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Optimum tuned mass damper design for preventing brittle fracture of RC buildings

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Abstract. Brittle fracture of structures excited by earthquakes can be prevented by adding a tuned mass damper (TMD). This TMD must be optimum and suitable to the physical conditions of the structure. Compressive strength of concrete is an important factor for brittle fracture. The application of a TMD to structures with low compressive strength of concrete may not be possible if the weight of the TMD is too much. A heavy TMD is dangerous for these structures because of insufficient axial force capacity of structure. For the preventing brittle fracture, the damping ratio of the TMD must be sufficient to reduce maximum shear forces below the values proposed in design regulations. Using the formulas for frequency and damping ratio related to a preselected mass, this objective can be only achieved by increasing the mass of the TMD. By using a metaheuristic method, the optimum parameters can be searched in a specific limit. In this study, Harmony Search (HS) is employed to find optimum TMD parameters for preventing brittle fracture by reducing shear force in additional to other time and frequency responses. The proposed method is feasible for the retrofit of weak structures with insufficient compressive strength of concrete.

Keywords: brittle fracture; metaheuristic methods; harmony search algorithm; tuned mass damper; optimization; structural control; earthquake

1. Introduction

Control of structures has various types such as active, passive, semi-active and hybrid systems. Passive ones are more practical in use and economical. Thus, especially base isolation systems and tuned mass dampers (TMD) are important areas for the researchers studying on optimization. Optimum design of the mechanical components of passive control systems are effective on reducing structural vibrations resulting from wind and earthquake excitations. Especially, TMDs can be effective on reducing shear forces resulting from earthquakes. Brittle fracture of reinforced concrete (RC) frame buildings with low compressive strength of concrete may be prevented with optimum TMDs if the mass of the TMD is not a trouble for the axial force capacity of the building.

The basic form of TMD is a vibration absorber device invented by Frahm (1911). This device only has a mass and stiffness elements so it is only effective on reducing the vibrations when the natural frequency of the device is close to the excitation frequency. Ormondroyd and Den Hartog

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(1928) added viscous dampers to that device for a more effective vibration damping under random vibrations.

Tuning of TMDs have been proposed in several studies. Den Hartog (1947) obtained closed form expressions for the design of TMDs. In these expressions acquired for undamped main systems with a single degree of freedom (SDOF), the optimum frequency (f_{opt}) and damping ratio ($\xi_{d_{opt}}$) of TMD are found according to preselected mass ratios (μ). After the development of the expressions of Den Hartog, damping in the main system was taken into account in several studies (Bishop and Welboum 1952, Snowdon 1959, Falcon *et al.* 1967, Ioi and Ikeda 1978). Warburton (1982) developed alternative frequency and damping ratio expressions which are also functions of a mass ratio for undamped main SDOF systems under harmonic and white noise excitations.

Close form expressions cannot be derived for the optimum design of TMD if the main mass has an inherent damping. All structures has an amount of damping so the optimum design of a TMD can be done by using numerical trials with the aim of reducing desired structural response (Rana and Soong 1998). Rana (1995) prepared several tables for optimum TMD design parameters for the structures with inherent damping. Sadek *et al.* (1997) searched numerically f_{opt} and $\xi_{d_{opt}}$ values for different mass ratios and main system damping ratio. The expressions of f_{opt} and $\xi_{d_{opt}}$ were found by using curve fitting. Chang (1999) found optimum TMD formulas for SDOF systems under wind and earthquake loadings. Bakre and Jangid (2007) developed explicit formulae for damped SDOF main system by using a numerical searching technique under base acceleration modeled as Gaussian white-noise random process.

Hoang *et al.* (2008) obtained simple formulas of the optimal frequency and damping ratio according to mass ratio for SDOF structures with TMD. It is found that the optimum TMD has lower frequency and higher damping ratio when the mass ratio increases.

In the studies mentioned above, the main system is SDOF. If the natural frequencies of building are well separated, the physical model of the building may be thought as an equivalent SDOF model (Warburton and Ayorinde 1980). For other situations and better optimization, participation of the other modes must be taken into account.

Sadek *et al.* (1997) also investigated MDOF systems with three different structural models. The optimum parameters for MDOF systems were described according to similarities of the optimum parameters for SDOF systems. An extended random decrement method was developed for the optimization of TMDs by taking a MDOF main system (Lin *et al.* 2001). The displacement and acceleration response spectra for structures with and without passive TMD under various earthquake excitations were investigated. Lee *et al.* (2006) proposed an optimum design theory for TMDs installed at different stories of MDOF structures.

Amini and Doroudi (2010) investigated several cases of building complex formed of one main building and one podium structure connected through Magneto- Rheological (MR) dampers and TMD. Pozos-Estrada *et al.* (2011) carried out parametric analyses of torsionally sensitive structures without or with TMDs to determine their reliabilities, if the structures are designed to just meet an adopted serviceability limit state criterion. Tributsch and Adam (2012) discussed and evaluated the optimal tuning of TMD parameters. The response reduction of TMDs depends on the structural period, inherent damping of the structure and mass ratio.

Metaheuristic algorithms, which simulate natural phenomena, have been used for the optimum design of TMDs. The evolutionary algorithm such as genetic algorithm (Hadi and Arfiadi 1998, Singh *et al.* 2002, Desu *et al.* 2006, Marano *et al.* 2010) and bionic algorithm (Steinbuch 2011) were used for optimum TMD design. Particle swarm optimization (PSO) was also employed for the optimization of TMD (Leung *et al.* 2008) and explicit expressions were proposed (Leung and Zhang 2009).

Marano *et al.* (2010) also optimized mass ratio in addition to frequency and damping ratio of TMD with reference to the ratios of the main system and the input frequencies. A SDOF main structure is used to develop two different optimization criteria in order to minimize the main system displacement or the inertial acceleration by employing genetic algorithm strategy.

The harmony search (HS) algorithm, which was developed by Geem *et al.* (2001), was modified to the optimization of TMD for MDOF structures (Bekdaş and Nigdeli 2011). A program was developed for the optimization of TMD parameters without using a preselected TMD parameter. So, the optimized parameters are mass, stiffness and damping coefficient of TMD. Criteria of the optimization procedure were the maximum first storey acceleration transfer function (TF) and the displacement of the first storey (x_1) under a sine wave loading with 1 g amplitude.

Bozer and Altay (2012) proposed a hybrid tracking controller with attached TMD in order to track the response of an oscillator and set the operating frequency of TMD.

In this study, a new TMD optimization strategy using HS was developed. The strategy of the method is to reduce shear forces at structures under earthquake excitations. Several earthquake data can be used at the optimization process. The method was tested with three storey RC frame structures with different compressive strength of concrete. Example structures are under the risk of brittle fracture according to the regulation of American Concrete Institute (ACI) (2005) and Turkish Earthquake Code (TEC2007) (2007). Also, the buildings have limited axial force capacity for carrying an additional TMD. By using an iterative searching method like HS, the solution domain can be limited according to physical condition of structures. For the explicit formulas of TMD design, it is not possible to use different ranges for all parameters of TMDs. These formulas depending on mass ratio of TMD are for optimum frequency and damping ratio of TMD. The formulas are not capable to find a specific optimum result when designing a TMD for a structure with restrictions.

2. TMD tuning formulas

In this section, the formulas of TMD frequency and damping ratio, which were compared with proposed method, are given. The methods contain basic formulas in order to obtain an optimum frequency and damping ratio according to mass ratio (μ).

The expressions of optimum frequency ratio (f_{opt}) and damping ratio of TMD ($\xi_{d_{opt}}$) which minimize the steady-state response of the undamped SDOF main mass subject to a harmonic main mass excitation can be seen in Eqs. (1) and (2), respectively (Den Hartog 1947).

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

$$\xi_{d_{opt}} = \sqrt{\frac{3\mu}{8(1+\mu)}} \tag{2}$$

For an undamped SDOF main system, the optimum parameters of TMD under random acceleration excitation with white noise spectral density are given in Eqs. (3) and (4) (Warburton 1982).

$$f_{opt} = \frac{\sqrt{1-(\mu/2)}}{1+\mu} \tag{3}$$

$$\xi_{d_{opt}} = \sqrt{\frac{\mu(1-\mu/4)}{4(1+\mu)(1-\mu/2)}} \tag{4}$$

The expressions of TMD parameters for damped SDOF structures are given in Eqs. (5) and (6) (Sadek *et al.* 1997). These expressions are also related to damping ratio of main system (ξ).

$$f_{opt} = \frac{1}{1+\mu}\left[1-\xi\sqrt{\frac{\mu}{1+\mu}}\right] \tag{5}$$

$$\xi_{d_{opt}} = \frac{\xi}{1+\mu} + \sqrt{\frac{\mu}{1+\mu}} \tag{6}$$

If the amplitude of first mode vibration for a unit modal participation factor at the location of the TMD is represented with Φ, the frequency ratio for the MDOF system is nearly equal to the frequency ratio for a SDOF system with a mass ratio of $\mu\Phi$. For a MDOF system, the TMD damping ratio is also approximately equal to the TMD damping ratio computed for a SDOF system multiplied by Φ. Thus, Eqs. (7) and (8) represents the optimum TMD parameters for a damped MDOF structure (Sadek *et al.* 1997).

$$f_{opt} = \frac{1}{1+\mu\Phi}\left[1-\xi\sqrt{\frac{\mu\Phi}{1+\mu\Phi}}\right] \tag{7}$$

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

For a damped SDOF structure under white noise base excitation, the optimum frequency ratio and damping ratio of TMD founded by using PSO algorithm are Eqs. (9) and (10), respectively (Leung and Zhang 2009).

$$f_{opt} = \frac{\sqrt{1-(\mu/2)}}{1+\mu} + (-4.9453 + 20.2319\sqrt{\mu} - 37.9419\mu)\sqrt{\mu}\xi + (-4.8287 + 25.0000\sqrt{\mu})\sqrt{\mu}\xi^2 \tag{9}$$

$$\xi_{d_{opt}} = \sqrt{\frac{\mu(1-\mu/4)}{4(1+\mu)(1-\mu/2)}} - 5.3024\xi^2\mu \tag{10}$$

The expressions given in this section are only related to mass ratio. It is not possible to see the effect of the period of the main system. Also, an optimum mass ratio cannot be found and these expressions cannot be suitable for the structures with limitations. This situation was explained on a numerical example in the fourth section.

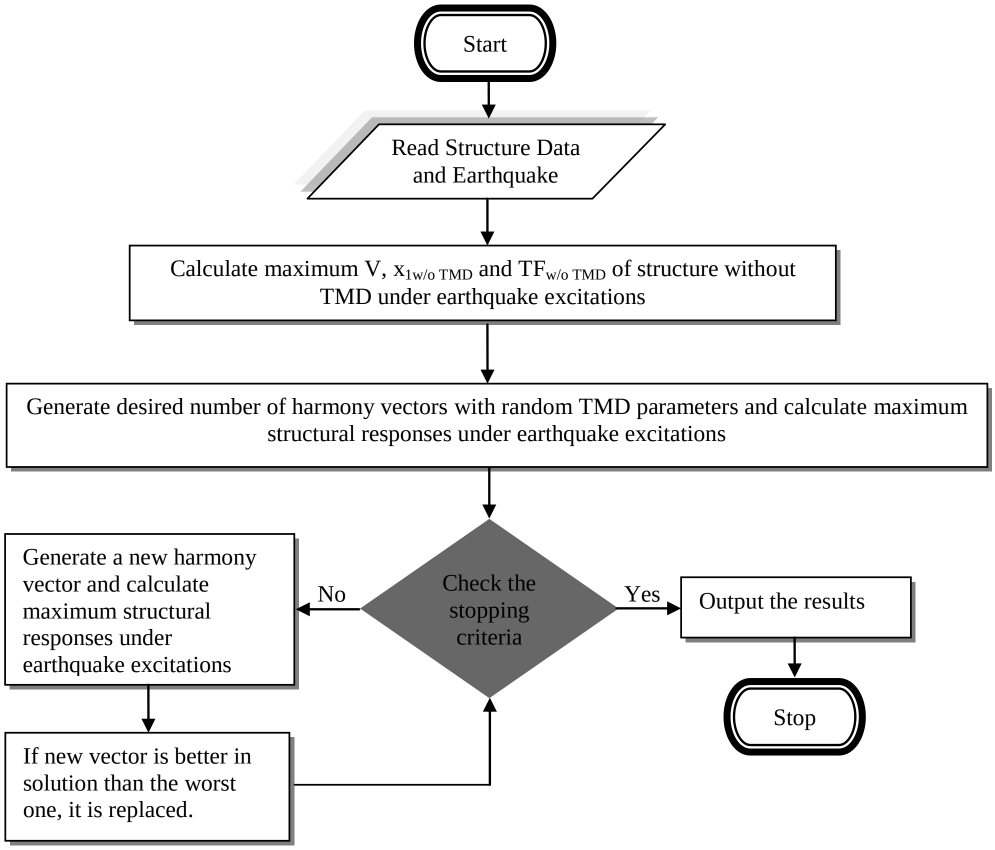

Fig. 1 Flowchart of the program

3. Methodology

In this study, a program employing HS algorithm was developed. The HS algorithm is inspired by the performance of a musician who searches a better state of harmony in order to gain the full support of the listeners. The HS method has five main steps (Geem *et al.* 2001).

i. Initialization of HS algorithm parameters such as a possible range, harmony memory size (HMS), harmony memory considering rate (HMCR), pitch adjusting rate (PAR) and termination criterion.

ii. Generation of initial harmony memory matrix with random numbers.

iii. Generation of a new harmony vector.

iv. Replacing of the new harmony vector with the worst existing harmony vector in the harmony matrix, if the solution of the new vector is better than the worst one.

v. Checking of the termination criterion or criteria. If not, the process must be continue from step iii until the termination criterion or criteria are satisfied.

In the study of Bekdaş and Nigdeli (2011), the optimum mass, stiffness and damping coefficient of TMD were found for damped MDOF structures by using HS algorithm. A sinus loading was used in the optimization process for the dynamic analysis and the main aim of the optimization was to reduce the maximum first story displacement.

The strategies used in this study are different from the previous one using HS for optimum TMD design. In the optimization process, six different earthquake records were used. Some of these earthquakes must be suitable to the design spectrum in codes and must represent the characteristics of the site. In addition to that, different types of earthquake records can be used to avoid seismic activity of blind-thrust and undetected faults.

The program has three aims and the main one is to reduce maximum shear force value resulting from the earthquake excitations. The flowchart of the proposed method can be seen in Fig. 1.

The program analyses time domain structural responses and frequency domain transfer functions of a MDOF structure with and without TMD. The maximum values of shear force (V), the first storey displacement ($x_{1w/o\,TMD}$) and acceleration transfer function of the first storey ($TF_{w/o\,TMD}$) are saved for the most critical earthquake. Then, harmony vectors as many as HMS are generalized with random TMD parameters including mass, period and damping ratio of TMD. In that way, it is possible to optimize three variable of TMD including the mass of it. The program uses random values in a defined range for all three variables. A defined range can be affected by physical limitations of structure (i.e., axial force capacity of the structural members) and economic conditions (i.e., cost of the high damping).

After the generation of the initial harmony vectors as many as HMS, new harmony vectors must be generated iteratively until the stopping criteria is satisfied. At all iterations, newly generated new harmony vector is replaced with the worst one if the generated one is better. Elements of the newly generated vector can be chosen either from existing vectors with a small different in value or from the whole solution range. Especially, while generating a new vector from the existing ones, the best vector has more chance. It is possible to overcome local optima problem with these techniques. The possibility to generate a new vector from an existing vector is HMCR. The same possibility is used when selecting the best one as the source of generation. The radius of the range is PAR of the general range for the generation of a new vector from the existing ones.

Three stopping criteria have been used in this methodology. The most important one is to reduce the maximum shear force value resulting from the most critical earthquake. This value must be smaller than the entered value by the user. Also, the program chooses the worst vector according to maximum shear force value. The second criterion is about the ratio of maximum first storey displacements of structure with (x_{1wTMD}) and without ($x_{1w/oTMD}$) TMD (Eq. (11)). This value must be smaller than a desired value (DV) defined by user.

$$x_{1R} = \frac{x_{1wTMD}}{x_{1w/oTMD}} \tag{11}$$

The program can lock if the user assigns a DV which is not physically possible to achieve within the desired range. In order to prevent this situation, after all 100 attempts, the program increases this value automatically with a 0.02 different. These values can be changed by user. For the last criterion, the maximum value of the acceleration transfer function of the first story for the structure with TMD (TF_{wTMD}) must be smaller than the uncontrolled case in value.

When the all set of optimum results are suitable for the stopping criteria, the optimization process ends. The optimum results are the values corresponding to the lowest maximum shear force value. By reducing the maximum shear force value, it is possible to prevent brittle fracture of the structure.

4. Numerical example

A three story symmetrical reinforced concrete (RC) structure with three spans in both horizontal directions was analyzed for the application of a TMD. The length of the spans is 4 m and the height of the each story is 2.8 m. All of the RC columns and beams have 400x400 mm and 500x200 mm cross-sections, respectively and the thickness of the slabs is 100 mm. The dead load on the slabs including the self-weight is 7.5 kN/m^2 and the live load is 2.5 kN/m^2. In that case, the maximum axial force on interior columns at the first floor is 585.72 kN. The total mass of a story of the building is 163.8 t.

Five different characteristic strength of concrete (8, 10, 12, 14 and 16 MPa) was investigated in order to check the feasibility and the efficiency of the proposed method and the other methods using basic formulas. Low compressive strengths of the concrete were taken into consideration so the building is in danger of brittle fracture in all cases. Also, the axial force capacity of the columns is low. The main aim of the application is to prevent brittle fracture by reducing maximum shear forces without exceeding the axial force capacity of the columns. The maximum shear and axial force capacity of the structure have been described in several regulations.

In ACI318 (2005) , the maximum shear force capacity of a column ($V_{n,max}$) is given in Eqs. (12) and (13). Also, the maximum shear force capacity in Turkish Earthquake Code (TEC2007) (2007) can be seen in Eq. (14). In these equations, $f_c^{'}$, f_{cd} and A_c are the characteristic strength of concrete, the design strength of concrete and the cross sectional area of a column. The design strength of concrete can be obtained by dividing $f_c^{'}$ to a safety coefficient of 1.5 (TS500 2001).

$$V_{n,max} = 0.2 f_c^{'} A_c \tag{12}$$

$$V_{n,max} = 5.5 A_c \tag{13}$$

$$V_{n,max} = 0.22 f_{cd} A_c \tag{14}$$

The maximum axial force capacity of a column ($N_{n,max}$) described in TEC2007 is given in Eq. 15. By using this equation, it is possible to find the maximum allowed mass of TMD by subtracting the axial force resulting from dead and live loads from $N_{n,max}$.

$$N_{n,max} = 0.5 f_c^{'} A_c \tag{15}$$

In Table 1, the stiffness of each storey (k), period of the structure (T), mass ratio (μ), mass of TMD ($m_{d,max}$) and the maximum allowed values of shear and axial force are given for different characteristic strength of the concrete. The damping was assumed as 5% and Rayleigh damping was used at the analyses.

Table 1 Properties of the structural models

$f_c^{'}$ (MPa)	k (kN/m)	T(s)	ACI318	TEC 2007		μ_{max}	$m_{d,max}$ (t)
			$\Sigma V_{n,max}$ (kN)	$\Sigma V_{n,max}$ (kN)	$N_{n,max}$ (kN)		
8	198569	0.406	3072	2253	640	0.041	20.3
10	207862	0.396	3840	2816	800	0.163	80.3
12	216263	0.389	4608	3379	960	0.285	140.2
14	223994	0.382	5376	3942	1120	0.407	200.2
16	231175	0.376	6144	4506	1280	0.529	260.1

The HS optimization process was conducted by using six earthquake records including a record of recent 23 October 2011 Van (Turkey) earthquake (Table 2). Also, the other methods were compared under these earthquakes. The chosen earthquakes show different characteristics of near and far fault regions. The optimization earthquakes can be selected according to geophysical condition of the region. In this study, the present approach was demonstrated by using a general solution because a structure in a region with high seismic activity can be effected by near and far faults excitations in different period of time. The Van earthquake record was taken from METU EERC and the other ones was taken from PEER database.

Table 2 Earthquake records used in the HS optimization

Earthquake	Date	Station	Component	PGA (g)	PGV (cm/s)	PGD (cm)
Kobe	1995	0 KJMA	KJM000	0.821	81.3	17.68
Imperial Valley	1940	117 El Centro Array #9	I-ELC180	0.313	29.8	13.32
Erzincan	1992	95 Erzincan	ERZ-NS	0.515	83.9	27.35
Van	2011	6503 Muradiye	NS	0.182	33.8	9.19
Northridge	1994	24514 Sylmar	SYL360	0.843	129.6	32.68
Loma Prieta	1989	16 LGPC	LGP000	0.563	94.8	41.18

According to Turkish Earthquake Code (TEC 2007), at least three different earthquake records which are suitable to design spectrum, must be selected. The average spectral acceleration values of these records at zero period must be bigger than acceleration of gravity (g) multiplied with effective ground acceleration coefficient (A_o). Between $0.2T_1$ and T_1 according to first period of structure (T_1), average of the spectral acceleration values shall not be less than 90% of elastic spectral accelerations ($S_{ae}(T)$).

For the first-degree seismic zone with effective ground acceleration coefficient (A_o) of 0.4, residential building with 1.0 importance factor (I) and local site class of Z4 defined in TEC2007, the graph of $S_{ae}(T)$ is given together with the average spectral acceleration plot of 4 near fault earthquakes (Kobe, Erzincan , Northridge, Loma Prieta) for 5% damping in Fig. 2.

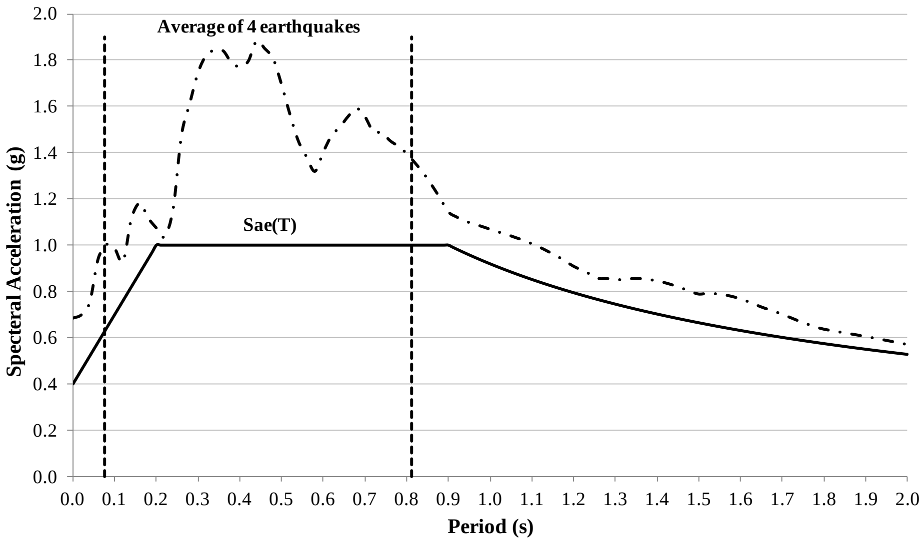

Fig. 2 Elastic spectral accelerations and average spectral acceleration of 4 earthquakes

The average spectral accelerations are higher than S_{ae} (T) for the period zero and the period range described in TEC2007.

The HS algorithm parameters HMS, HMCR and PAR are taken 5, 0.5 and 0.1 respectively. By taking HMCR as 0.5, equal probability was given to generate a new vector from the whole domain or existing ones. Increasing the HMCR value may shorten the optimization process but an average value was used to prevent the results in local regions. The value of PAR was taken as small to find more precise optimum results.

The maximum responses of the uncontrolled structure can be seen in Table 3. Instead of checking maximum base shear divided by R (numerical coefficient representative of the inherent over strength and global ductility capacity of lateral force-resisting systems), the shear forces at a story in which the numerical value is the maximum, was checked in the analysis of the three story RC building. For a three story RC building, the maximum base shear may be three times of the story shear, while R is equal to 3.5 for an ordinary RC building at ACI318. This approximation was applied in order to investigate the structure for different suggests in regulations in which the value of R was approached differently. The main aim of the study is to reduce shear forces to a desired value without exceeding the desired axial force. For all characteristic strength of the concrete, the maximum shear force value of the structure exceeds the allowed maximum values in TEC2007 under Northridge earthquake.

Table 3 The maximum responses of the uncontrolled structure

$f_c^{'}$ (MPa)	Response	Earthquake Record					
		Kobe	Imperial Valley	Erzincan	Van	Northridge	Loma Prieta
8	x_{1max} (cm)	4.91	1.38	1.77	1.38	5.92	3.13
	V_{max} (kN)	4133.80	1283.00	1480.38	1216.97	5323.53	2630.03
10	x_{1max} (cm)	5.07	1.41	1.72	1.33	5.71	2.79
	V_{max} (kN)	4513.55	1302.81	1486.41	1226.54	5397.76	2555.80
12	x_{1max} (cm)	5.04	1.36	1.68	1.32	5.54	2.48
	V_{max} (kN)	4739.93	1350.82	1496.31	1246.97	5442.36	2470.26
14	x_{1max} (cm)	4.90	1.33	1.65	1.30	5.39	2.22
	V_{max} (kN)	4830.50	1379.43	1512.06	1269.55	5472.31	2377.82
16	x_{1max} (cm)	4.75	1.33	1.62	1.26	5.27	2.06
	V_{max} (kN)	4873.97	1405.03	1531.50	1264.57	5497.44	2309.65

The compared methods were investigated for the mass ratio between 1% and 20%. In order to adapt these methods for MDOF structures, the first vibration mode and modal mass was taken into account. The first modal mass is 301.6 t. In that case, the optimum period and damping ratio of TMD for different methods can be seen in Table 4. The comparison of present approach with TMD design formulas may not be fair because these formulas were developed SDOF systems. For MDOF systems, the TMD damping ratio is also approximately equal to the TMD damping ratio computed for a SDOF system multiplied by Φ according to Sadek *et al*. (1997). In this study the value of Φ is 0.82. This value is lower than 1, so the multiplication of this value with damping ratio decreases $\xi_{d_{opt}}$. By using this procedure, it is not possible to obtain better displacement and shear force solutions if Φ is lower than 1.

The maximum x_{1R} and V_{max} values are given in Table 5 for $f_c^{'}$=8 MPa for compared methods. These maximum values are for the most critical earthquake record. All compared methods are not effective on reducing the maximum shear force value to the values calculated according to design codes (exceeding values shown in *italic*). The control of the structure may be possible if the damping ratio of the TMD is bigger. But, in order to use these methods and obtain bigger damping ratios, the mass ratio must be increased. This situation is not possible for this problem with $f_c^{'}$=8 MPa because the axial force capacity is over the limit for the mass ratio bigger than 0.06 (exceeding values shown in **bold**). By using a numerical search instead of using design formulas, it possible to find an optimum value without exceeding this limit.

Table 4 The optimum period and damping ratio for the methods

μ_m	m_d (*t*)	Den Hartog		Warburton		Sadek *et al.*		Leung and Zhang	
		$T_{d_{opt}}$ (s)	$\xi_{d_{opt}}$	$T_{d_{opt}}$ (s)	$\xi_{d_{opt}}$	$T_{d_{opt}}$ (s)	$\xi_{d_{opt}}$	$T_{d_{opt}}$ (s)	$\xi_{d_{opt}}$
0.01	3.02	0.38	0.06	0.38	0.05	0.37	0.15	0.36	0.05
0.02	6.03	0.38	0.09	0.39	0.07	0.37	0.19	0.36	0.07
0.03	9.05	0.39	0.10	0.39	0.09	0.37	0.22	0.35	0.09
0.04	12.06	0.39	0.12	0.39	0.10	0.36	0.24	0.35	0.10
0.05	15.08	0.39	0.13	0.40	0.11	0.36	0.27	0.34	0.11
0.06	18.09	0.40	0.15	0.40	0.12	0.36	0.29	0.34	0.12
0.07	21.11	0.40	0.16	0.41	0.13	0.36	0.30	0.33	0.13
0.08	24.13	0.41	0.17	0.41	0.14	0.35	0.32	0.33	0.14
0.09	27.14	0.41	0.18	0.42	0.15	0.35	0.33	0.32	0.14
0.10	30.16	0.41	0.18	0.42	0.15	0.35	0.35	0.32	0.15
0.11	33.17	0.42	0.19	0.43	0.16	0.34	0.36	0.32	0.16
0.12	36.19	0.42	0.20	0.43	0.17	0.34	0.37	0.31	0.16
0.13	39.21	0.42	0.21	0.44	0.17	0.34	0.38	0.31	0.17
0.14	42.22	0.43	0.21	0.44	0.18	0.34	0.39	0.30	0.18
0.15	45.24	0.43	0.22	0.45	0.18	0.33	0.40	0.30	0.18
0.16	48.25	0.44	0.23	0.45	0.19	0.33	0.41	0.29	0.19
0.17	51.27	0.44	0.23	0.46	0.19	0.33	0.42	0.29	0.19
0.18	54.28	0.44	0.24	0.46	0.20	0.32	0.43	0.28	0.20
0.19	57.30	0.45	0.24	0.47	0.20	0.32	0.44	0.28	0.20
0.20	60.32	0.45	0.25	0.48	0.21	0.32	0.45	0.27	0.21

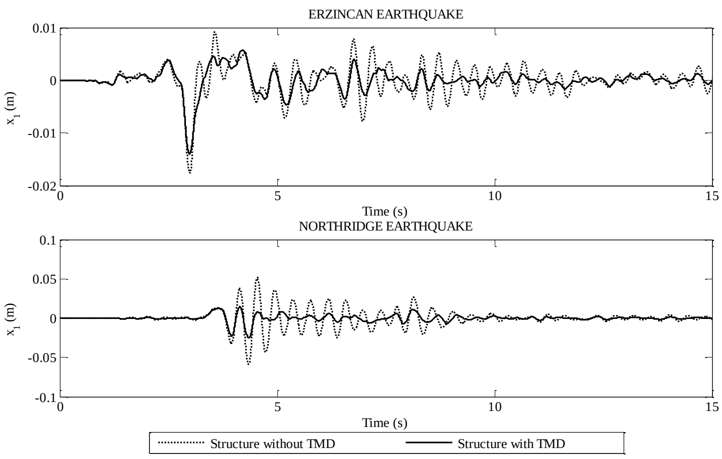

Fig. 3 Time history plots for $f_c^{'}$ =8 MPa

Table 5 Maximum x_{1R} and V_{max} for the methods ($f_c^{'}$=8 MPa)

Mass	Den Hartog		Warburton		Sadek *et al.*		Leung and Zhang	
Ratio (μ)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)
0.01	1.01	*4987.18*	1.04	*5104.20*	0.94	*4185.61*	1.01	*5137.07*
0.02	0.98	*4567.65*	1.01	*4712.92*	0.92	*3782.84*	1.06	*4769.86*
0.03	0.97	*4258.54*	0.98	*4423.08*	0.90	*3509.21*	1.11	*4483.28*
0.04	0.95	*4008.68*	0.97	*4188.48*	0.89	*3303.61*	1.15	*4246.49*
0.05	0.95	*3797.56*	0.96	*3990.05*	0.89	*3141.60*	1.18	*4046.89*
0.06	0.94	*3614.72*	0.95	*3818.09*	0.88	*3010.16*	1.20	*3876.58*
0.07	0.93	*3453.79*	0.95	*3667.21*	0.88	*2901.26*	1.22	*3730.68*
0.08	0.93	*3310.77*	0.95	*3534.05*	0.88	*2809.62*	1.24	*3606.46*
0.09	0.93	*3182.88*	0.95	*3416.23*	0.88	*2731.68*	1.26	*3501.62*
0.10	0.93	*3068.33*	0.95	*3312.03*	0.89	*2664.51*	1.28	*3452.05*
0.11	0.93	*2965.23*	0.95	*3220.03*	0.90	*2606.34*	1.30	*3485.97*
0.12	0.93	*2872.26*	0.95	*3138.97*	0.91	*2575.72*	1.32	*3516.96*
0.13	0.93	*2788.51*	0.95	*3067.80*	0.92	*2587.11*	1.34	*3546.23*
0.14	0.93	*2712.92*	0.96	*3005.61*	0.94	*2597.36*	1.36	*3574.40*
0.15	0.93	*2644.53*	0.96	*2951.29*	0.95	*2606.52*	1.38	*3601.77*
0.16	0.93	*2582.87*	0.96	*2903.94*	0.96	*2614.69*	1.40	*3628.64*
0.17	0.93	*2527.09*	0.96	*2863.05*	0.98	*2621.89*	1.42	*3654.75*
0.18	0.93	*2476.60*	0.97	*2827.75*	0.99	*2628.09*	1.44	*3680.09*
0.19	0.93	*2431.08*	0.97	*2797.36*	1.00	*2633.30*	1.47	*3704.40*
0.20	0.94	*2389.77*	0.97	*2771.60*	1.02	*2637.54*	1.49	*3727.39*

As seen in Table 6, for the limit of $\mu \leq 0.04$ and $\xi_d \leq 0.5$, the maximum shear force of the structure for $f_c^{'}$ =8 MPa can be under the maximum values determined in the design codes. It is not physically possible to reduce shear force values for a damping ratio less than 0.49. For the optimum TMD values m_d=19.008 t, $T_{d_{opt}}$ =0.4198 s and $\xi_{d_{opt}}$ =0.4928, the maximum x_{1R} and shear force of the structure for $f_c^{'}$ =8 MPa are 0.7871 and 2154.13 kN, respectively. Also, the optimum parameters and maximum results of the structures with different $f_c^{'}$ can be seen in Table 6 for two different cases. Also, the ratios between first story acceleration transfer functions of controlled and uncontrolled structure (TFR) are given in Table 6. The maximum responses given in this table is for the most critical earthquake. The maximum shear force values occur under Northridge earthquake but the maximum x_{1R} values occur under Erzincan earthquake except for the case $\mu \leq 0.1$, $\xi_d \leq 0.3$ and $f_c^{'}$ =16 MPa. In this case, Loma Prieta excitation is the most critical earthquake for maximum x_{1R}. For f_c' =8 MPa, the time history displacement responses of the first storey (x_1) obtained by using present approach can be seen in Fig. 3 under Northridge and Erzincan earthquake excitations.

Table 6 Optimum TMD parameters and maximum responses obtained by using present approach

Case	f_c' (MPa)	$m_{d_{opt}}$ (t)	$T_{d_{opt}}$ (s)	$\xi_{d_{opt}}$	x_{1R}	V_{max} (kN)	TFR
$\mu \leq 0.04$, $\xi_d \leq 0.5$	8	19.008	0.4198	0.4928	0.7871	2154.13	0.714
$\mu \leq 0.1$, $\xi_d \leq 0.3$	10	48.935	0.413	0.2893	0.8805	2186.85	0.332
	12	48.973	0.4148	0.2958	0.8689	2218.95	0.299
	14	48.602	0.4138	0.2973	0.8592	2258.94	0.280
	16	48.2481	0.4063	0.2977	0.9049	2277.55	0.286
$\mu \leq 0.1$, $\xi_d \leq 0.4$	10	49.053	0.4177	0.3876	0.8454	1973.28	0.388
	12	47.719	0.4124	0.386	0.835	2034.12	0.387
	14	48.839	0.3984	0.3883	0.8288	2045.76	0.398
	16	49.088	0.4124	0.3919	0.815	2057.01	0.360

Table 7 Maximum x_{1R} and V_{max} for the methods (f_c'=10 MPa)

Mass Ratio (μ)	Den Hartog		Warburton		Sadek *et al.*		Leung & Zhang	
	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)
0.01	1.00	*5088.23*	1.01	*5208.42*	0.94	*4272.08*	1.01	*5242.43*
0.02	0.98	*4663.18*	1.00	*4811.99*	0.92	*3866.81*	0.99	*4878.02*
0.03	0.97	*4344.94*	0.98	*4511.68*	0.90	*3591.70*	1.05	*4591.34*
0.04	0.95	*4087.58*	0.97	*4268.49*	0.89	*3385.66*	1.12	*4355.36*
0.05	0.95	*3870.94*	0.96	*4064.07*	0.89	*3223.78*	1.17	*4156.43*
0.06	0.94	*3683.70*	0.95	*3887.87*	0.88	*3092.81*	1.21	*3986.64*
0.07	0.93	*3519.06*	0.95	*3733.57*	0.89	*2984.67*	1.25	*3841.53*
0.08	0.93	*3373.05*	0.94	*3597.16*	0.91	*2894.11*	1.28	*3718.56*
0.09	0.92	*3242.21*	0.94	*3476.02*	0.92	*2817.11*	1.30	*3615.66*
0.10	0.92	*3124.44*	0.94	*3368.42*	0.93	2751.18	1.33	*3531.27*
0.11	0.92	*3018.30*	0.94	*3272.87*	0.95	2694.09	1.36	*3463.87*
0.12	0.92	*2922.14*	0.94	*3188.08*	0.96	2644.62	1.38	*3480.31*
0.13	0.92	*2835.15*	0.94	*3112.99*	0.98	2601.44	1.41	*3515.82*
0.14	0.92	2756.26	0.95	*3046.98*	1.00	2594.02	1.43	*3550.75*
0.15	0.92	2684.64	0.95	*2988.90*	1.01	2608.92	1.46	*3585.39*
0.16	0.92	2619.78	0.95	*2937.90*	1.03	2623.03	1.48	*3619.82*
0.17	0.92	2560.75	0.95	*2893.66*	1.04	2636.20	1.50	*3653.85*
0.18	0.92	2507.38	0.95	*2855.06*	1.06	2648.60	1.53	*3687.39*
0.19	0.92	2458.73	0.96	*2821.76*	1.08	2660.12	1.55	*3720.18*
0.20	0.92	2414.80	0.96	2793.09	1.09	2670.76	1.57	*3751.99*

In Table 7, the maximum x_{1R} and V_{max} values are given for $f_c^{'}$=10 MPa. For the methods of Den Hartog , Warburton, Sadek *et al*. and Leung and Zhang the maximum shear forces are 2414.80 kN, 2793.09 kN, 2594.02 kN and 3463.87 kN, respectively. Leung and Zhang (PSO) is not effective on reducing the shear force under regulations values. By using proposed method, for the cases with maximum 30% and 40% damping ratio , the maximum values of x_{1R} are 0.8805 and 0.8454 and shear force are 2186.85 kN and 1973.28 kN, respectively. The compared methods have bigger masses and damping ratios for some mass ratios. Optimum values obtained by the present approach are more effective on reducing structural vibrations and shear forces because the optimization process was conducted for MDOF systems.

For the other characteristic strength of the concrete ($f_c^{'}$=12, 14 and 16 MPa), x_{1R} and V_{max} values obtained by the compared methods are given in Appendix. The maximum x_{1R} and shear force obtained by the present approach are lower than the other methods except the case $\mu \leq 0.1$, $\xi_d \leq 0.3$ and $f_c^{'}$=16 MPa for the maximum x_{1R}. For masses bigger than 39.21 *t*, the maximum x_{1R} is 0.89 when using Den Hartog formulas. When the limit values of mass and damping ratio of TMD are 10% and 30% for $f_c^{'}$=16 MPa, the maximum x_{1R} obtained by the present study is 0.9. But, the main objective maximum shear force values are lower than the compared methods.

5. Conclusions

The objective of this paper is to prevent the risk of brittle fracture of RC buildings by adding a TMD on the top of the structure. Structures with different compressive strength of the concrete were chosen as case study and all structures are under trouble of brittle fracture. Also, their axial force capacities are limited for a heavy TMD application. The challenge of the methodology is to find optimum TMD values for reduction of shear forces without exceeding the axial force capacity of the structure according the rules of seismic codes.

In practice, several design formulas for tuning of TMDs have been used for improving the seismic performance of multi-story structures although these design formulas were developed for the minimization of single degree of freedom systems based on different optimum criteria and external excitation. Although these formulas are derived for SDOF systems, some modifications for using these formulas for MDOF systems were proposed. In order to find the best and suitable optimum value by considering the physical properties of the structure and construction site, a numerical search algorithm is the best suitable tool for this aim. A random search method like HS is a great source for the specific structures by using correct stopping and checking criteria under suitable external excitations.

The case study was investigated for reduction of the maximum values of shear force, first story displacement and acceleration transfers function. It must be noted that the optimum solutions may vary when different criteria, external excitations and structure is employed for the research. The design structure must be also checked for the resistance of overturning moment for possible restriction of axial force capacity. The HS optimized TMD can be used for the retrofit of weak structures in mean of insufficient shear force safety.

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Appendix

Table 8 Maximum x_{1R} and V_{max} for the methods ($f_c^{'}$=12 MPa)

Mass	Den Hartog		Warburton		Sadek *et al.*		Leung and Zhang	
Ratio (μ)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)
0.01	1.00	*5154.37*	1.00	*5277.59*	0.94	*4327.08*	1.04	*5301.88*
0.02	0.98	*4728.03*	0.99	*4881.06*	0.91	*3921.47*	1.05	*4941.75*
0.03	0.98	*4403.30*	1.01	*4572.88*	0.90	*3646.53*	1.05	*4660.34*
0.04	0.98	*4139.73*	1.01	*4321.78*	0.89	*3441.37*	1.08	*4429.12*
0.05	0.97	*3917.93*	0.99	*4111.13*	0.91	3280.77	1.14	*4233.61*
0.06	0.95	*3726.60*	0.97	*3930.36*	0.92	3151.53	1.19	*4066.67*
0.07	0.93	*3559.17*	0.94	*3772.66*	0.94	3045.27	1.24	*3924.79*
0.08	0.92	*3410.40*	0.94	*3633.60*	0.96	2956.50	1.28	*3805.30*
0.09	0.92	3277.36	0.94	*3510.29*	0.97	2881.67	1.33	*3706.61*
0.10	0.91	3157.51	0.93	*3400.34*	0.99	2817.71	1.37	*3626.65*
0.11	0.91	3049.14	0.93	3302.17	1.01	2762.89	1.41	*3563.64*
0.12	0.91	2950.93	0.93	3214.95	1.03	2715.46	1.45	*3515.89*
0.13	0.91	2861.63	0.93	3137.29	1.04	2674.34	1.48	*3481.44*
0.14	0.91	2780.54	0.93	3068.31	1.06	2638.72	1.52	*3497.00*
0.15	0.91	2706.63	0.94	3007.58	1.08	2607.98	1.55	*3536.27*
0.16	0.91	2639.49	0.94	2953.93	1.10	2607.41	1.58	*3575.69*
0.17	0.91	2578.23	0.94	2906.96	1.12	2625.67	1.61	*3615.14*
0.18	0.91	2522.58	0.94	2865.91	1.14	2643.25	1.64	*3654.39*
0.19	0.91	2471.82	0.94	2830.20	1.16	2660.07	1.66	*3693.30*
0.20	0.91	2425.69	0.95	2799.35	1.18	2676.16	1.69	*3731.54*

Table 9 Maximum x_{1R} and V_{max} for the methods ($f_c^{'}$=14 MPa)

Mass Ratio (μ)	Den Hartog		Warburton		Sadek *et al.*		Leung and Zhang	
	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)
0.01	1.03	*5191.98*	1.05	*5316.95*	0.93	*4358.87*	1.07	*5328.85*
0.02	0.98	*4766.65*	1.00	*4922.86*	0.91	*3954.47*	1.12	*4973.27*
0.03	1.00	*4439.03*	1.02	*4610.92*	0.91	3681.43	1.14	*4699.72*
0.04	1.02	*4171.42*	1.05	*4354.15*	0.93	3478.56	1.14	*4474.74*
0.05	1.03	*3945.72*	1.06	*4138.29*	0.94	3320.63	1.12	*4284.37*
0.06	1.02	3751.29	1.04	*3953.29*	0.96	3194.08	1.16	*4122.48*
0.07	1.00	3581.08	1.02	3792.36	0.98	3090.56	1.21	*3986.27*
0.08	0.98	3430.20	1.00	3651.11	1.00	3004.90	1.26	3872.97
0.09	0.96	3295.31	0.97	3525.74	1.02	2932.80	1.31	3780.64
0.10	0.94	3173.82	0.94	3413.91	1.04	2871.85	1.36	3707.18
0.11	0.92	3063.94	0.92	3314.27	1.06	2819.68	1.41	3650.37
0.12	0.90	2964.18	0.92	3225.08	1.08	2774.92	1.46	3608.04
0.13	0.90	2873.40	0.92	3145.46	1.11	2736.44	1.51	3578.49
0.14	0.90	2790.71	0.92	3074.68	1.13	2703.28	1.56	3559.89
0.15	0.90	2715.22	0.92	3011.64	1.15	2674.82	1.60	3550.98
0.16	0.90	2646.43	0.93	2956.10	1.17	2650.57	1.64	3550.71
0.17	0.90	2583.50	0.93	2906.99	1.19	2630.40	1.68	3558.37
0.18	0.90	2526.26	0.93	2864.01	1.21	2621.92	1.72	3600.05
0.19	0.90	2473.84	0.93	2826.38	1.24	2643.08	1.76	3643.21
0.20	0.90	2426.16	0.93	2793.79	1.26	2663.63	1.79	3686.16

Table 10 Maximum x_{1R} and V_{max} for the methods ($f_c^{'}$=16 MPa)

Mass Ratio (μ)	Den Hartog		Warburton		Sadek *et al.*		Leung and Zhang	
	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)	x_{1R}	V_{max} (kN)
0.01	1.05	*5211.75*	1.07	*5337.27*	0.95	4377.93	1.07	*5340.04*
0.02	1.03	*4788.17*	1.04	*4945.73*	0.92	3975.45	1.15	*4988.45*
0.03	0.99	4460.86	1.01	*4633.94*	0.91	3705.21	1.18	*4721.75*
0.04	1.03	4191.38	1.06	4374.47	0.93	3505.47	1.18	4502.42
0.05	1.05	3963.34	1.08	4154.85	0.95	3350.82	1.17	4317.66
0.06	1.05	3766.32	1.08	3966.37	0.97	3227.58	1.15	4162.06
0.07	1.04	3593.81	1.07	3802.45	0.99	3127.50	1.15	4032.75
0.08	1.03	3440.99	1.05	3658.79	1.01	3045.02	1.20	3926.92
0.09	1.01	3304.34	1.02	3531.50	1.03	2976.13	1.25	3842.16
0.10	0.99	3181.47	0.99	3418.07	1.06	2918.12	1.30	3775.97
0.11	0.96	3070.13	0.96	3316.89	1.08	2868.93	1.35	3725.85
0.12	0.94	2969.23	0.93	3226.15	1.10	2826.90	1.40	3689.47
0.13	0.92	2877.14	0.91	3145.09	1.12	2790.96	1.45	3664.98
0.14	0.89	2793.27	0.91	3072.62	1.15	2760.30	1.50	3650.52
0.15	0.89	2716.55	0.91	3007.99	1.17	2734.17	1.55	3644.91
0.16	0.89	2646.41	0.92	2950.70	1.19	2712.15	1.60	3646.94
0.17	0.89	2582.33	0.92	2899.86	1.22	2693.93	1.65	3655.99
0.18	0.89	2523.56	0.92	2855.25	1.24	2679.22	1.70	3671.53
0.19	0.89	2470.05	0.92	2815.96	1.27	2668.07	1.75	3693.45
0.20	0.89	2420.98	0.92	2781.85	1.29	2660.56	1.79	3721.52