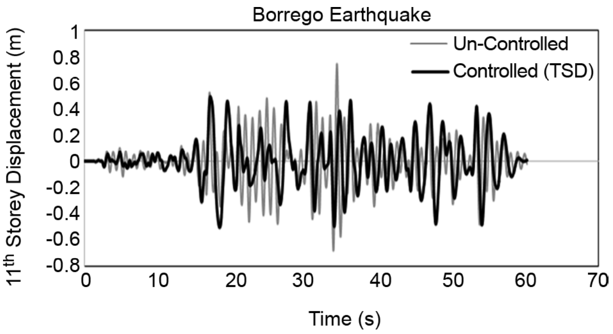

Figure 5. Comparison of the controlled and uncontrolled displacement of the top floor for the Borrego earthquake.

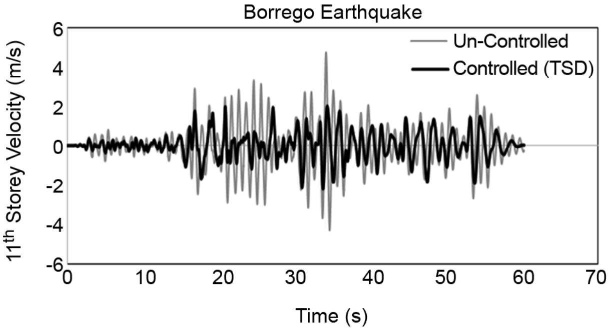

Figure 6. Comparison of the controlled and uncontrolled velocity of the top floor for the Borrego earthquake.

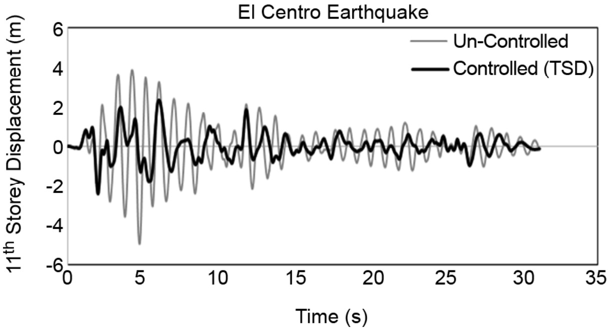

Figure 7. Comparison of the controlled and uncontrolled displacement of the top floor for the El Centro earthquake.

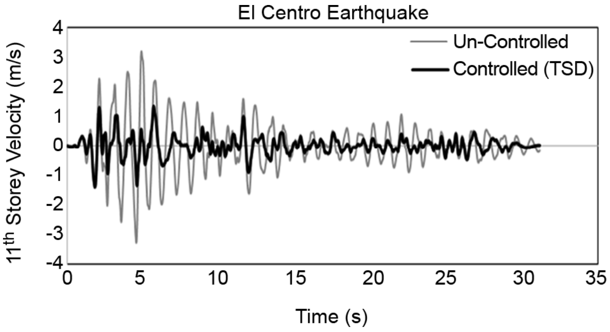

Figure 8. Comparison of the controlled and uncontrolled velocity of the top floor for the El Centro earthquake.

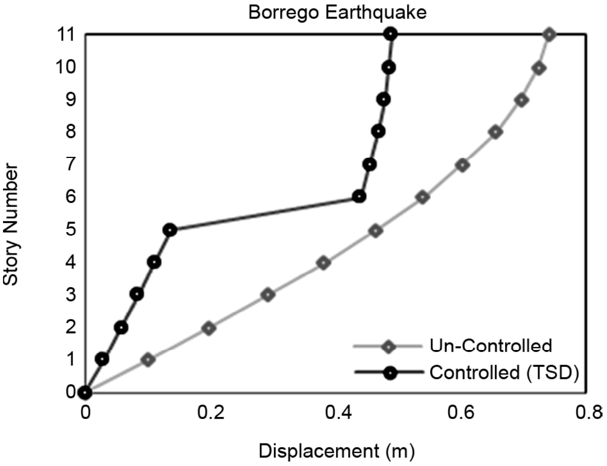

Figure 9. Comparison of the controlled and uncontrolled maximum displacement of all floors for the Borrego earthquake.

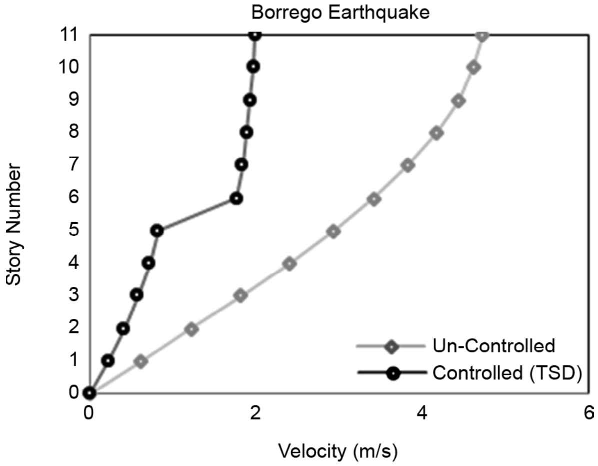

Figure 10. Comparison of the controlled and uncontrolled maximum velocity of all floors for the Borrego earthquake.

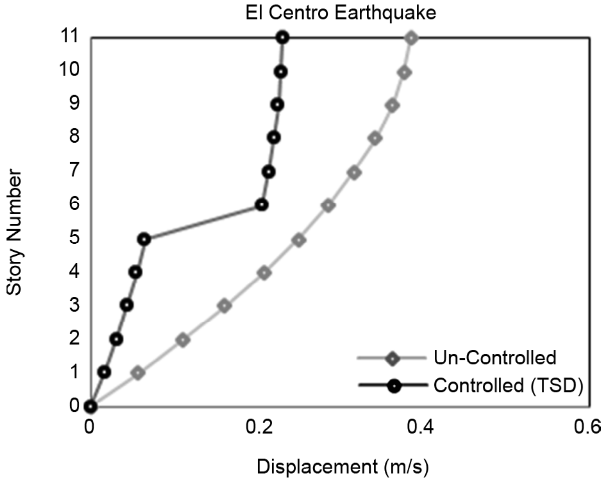

Figure 11. Comparison of the controlled and uncontrolled maximum displacement of all floors for the El Centro earthquake.

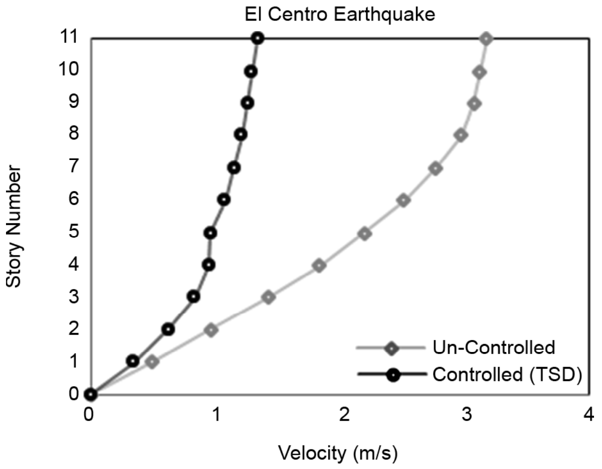

Figure 12. Comparison of the controlled and uncontrolled maximum velocity of all floors for the El Centro earthquake

Finally, the optimally designed TSMD system is analyzed subjected to Tabas and Chichi earthquakes and is compared with the controlled results of the system that was proposed by Zahrai et al [8], in which the top floor of the 11-story building with 7.1401 MN.s/m extra damping was used as mass damper and damping ratio of the structure was considered to be 1%. Results show that the optimally designed TSMD system reduced maximum displacement of the roof by 16% in Tabas earthquake and by 47% in Chichi earthquake, while in reference [8] the top floor passive mass damper reduced maximum displacement of the roof by 21% in Tabas earthquake and by 17% in Chichi earthquake.

5. Conclusions

In this paper, a Tuned Story Mass Damper is considered to control seismic responses of medium rise buildings. The performance of TSMD is enhanced by optimally designing its parameters using multi-objective genetic algorithm, by which the best location and optimum parameters of the system are determined by investigating among various possible cases in an 11-story building.

Numerical results indicating that by considering the TSMD on the 5th floor of the building under study and utilizing a set of optimum design parameters makes it possible to reduce 31% on maximum displacement and 42% on maximum velocity of the top floor compared with uncontrolled system. Besides, responses of the other floors are controlling.

Despite the impression which part of the story mass that acts as TSMD need to have large displacement in order to create necessary control reciprocity, results show that the responses of this part also declined within a reasonable range.

Comparing the results with other similar studies, show that the proposed optimum designed TSMD has a better performance along with lesser mass, stiffness and damping values.

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