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SEISMIC DESIGN OF FUZZY CONTROLLER FOR SEMI-ACTIVE TUNED MASS DAMPERS USING TOP STORIES AS THE MASS

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ABSTRACT

A fuzzy controller is designed in this paper for semi-active tuned mass damper to decrease seismic vibration of buildings. To reach a more desirable performance, the upper stories of an 11-story structure are used as mass damper, i.e. in the first stage the top story, and in the next stage the upper two stories are used as mass damper. The structure analyses are performed for uncontrolled, passive control and semi-active control cases and in each case, maximum displacement, RMS displacement of the stories and RMS base shear are compared. Moreover, applied damping coefficient and damping force are investigated in each case. The results show that the proposed semi-active tuned mass damper decreases the structural displacements where more desirable results can be obtained with smaller structural damping. By adopting top story as mass damper, the reduction of peak displacements is more than 35% and by designating the two last stories as mass damper, this reduction will exceed 55%.

Keywords: Semi-active control; tuned mass damper; multi–story building; seismic response; fuzzy controller.

1. INTRODUCTION

Structures can have desirable efficiency against natural hazards such as wind and earthquake if the maximum displacements remain as small as possible. In order to decrease the structural undesirable seismic vibration, tuned mass dampers have been studied. Tuned mass dampers may be used in various ways: Passive Tuned Mass Damper (TMD), Active Tuned Mass Damper (AMD), Semi-Active Tuned Mass Damper (SAMD), and Hybrid Tuned Mass

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Damper (HMD) are the most usual among them. In TMDs, a mass with constant stiffness and constant damping is attached over the structure and to some extent can decrease its undesirable vibration. AMDs have the same specification as TMD, except that they also benefit from an external force. SAMDs are like TMDs with the difference that in these systems, the damping and/or stiffness of damper can change at each moment. The combination of TMDs and AMDs results in hybrid mass dampers, which usually offer better performance against external excitations.

In SAMDs, the proper time depending damping can be determined using fuzzy control. Fuzzy control can connect input variables, to output ones and due to using linguistic variables rather than of numeric variables not only the computational efforts are reduced but the uncertainty of parameters can also be considered and investigated.

Hrovat et al. [1] studied semi-active tuned mass damper to decrease the vibrations caused by wind. They showed that the performance of SAMD is similar to TMD. Considerable effort has been devoted to develop semi-active control methods for reducing structural response [2-5].

By considering high and uniform damping coefficients in the compound modes of vibration, Sadek et al. [6] provided proper relation for determining TMD parameters. They concluded that for a structure with small damping ratio subjected to different excitation, TMD displacement may be large.

Pinkaew and Fujino [7] studied SAMD with variable damping to analyze a single degree of freedom structure with coupled AMD by applying numerical technique and optimal control theory. The transient and steady state responses of system subjected to harmonic loading have been verified.

As an active control of earthquake excited structures, Park et al. [8] used a fuzzy controller in higher level and several LQR sub controllers in lower levels. They concluded that fuzzy controller results in better performance of sub-controllers.

By studying an experimental model of a 5-story building, Samali and Al-dawod [9] assessed the performance of AMD with fuzzy controller and concluded that fuzzy controller has higher ability than LQR controller to decrease undesirable responses of structures.

Pourzeynali et al. [10] used AMD from fuzzy-genetic control for performance improvement and optimized mass damper and fuzzy controller parameters with genetic algorithm and obtained desirable results.

By using two actuators installed in the first and last stories of a 15-story building, Guclu and Yazici [11] decreased the displacement and acceleration of building floors subjected to specified earthquakes.

As semi-active control of a wind excited benchmark 76-story reinforced concrete office tower, Zahrai and Shafieezadeh used a collection of dampers at the first story in which the damping was created through the fuzzy logic controller. Higher levels of performance were achieved in mitigating structural responses especially the average RMS displacement response through the application of the fuzzy controller [12].

Chey et al. [13, 14] studied seismic application of SAMD on single degree of freedom structures. They offered a model in which the top stories of structure were used as mass damper. They demonstrated the effectiveness of the semi-active system in reduction of the building response, but they did not show any comparison of the results to those of an alternative fuzzy controller.

In this research, a fuzzy controller is suggested for semi-active tuned mass damper, in which the upper stories of an 11-story building are used as mass damper and their influence on the vibration characteristics of the system are examined.

2. FUZZY CONTROLLER

A fuzzy controller is composed of four sections including fuzzifier, knowledge base, inference system and defuzzifier. In the fuzzifier section the inputs are converted to fuzzy set by using the membership functions. In this study, displacement and velocity of the story with mass damper are as inputs of fuzzy controller and damping of mass damper are assumed as outputs of fuzzy controller. These membership functions have been shown in Figures 1 and 2.

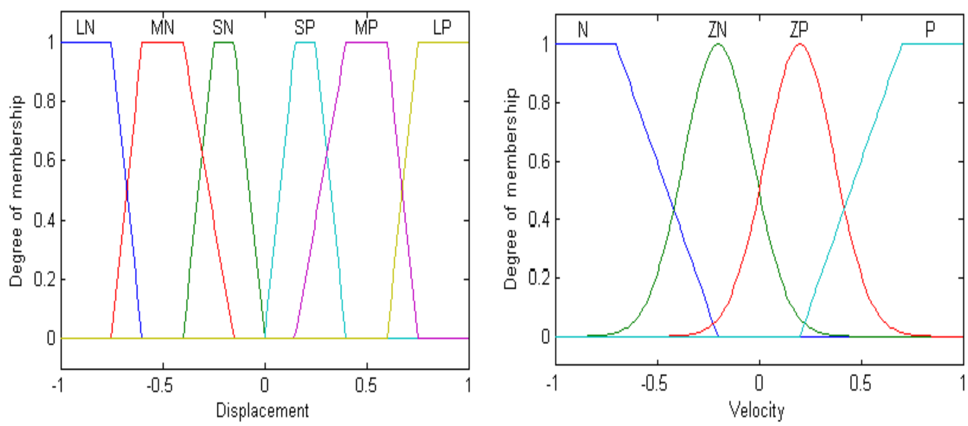

Figure 1. Membership functions of displacement and velocity

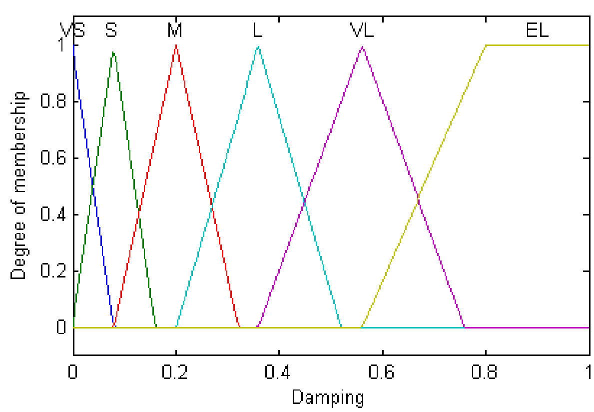

Figure 2. Membership function of damping

The abbreviations of these functions have been defined in Table 1.

Table 1: Description of fuzzy variables

Input displacements	LP	MP	SP	SN	MN	LN
Definition	Large positive	Medium positive	Small positive	Small negative	Medium negative	Large negative
Input velocities	P	ZP	ZN	N	-	-
Definition	Positive	Small positive	Small negative	Negative	-	-
Output dampings	VS	S	M	L	VL	EL
Definition	Very small	Small	Medium	Large	Very large	Extremely large

"Knowledge base" has been constructed of a set of IF-THEN rules. Proposed fuzzy controller for the building considered in this paper, has 24 "IF-THEN" rules. These rules have been showed in Table 2.

Table 2: Proposed fuzzy rules

Velocity \ **Displacement**	**LN**	**MN**	**SN**	**SP**	**MP**	**LP**
N	EL	VL	L	VS	S	M
ZN	VL	L	M	VS	S	M
ZP	M	S	VS	M	L	VL
P	M	S	VS	L	VL	EL

As an example in Table 2, using inputs as displacement "LN" in the second column and velocity "N" in the second row the fuzzy rules give the damping "EL" as output, i.e.

"IF velocity is N and displacement is LN, THEN damping is EL."

The base of these rules formation is in such a way that if displacement and velocity have the same sign, then the velocity of structure is increasing and therefore high damping force is needed. On the contrary, if displacement and velocity do not have the same sign it may be concluded that the structure is returning to equilibrium state and a very small damping force is required. On the other hand, if the input values are low, it can be concluded that a small damping force is required and vice versa.

Using fuzzy inputs and regarding fuzzy rules, "Inference system" determines the fuzzy output. "Mamdani minimum inference system" is one of most important fuzzy inference systems and needs simple computation, therefore, in this research it has been used as interference system.

The final stage of fuzzy controller is defuzzier that changes the output of "Fuzzy Inference System" to a digit. Here in this paper, the "Center of Gravity Defuzzier" that by receiving fuzzy sets considers the center of surface under the curves of membership functions and offers it as output is used as defuzzier.

3. TWO DEGREES OF FREEDOM MODEL

In order to compare the suggested controller, a two degrees of freedom system is considered. This system is shown in Figure 3.

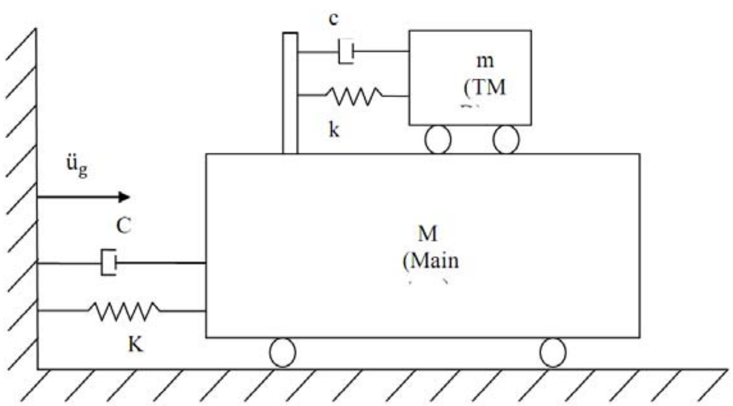

Figure 3. Schematics of two degrees of freedom system

The main mass has natural period and damping ratio of 0.25s and 0.02, respectively, and the ratio of mass damper and its fundamental frequency to mass and fundamental frequency of main system are 0.1 and 0.9036, respectively. Damping ratio of TMD is 0.3196. This system has been studied by Sadek et al. [6] in two different cases of uncontrolled and passive control system.

When the structure is subjected to ground acceleration, its equation of motion is as follows:

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

where [M], [C], and [K] are matrices of mass, damping and stiffness, respectively. {u} and {r} are displacement vector of structure and impact coefficient vector, respectively. Also, üg is the earthquake acceleration. The equation of motions of this structure in state space is as following:

$$\begin{Bmatrix}\{\dot{u}\}\\ \{\ddot{u}\}\end{Bmatrix}=\begin{bmatrix}O_{n\times n} & I_{n\times n}\\ -[M]^{-1}[K] & -[M]^{-1}[C]\end{bmatrix}\begin{Bmatrix}u\\ \dot{u}\end{Bmatrix}+\begin{bmatrix}O_{n\times n}\\ I_{n\times n}\end{bmatrix}\{r\}_{n\times 1}\,\ddot{u}_g(t) \tag{2}$$

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

The above-mentioned system is now subjected to the Borrego earthquake acceleration and analyzed. The time history record of this earthquake acceleration has been shown in Figure 4 and the results for three cases of uncontrolled system, with TMD system and with SAMD system are given in Table 3 and compared with those in Ref. [6] showing a good agreement.

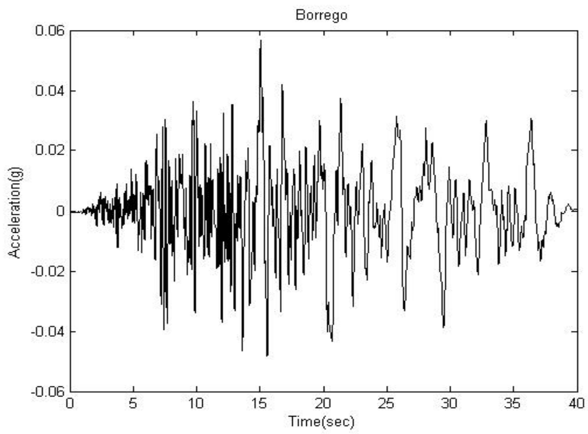

Figure 4. Time history of the Borrego earthquake acceleration

As observed in Table 3, TMD results in 44% decrease in displacement and SAMD shows better performance with 49% decrease in displacement compared to the uncontrolled system.

Table 3: Maximum displacement of two degrees of freedom structure

		without control	TMD	SAMD
Max displacement of main system	Reference [6]	4.3 mm	2.4 mm	-
	Proposed	4.3 mm	2.4 mm	2.2 mm

4. STRUCTURAL MODEL

A multi-degree of freedom building structure with eleven stories for three cases, i.e. without damper, with TMD and with SAMD, is now analyzed. This building has been subjected to the Tabas and Chichi earthquakes with peak acceleration equal to 0.688g and 0.902g, respectively. The time history records of these two earthquakes are shown in Figure 5.

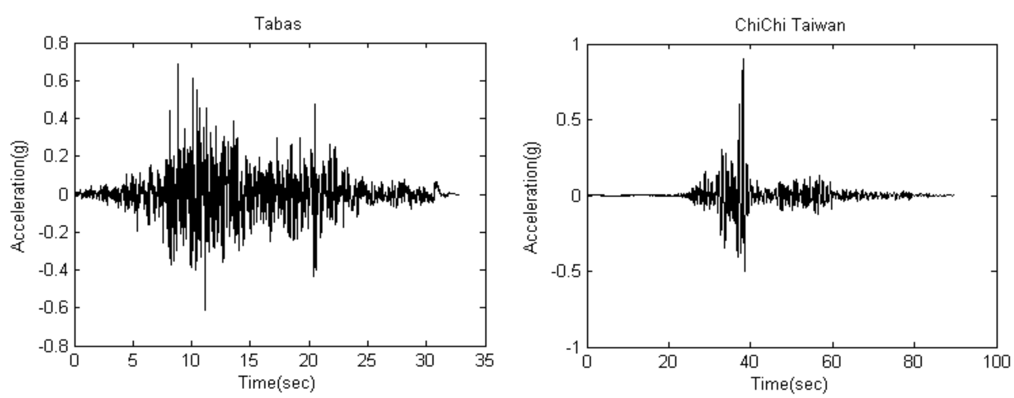

Figure 5. Time history records of the Tabas earthquake, 1978; and Chichi earthquake, 1999.

The investigated structure is a steel flexible building with eleven degrees of freedom. The two-dimensional view of this structure is shown in Figure 6.

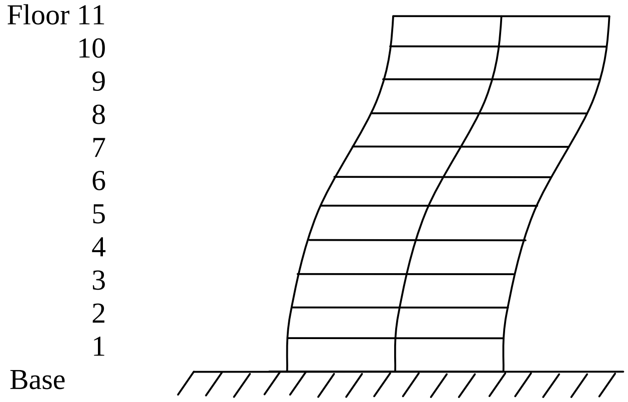

Figure 6. Two-dimension view of the structure

The stories' mass and stiffness of this structure have been shown in Table 4.

Table 4: The properties of an 11-story building

Story number	1	2	3	4	5	6	7	8	9	10	11
Mass (kN.s2/m)	215	201	201	200	201	201	201	203	203	203	176
Stiffness (MN/m)	468	476	468	450	450	450	450	437	437	437	312

It is worth noting that damping of this structure is obtained according to Rayleigh damping considered as follows:

$$[C] = 0.0981347[M] + 0.0007714[K] \tag{3}$$

5. MASS DAMPER AND THE RESPONSE OF STRUCTURAL SYSTEM

For the first phase, the top story of the building is used as mass damper. The practical detail of this damper is provided in Figure 7.

In passive system, the stiffness and damping coefficient of eleventh story, which is mass damper, is considered 2.0185×106 N/m and 7.1401×106 N.sec/m, respectively. In semi-active system, the stiffness of damper is the same 2.0185×106 N/m but its damping coefficient is between zero and 7.1401×106 N.sec/m and is determined by fuzzy controller.

The displacement diagram of the structure's 10th and 11th stories under the Tabas and Chichi earthquakes in uncontrolled system, with TMD system and with SAMD system are shown in Figure 8, where the designed controller not only has resulted in the reduction of its downstairs displacement but also has decreased the maximum displacements of top story that is a mass damper.

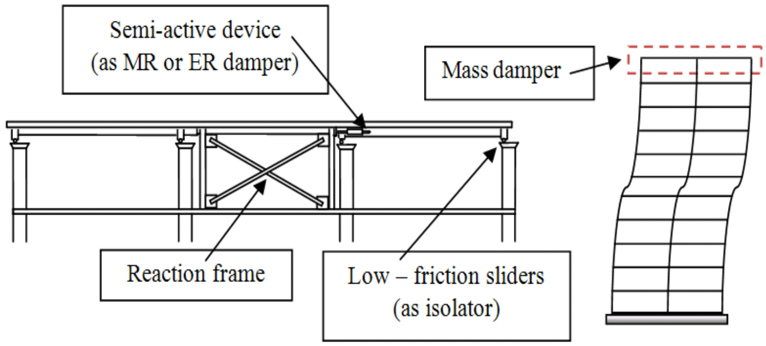

Figure 7. Structure with top story designated as mass damper

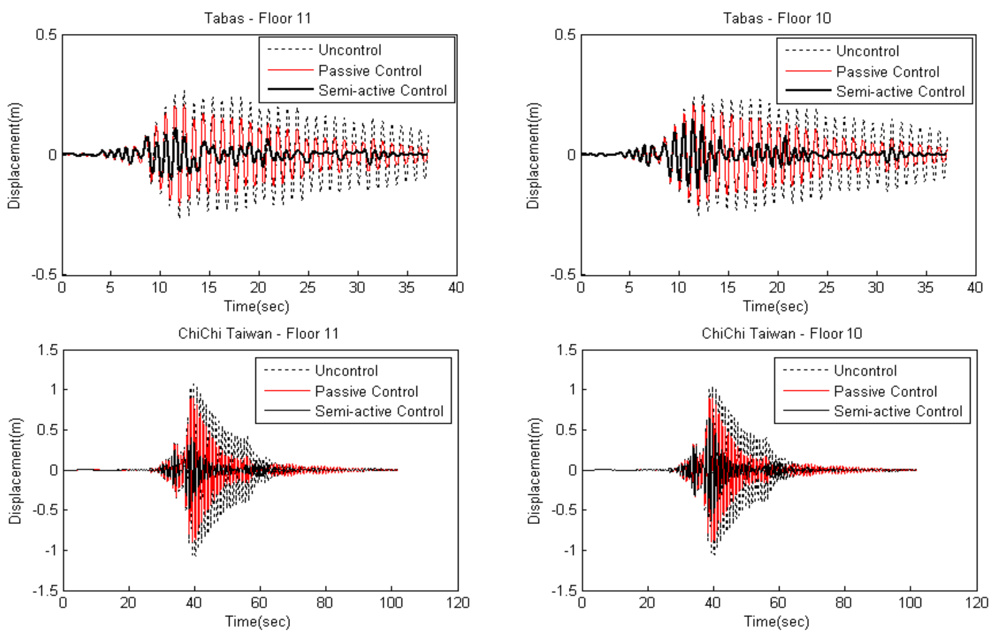

Figure 8. Lateral displacements at the Tenth and eleventh stories of the structure

According to time history diagram of the Tabas earthquake (Figure 5), even though after the thirty third second, no seismic force affects the structure but the structure displacements is very high in uncontrolled system, but this displacement in passive control is less and in semi-active control decreases so much. This decrease prevents from more fatigue failure in the structural members and creates more certainty and calmness in the building habitants.

The diagram of damping force in the damper location for uncontrolled system, with TMD system and with SAMD system and the required damping by fuzzy controller are presented in Figure 9, where damping and effective damping force needed in each moment is shown different such that uniform high damping does not necessarily result in better performance of the structure.

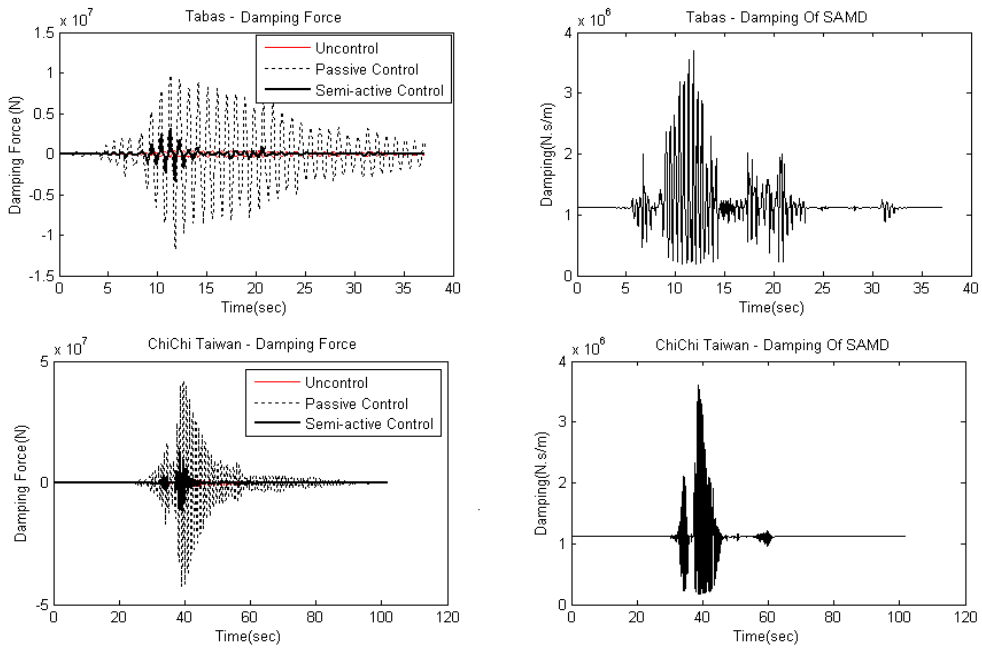

Figure 9. Produced damping coefficient and damping force

Tables 5 and 6 respectively, compare the RMS and peak displacement and RMS shear force of the uncontrolled structure, the structure with passive damper, and the structure controlled with fuzzy logic controller. These Tables reveal that the structural responses in the passive control have decreased relative to uncontrolled system. Moreover semi-active control system has a better performance than both others.

Table 5: The responses of structure under the Tabas earthquake with designating top story as mass damper

Earthquake	Response of floor	Type of system	Floor number					
			1	3	5	7	9	11
Tabas	Max displacement (cm)	Without control	3.54	9.69	15.21	20.07	23.87	26.54
		With TMD	3.18	8.86	13.73	17.74	20.46	20.93
		With SAMD	2.1	5.48	8.54	11.39	13.90	11.02
	RMS displacement (cm)	Without control	0.023	0.192	0.494	0.836	1.125	1.279
		With TMD	0.010	0.086	0.221	0.373	0.501	0.541
		With SAMD	0.002	0.019	0.046	0.075	0.099	0.083
	RMS shear (×1013N)	Without control	5.493	4.770	3.533	2.122	0.876	0.098
		With TMD	5.084	4.387	3.194	1.841	0.678	0.039
		With SAMD	4.554	3.887	2.761	1.511	0.483	0.009

Table 6. The responses of structure under the Chichi Taiwan earthquake with designating top story as mass damper

Earthquake	Response of floor	Type of system	Floor number					
			1	3	5	7	9	11
ChiChi Taiwan	Max displacement (cm)	Without control	14.3	41.6	67.0	87.3	101.2	107.7
		With TMD	12.0	35.1	56.7	74.2	86.2	89.4
		With SAMD	8.8	24.8	39.5	53.3	62.9	48.7
	RMS displacement (cm)	Without control	0.087	0.737	1.913	3.247	4.369	4.960
		With TMD	0.043	0.368	0.954	1.618	2.175	2.342
		With SAMD	0.015	0.125	0.311	0.514	0.676	0.395
	RMS shear (×1013N)	Without control	19.34	17.22	12.98	7.72	3.00	0.29
		With TMD	17.74	15.72	11.68	6.73	2.40	0.14
		With SAMD	15.58	13.69	9.94	5.42	1.65	0.03

Now in the 2nd phase, the last two stories of building are used as mass damper. The practical detail of this system has been shown in Figure 10.

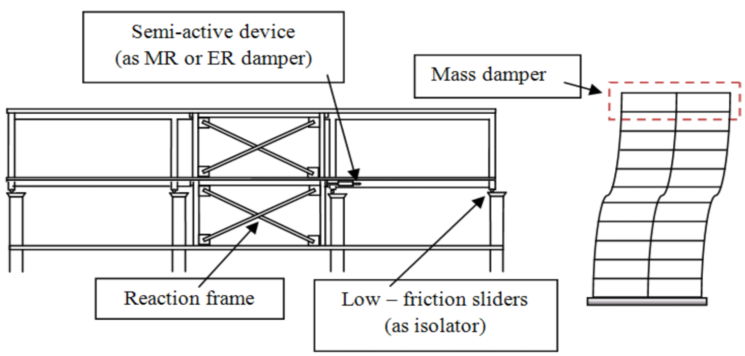

Figure 10. Structure with designation of last two stories as mass damper

In the uncontrolled system, the stiffness and damping coefficient of 10th story are considered 1.8135×106 N/m and 8.3714×106 N.sec/m, respectively. Also, in the semi-active control, the stiffness of damper is 1.8135×106 N/m and its damping coefficient varies between zero and 8.3714×106N.sec/m.

The system is now analyzed subjected to the Tabas and Chichi earthquakes and the stories displacement diagram of eleventh and ninth of the structure in the uncontrolled system, with TMD system and with SAMD system are shown in Figure 11.

By observing Figure 11, it is recognized that the increase of mass damper produces an efficient decrease of displacements relative to the case in which only the eleventh story has been adopted as mass damper. In the Tabas earthquake, by considering the two last stories as SAMD, the displacements of eleventh and ninth stories decrease 63.3 and 65.1% respectively, while by considering the top story as SAMD the decrease of displacements become 58.5 and 41.8%. Also, such displacement reductions in the Chichi Taiwan earthquake by designing the two last stories as SAMD are 68.9 and 58.3%, compared to the case of adopting only the top story as SAMD, with amounts of 54.8 and 37.9%, respectively.

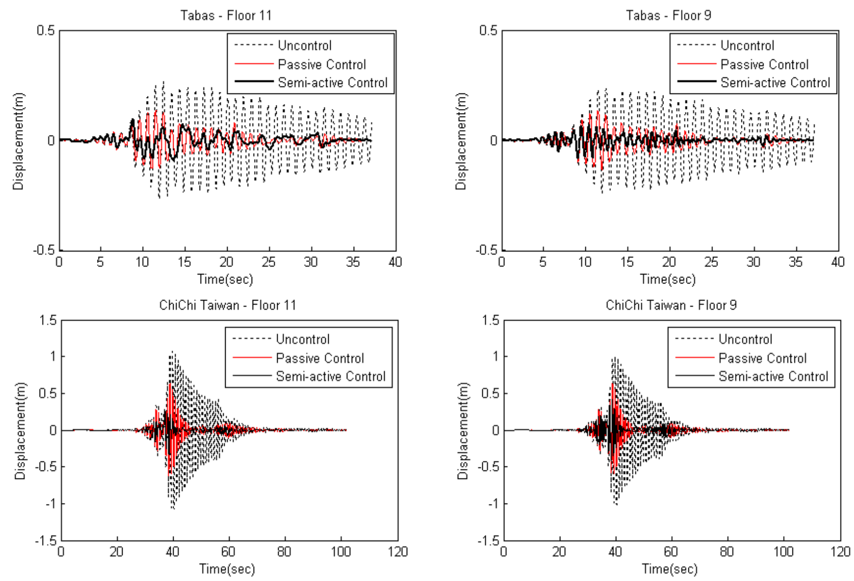

Figure 11. Lateral displacements at the ninth and eleventh stories of the structure

The diagram of damping force in the damper location for uncontrolled system, with TMD system and with SAMD system and determined damping diagram by fuzzy controller are presented in Figure 12.

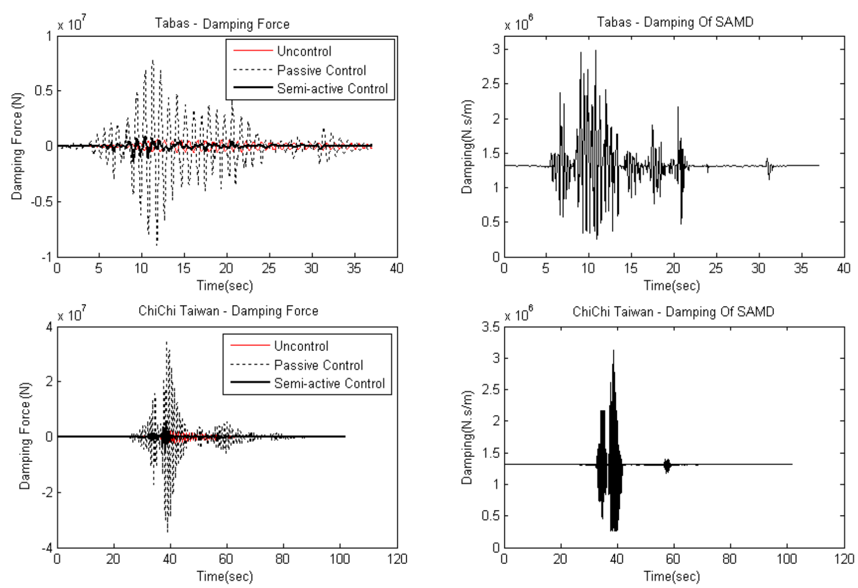

Figure 12. Produced damping coefficient and damping force

Comparing Figures 12 and 9, it is observed that maximum damping coefficient and needed damping force in the designing state of two top stories as mass damper relative to designating only the top story as mass damper, have decreased. Therefore, using semi-active control can reduce maximum damping needed in the structure.

Tables 7 and 8 perform a comparison between maximum displacement and RMS displacement and also RMS shear of structure stories in uncontrolled system with passive control and with fuzzy semi-active control.

Table 7: The responses of structure under the Tabas earthquake with designating two top stories as mass damper

Floor Number						Type of system	Response of floor	Earthquake
11	9	7	5	3	1			
26.54	23.87	20.07	15.21	9.69	3.54	Without control	Max displacement (cm)	Tabas
13.57	13.54	12.14	9.66	5.97	2.22	With TMD		
9.74	8.33	7.06	5.79	3.84	1.37	With SAMD		
1.279	1.125	0.836	0.494	0.192	0.023	Without control	RMS displacement (cm)	
0.135	0.130	0.097	0.058	0.023	0.003	With TMD		
0.072	0.037	0.030	0.019	0.008	0.001	With SAMD		
0.098	0.876	2.122	3.533	4.770	5.493	Without control	RMS shear (×1013N)	
0.014	0.520	1.579	2.855	3.996	4.672	With TMD		
0.005	0.442	1.444	2.677	3.790	4.452	With SAMD		

Table 8: The responses of structure under the Chichi Taiwan earthquake with designating two top stories as mass damper

Floor number						Type of system	Response of floor	Earthquake
11	9	7	5	3	1			
107.7	101.2	87.3	67.0	41.6	14.3	Without control	Max displacement (cm)	ChiChi Taiwan
63.6	63.4	55.0	42.4	26.4	9.1	With TMD		
33.5	42.2	36.2	27.2	17.8	6.3	With SAMD		
4.960	4.369	3.247	1.913	0.737	0.087	Without control	RMS displacement (cm)	
0.714	0.694	0.520	0.308	0.119	0.014	With TMD		
0.128	0.250	0.205	0.131	0.055	0.007	With SAMD		
0.29	3.00	7.72	12.98	17.22	19.34	Without control	RMS shear (×1013N)	
0.05	1.83	5.74	10.37	14.20	16.12	With TMD		
0.01	1.50	5.15	9.57	13.26	15.12	With SAMD		

It is observed that in the passive control, the RMS displacement is less than that of the uncontrolled system. Of course, if SAMD is used, RMS displacements relative to passive control decreases even more. Moreover it is observed that in these tables RMS base shear of each story is reduced, and therefore in most times during an earthquake, the structure with

SAMD endures less force relative to structure with TMD and without damper.

It is necessary to note that although by the increase in number of stories used for damper, the mass of damper increases, reducing the response of structure, but due to reduction in stiffness in the connection joint of damper to lower stories, structure may become unstable, hence it is generally recommended to use less number of stories as mass damper for practical purposes.

6. CONCLUSION

The implemented research shows that the performance of structure with SAMD is better than that with just TMD, resulting in a decrease in the floor displacements and story shear of the structure. By adopting top story as mass damper and using fuzzy controller, the reduction of peak displacements is more than 35% and by designating the two last stories as mass damper, this reduction will exceed 55%. If the top stories of the structure are used as mass damper, by the increase of story number for semi-active tuned mass damper, the consumed damping and produced damping force will be small enough in which less damping is required to obtain desirable results. It is worth noting that for certain mass damper, applied damping coefficient and damping force in the semi-active damper are less than those in case of passive damper alone.

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