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Structural Control Strategy of using Optimum Tuned Mass Damper System for Reinforced Concrete Framed Structure

[1]Min-Ho Chey, [1]Seong-Il Kim and [2]Hyung-Jin Mun
[1]Faculty of Architecture and Civil Engineering, Keimyung University, 42601 Daegu, Korea
[2]Department of Information and Communication Engineering, Sungkyul University, 14097 Anyang, Korea

Abstract: This study explores the effectiveness of a passive Tuned Mass Damper (TMD) system as a seismic damping strategy to suppress structural vibrations for reinforced concrete structure. The optimised TMD parameters or a curve-fitting scheme has been employed subjected to a series of earthquake excitations. The response performance of the target structures and the TMD used are examined and the effectiveness of the TMD is presented. As for the optimum parameters with respect to displacement, the optimum frequency tuning ratio increases and the optimum TMD damping ratio decreases with increasing mass ratio. For a given level of critical damping in the structure increasing the mass ratio makes the TMD more effective in reducing structural response. Despite of the some uncertainty due to the effectiveness of the TMD for the individual earthquakes, a suggested optimum TMD system reduces the inter-storey drifts clearly, especially for the earthquake records having large spectral displacements. From the viewpoint of the Root-Mean-Square (RMS), values for the some earthquake motions used, the RMS stroke lengths of the TMDs are relatively larger than under the other excitations and this response property of the TMDs corresponds to larger displacement of the corresponding top floors. Thus, it can be noted that the TMD stroke increases as the top floor displacement increases. As the response of the structure (top floor response) is increased, the corresponding TMD response is increased with regard to TMD stroke.

Key words: Structural control, earthquake, tuned mass damper, inter-story drift, TMD stroke, excitations

INTRODUCTION

One of the classical and widely verified dynamic vibration damping device is the Tuned Mass Damper (TMD), consisting of a sub-mass of around 1% of the mass of the target structure, located at the top of the building and connected through a passive spring and damper to control any undesirable vibrations. It is well known that the TMD will minimise the vibration if the TMD frequency is set equal to the frequency of the disturbing force and there are still many medium-rise structures that can benefit by use of a passive TMD as a damping device rather than any other kind of damping device. Also, the TMD is relatively easy to implement in new buildings and in the retrofit of existing ones. It offers the advantages of portability and ease of installation (because of the small size of an individual damper) which makes it attractive not only for new installation but also for temporary use during construction or for retrofit in existing structures. The TMD does not require an external power source to operate and does not interfere with vertical and horizontal load paths as do some other passive devices. These advantages and properties of the TMD, the TMD system can be a suitable damping device for many structures. However, most TMD applications have been made to mitigate wind-induced motion whereas the seismic effectiveness of TMD still remains an important issue for study and these facts have provided motivation for this study. Therefore, in this study, the optimum parameters of a TMD design that can reduce the response of a relatively medium-rise damped structure to a satisfactory level of displacement is developed. Furthermore, the suggested TMD parameters are adopted to a 12 storey bench-marking reinforced concrete to investigate the effectiveness of the TMD optimised.

Literature review: Recently, numerical and experimental studies have been carried out on the effectiveness of TMDs in reducing seismic response of structures (Kwok and Samali, 1995; Soong and Dargush, 1997; Chey and Kim, 2012). Numerical and experimental results show that the effectiveness of TMDs on reducing the

Corresponding Author: Min-Ho Chey, Faculty of Architecture and Civil Engineering, Keimyung University, 42601 Daegu, Korea

response of the same structure during some earthquakes, or of different structures during the same earthquake is significantly different, some cases giving good performance and in others having little or even no effect. This implies that there is a dependency of the attained reduction in response on the characteristics of the ground motion that excites the structures. Recently, these response reduction effects have been increased by adopting active control techniques and damping devices (Nagashima, 2001; Samali and Dawod, 2003).

A number of practical considerations must be observed in the engineering design of a TMD system. First and foremost is the amount of added mass that can be practically placed on the top of a building. TMD travel relative to the building is another important design parameter. Large movements often need to be accommodated for a reasonable response reduction of the building. Another major engineering technique associated with a sliding mass arrangement is to provide a low-friction bearing surface, so that, the mass can respond to the building movement at low levels of excitation. This becomes more critical when TMD functions are used as an additional damper to improve occupant comfort. Noting that base-isolated system responses are dominated by the first-mode contribution and that TMDs are able to reduce the fundamental modal response by Palazzo (2008) proposed a new idea of combining both properties into a unique system. Analytical results show that use of the TMD in a base-isolated system has the advantage of absorbing seismic energy without contaminating the isolating effect and the relative base displacement of the system may be reduced significantly.

MATERIALS AND METHODS

Parametric optimization of TMD: In general, the optimum parameters such as the 'damping ratio' and the 'frequency' of the TMD need to be determined to achieve the optimum structural performance. The optimum parameters can be derived for the required dynamic load depending on the control criteria such as displacement and acceleration. The classically suggested control criteria (Hartog, 1985) were used by minimizing the displacement of the structure. Displacement essentially determines safety and integrity of a structure under external excitations. Meanwhile, large accelerations of a structure under excitations produce detrimental effects in functionality of non-structural components, base shear and occupant comfort. Thus, minimizing structural acceleration can also be a viable control criterion. The TMD travel relative to the building is another important design criterion. However, the large movements of the TMD often need to be accommodated for a reasonable response reduction for the building. Generally, speaking, if a building is subjected to a far-field earthquake of long duration, the absolute acceleration of the TMD needs to be reduced to improve the comfort of occupants. However, for a near-field earthquake of strong intensity, the priority of the control objective changes to the reduction of the structure displacement to protect the structure itself. It is clear that some of the above criteria overlap with each other and have similarities. In this study, the inter-storey drift the main structure and the displacement of the TMD will be examined to observe the effects of the TMD.

Table 1: Optimum TMD parameters

$\mu/\xi 1$	f_{2dopt}	ξ_{2dopt}	k_{2dopt}	c_{2dopt}
0.003				
0.00	0.9963	0.0274	50.370	0.8279
0.01	0.9947	0.0274	50.213	0.8262
0.02	0.9927	0.0274	50.015	0.8246
0.03	0.9904	0.0274	49.778	0.8227
0.05	0.9845	0.0274	49.187	0.8178
0.01				
0.00	0.9876	0.0498	165.010	4.9792
0.01	0.9850	0.0498	164.110	4.9662
0.02	0.9819	0.0498	163.100	4.9507
0.03	0.9784	0.0498	161.950	4.9335
0.05	0.9704	0.0498	159.300	4.8930
0.02				
0.00	0.9755	0.0702	321.940	13.8640
0.01	0.9718	0.0702	319.540	13.8090
0.02	0.9678	0.0702	316.900	13.7520
0.03	0.9634	0.0702	314.020	13.6890
0.05	0.9534	0.0702	307.560	13.5490
0.05				
0.00	0.9406	0.1097	748.340	52.2430
0.01	0.9350	0.1098	739.380	51.9600
0.02	0.9292	0.1098	730.220	51.6400
0.03	0.9230	0.1098	720.550	51.3010
0.05	0.9096	0.1098	699.750	50.5630
0.1				
0.00	0.8861	0.1527	1328.300	136.9800
0.01	0.8789	0.1528	1306.700	135.8800
0.02	0.8714	0.1528	1284.400	134.7500
0.03	0.8635	0.1528	1261.300	133.5600
0.05	0.8468	0.1529	1212.900	131.0200

Five different damped systems are shown in bold values

Table 2: Optimum TMD parameters (curve-fitting equations)

Parameter title	Optimum parameters
Frequency tuning ratio (f_{2dopt})	$1.00-1.24\mu+1.0\mu^2+(-0.13-11.36\mu+55.84\mu^2)\xi_1-(2.04+11.26\mu-72.89\mu^2)\xi_1^2$
Damping ratio (ξ_{2dopt})	$0.03+2.24\mu-9.68\mu^2$ $(-0.002+0.15\mu-1.08\mu^2)\xi_1+(0.026-2.28\mu+20.88\mu^2)\xi^2_1$
TMD stiffness (k_{2dopt})	$1.68+16630\mu-33654\mu^2+(52.82-13972\mu-77802\mu^2)\xi_1+(-117-50079\mu+1355929\mu^2)\xi^2_1$
TMD damping Coefficient (c_{2dopt})	$-2.67+762\mu+6355\mu^2+(0.22-59.8\mu-10083\mu^2)\xi_1+(11.15-2158\mu-4521\mu^2)\xi^2_1$

In the previous study by Chey and Kim (2012), proposed the optimum TMD parameters and the corresponding responses for different mass ratios (μ = 0.0-0.1) with five different critical damping ratios of the target structures (ξ_1 = 0, 0.01, 0.02, 0.03 and 0.05) as shown in Table 1 and 2. Meanwhile, for convenience in future applications, explicit mathematical expressions that correspond to the computed optimum values are determined. From the numerical data of Table 1 and 2, four parametric closed form formulae are obtained using curve-fitting methods as shows in Table 2. The optimum tuning frequency ratios (f_{2dopt}) and optimum TMD damping ratios (f_{2dopt}) in terms of the displacement response for the five different damped systems are listed (Table 1) and the curves of the closed-form expressions (Table 2). The optimum TMD damping stiffness (k_{2dopt}) and optimum TMD damping coefficient (ξ_{2dopt}) are also calculated and listed in Table 1 and 2.

Modelling of framed structure and earthquake records used: A 12 storey, reinforced concrete framed structure was adopted to demonstrate the effects of the TMD as shown in Fig. 1. This model was designed originally by Jury (1978) according to the New Zealand Loadings Code (SANZ, 1976). It was assumed that the frame would be required to resist the component of earthquake motion in the plane of the frame only. No torsional effects for the building as a whole were taken into account. According to the NZS code for beam design, all frames share in carrying gravity and seismic-induced loads, then moment redistribution was carried out using a method developed by Paulay (1976) and the column dimensions were increased by Thomson (1991). The dynamic properties of the frame such as the natural frequency, modal effective mass, modal damping ratios and participation factors are calculated and listed in Table 3.

In the computational study, four different earthquake records which have various Peak Ground Acceleration (PGA) levels are used. Only the first 20 sec of these records (Fig. 2) are used in the analyses and the excitations used as: 1992, NZS 4203-Artificial, 1940, Imperial Valley-El Centro (NS), 1971, San Fernando-Pacoima Dam (S16E), 1994, Northridge-Sylmar County Hospital (NS).

The artificial accelerogram is generated by the SIMQKE program (Vanmarke, 1976) to produce an artificial accelerogram to match the spectra specified in the New Zealand Standard (SANZ, 1976). It is specified that the target Peak Ground Acceleration (PGA) is 0.5 g, the time step size is 0.02 and the number of spectral points are 200. Then, the record is multiplied by a zone factor of 1.2 which represents the highest zone factor value in the New Zealand Loadings Code. In order to observe the seismic responses under typical earthquakes, a design-based classical earthquake record, the El Centro is used. This record has magnitudes of 6.4 on the Richter scale and the accelerograph was recorded at sites 9 km from the epicentre and has PGA of 0.34 g. The Pacoima Dam

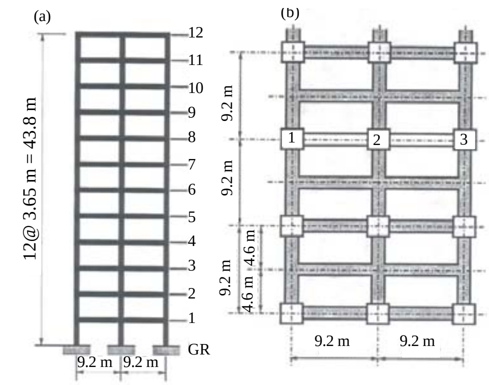

Fig. 1: 12 storey reinforced concrete target structure

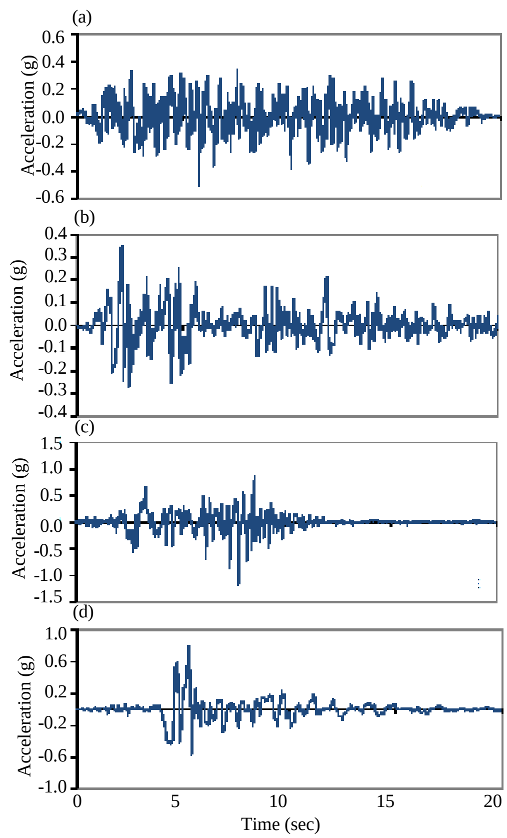

Fig. 2: Earthquake record; a) Artificial; b) El centro NS; c) Pacoima Dam SI6E and d) Sylmar NS

Table 3: Dynamic properties of the structure

Mode	Natural frequencies (Hz)	Modal eff. mass (kN-sec^2/m)	Participation factor
1	0.532	1.514E+03	1.366E+00
2	1.533	2.527E+02	-5.321E-01
3	2.756	7.408E+01	-2.752E-01
4	3.853	7.899E-29	3.064E-16
5	3.885	3.596E+01	-1.700E-01
6	4.525	5.616E+00	-9.368E-02
7	5.131	1.944E-28	-4.722E-16
8	5.279	2.056E+01	-1.436E-01
9	6.652	1.548E+01	-1.118E-01

acceleration record which has a magnitude of 6.6 on the Richter scale is used to examine the large response of the structure. The PGA recorded is 1.17 g. The 1994 Sylmar earthquake accelerogram is recorded at the ground floor in the Sylmar County Hospital on the site of the old Olive View Hospital building which suffered major and irreparable damage during the 1971 San Fernando earthquake. A magnitude of 6.4 on the Richter scale is recorded and the epicentre distance is 15.0 km. A PGA recorded at the ground floor is 0.80 g.

RESULTS AND DISCUSSION

Relative displacement of top floor: The displacement of the top floor relative to the ground which represents the largest response of the structure was used as the other index of the integrity of the structure.

Figure 3 and 4 show the first 20 sec of the relative displacement time-histories between the top floor and the ground and Table 3 shows summarised values of the top floor relative displacement and TMD effectiveness under each excitation in terms of the RMS value. The TMD are effective in reducing the lateral displacement of the framed structure under all the excitations used. There are great reductions of displacement under the artificial, Pacoima N16E and Sylmar NS excitations. These three earthquake motions produced relatively larger maximum displacements than the other earthquake records for the particular natural period and give rise to increases of the spectral displacements at long periods. Hence, larger displacement responses occurred and it can be observed that the TMDs were more effective under these earthquake motions.

In terms of the RMS values, under the Pacoima excitation, there are 56 and 65% reductions for the cases of the 2% TMD and the 5% TMD for the 2% Rayleigh damping model and 41 and 50% for the 5% Rayleigh damping model, respectively. Under the artificial excitation as a target excitation, the RMS relative displacement of the 2% Rayleigh damping model without TMD (0.210 m) is reduced by 54% (0.097 m) when the 2% TMD is introduced and by 56% (0.093 m) with the 5% TMD. For the 5% Rayleigh damping structure, the RMS value is reduced to 34% with the 2% TMD and to 36%

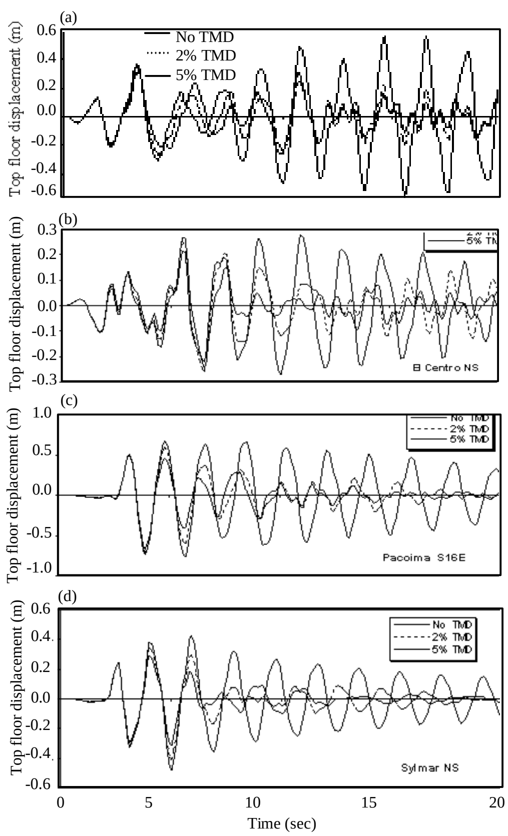

Fig. 3: Relative displacement of top floor (2% Rayleigh damping) a) Artificial; b) El centro NS; c) Pacoima Dam SI6E and d) Sylmar NS

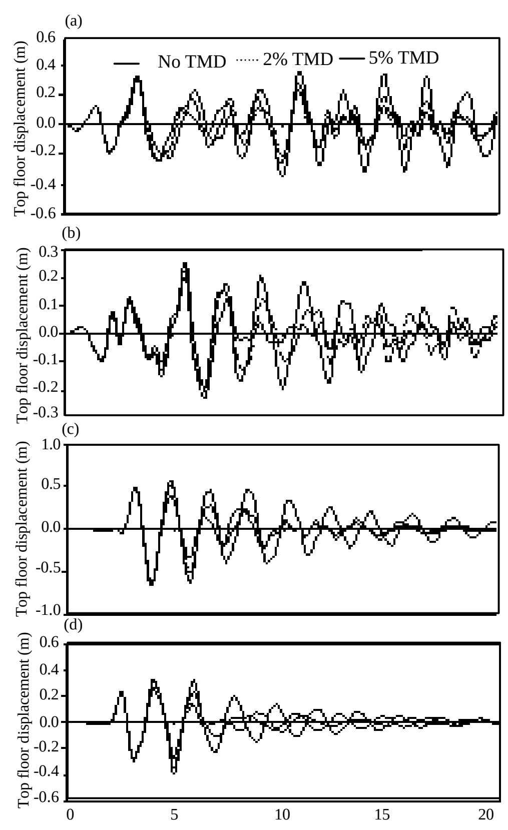

Fig. 4: Relative displacement of top floor (5% Rayleigh damping); a) Artificial; b) El centro NS; c) Pacoima Dam SI6E and d) Sylmar NS

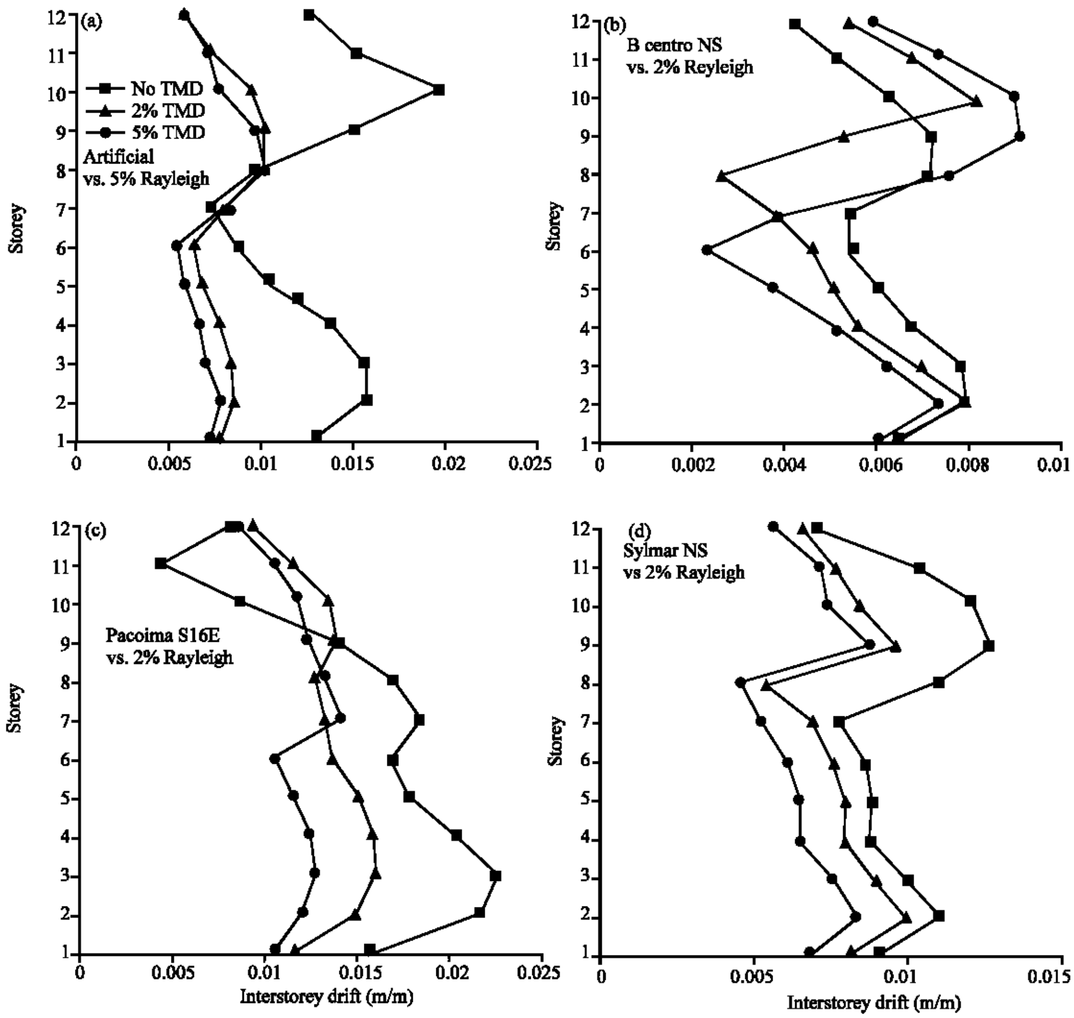

Fig. 5: Inter-storey drift (2% Rayleigh damping)

with the 5% TMD. It can be noted that the TMD is highly effective in reducing the displacement of the structures subjected to seismic excitations and the effectiveness is increased by increasing the mass ratio and by decreasing the critical damping ratio of the structures. These overall results are listed in Table 4 and 5.

Maximum inter-storey drift: Figure 5 and 6 show the maximum inter-storey drifts without and with 2 and 5% TMD for different structural damping values (2 and 5% Rayleigh damping). In general, the efficiency of the TMD is higher for a 2% Rayleigh damped structure than a 5% Rayleigh damped one. It is observed that at some storeys the higher reductions do not correspond to the higher mass ratio. From the profiles, the higher mass ratio seems to provide satisfactory reductions over the lower half of the height of the frame but it can be seen that the envelopes have irregular or contrary shape in the upper part of the frames. The envelopes for the artificial excitation show good reductions of inter-storey drift with the TMD except at mid-height levels for the 2% Rayleigh structure and at upper levels for the 5% Rayleigh

Table 4: Summary of top floor displacement (2% rayleigh damping)

Top floor relative displacement	No TMD	TMD (2%)		TMD (5%)	
	RMS (m)	RMS (m)	Effect (%)	RMS (m)	Effect(%)
Artificial	0.210	0.097	54	0.093	56
El Centro (NS)	0.112	0.072	36	0.050	55
Pacoima (N16E)	0.299	0.130	56	0.103	65
Sylmar (NS)	0.145	0.068	53	0.051	65

Table 5: Summary of top floor displacement (5% rayleigh damping)

Top floor relative displacement	No TMD	TMD (2%)		TMD (5%)	
	RMS (m)	RMS (m)	Effect (%)	RMS (m)	Effect (%)
Artificial	0.136	0.089	34	0.088	36
El centro (NS)	0.074	0.065	12	0.045	40
Pacoima (N16E)	0.177	0.105	41	0.088	50
Sylmar (NS)	0.081	0.053	29	0.044	46

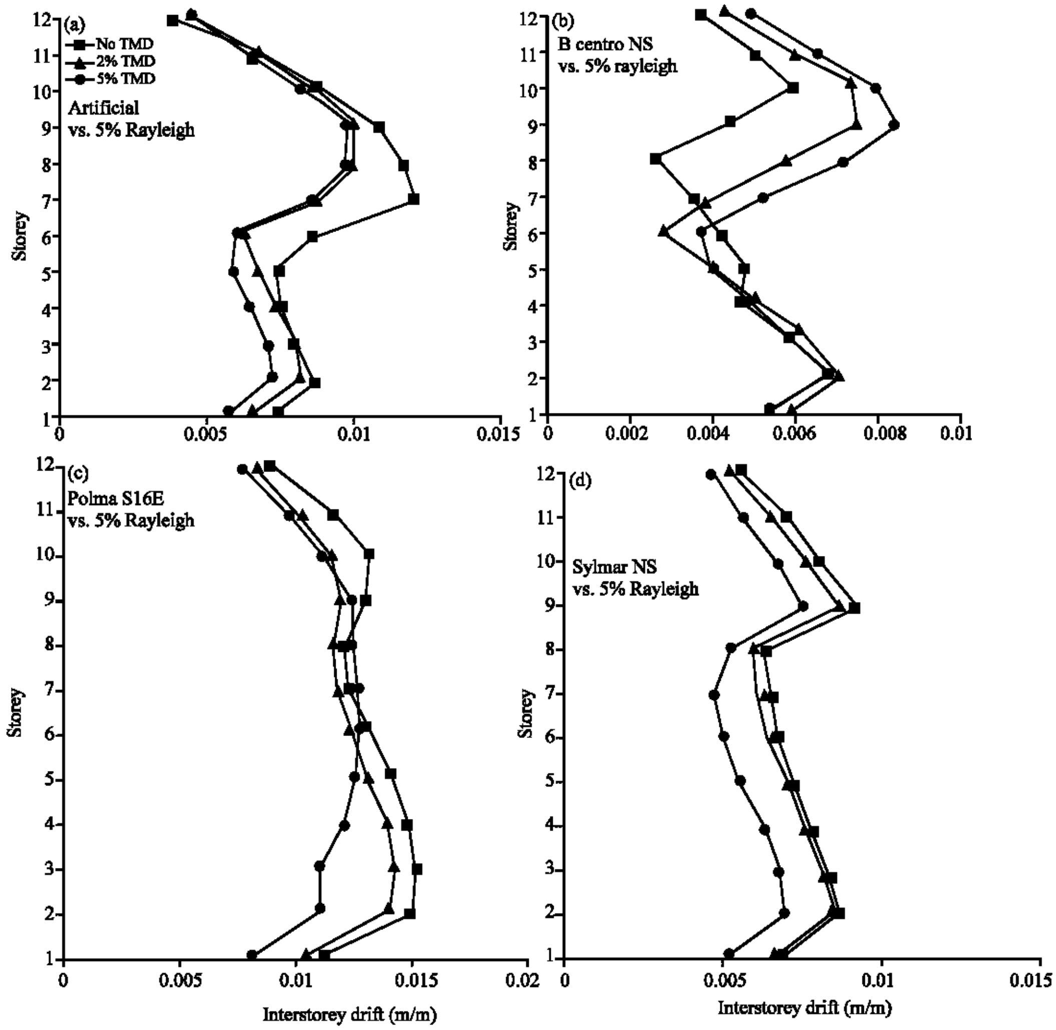

Fig. 6: Inter-storey drift (5% Rayleigh damping)

structure. For the El Centro excitation, these exceptions are found over the upper level of the structure for both 2% and 5% Rayleigh structures. There are relatively large inter-storey drifts under the Pacoima Dam excitation but with exceptions at some storeys. The Sylmar excitation produces good reductions of inter-storey drift without any exception over the height of the structure.

In some cases, the specified TMD produced a negative effect and it amplifies the response slightly. This poor performance is attributed to the ineffectiveness of the TMD which has only linear properties and its inability to reach a resonant condition in the structure. When the structure experiences elasto-plastic deformations, the frequency of the system decreases, so that, the TMD loses part of its effectiveness due to this detuning effect. However, the investigated graphical results for the structure could be used to aid the design of the advanced inelastic system under seismic excitations.

Behaviour of TMD: The large displacement of the TMD may contribute substantially to the costs of the TMD itself and to the costs of accommodating the displacements of the structures. Some TMDs require large strokes to be effective. Therefore, the TMD physical responses are usually an important design consideration. Through these parameters, the designer can check the property of TMD movement and it may give good information to help design an appropriate TMD system.

In this study, the travel of TMD relative to the top floor (the stroke) was also selected. The optimum damping is not the only constraint in the selection of the TMD. Available space will limit the travel of the TMD relative to the structure. The designer may wish to select a TMD damping larger than the optimum value to reduce the TMD travel. Hence, other control parameters in terms of the TMD behaviour were required and can be

Table 6: Summary of the TMD stroke (2% rayleigh damping)

	TMD (2%)		TMD (5%)	
Earthquake record	RMS (m)	Stroke ratio	RMS (m)	Stroke ratio
Artificial	0.422	3.0	0.245	2.3
El centro (NS)	0.275	3.5	0.141	2.5
Pacoima (N16E)	0.558	3.2	0.275	2.1
Sylmar (NS)	0.308	3.2	0.144	2.5

Table 7: Summary of the TMD stroke (5% Rayleigh damping)

	TMD (2%)		TMD (5%)	
Earthquake record	RMS (m)	Stroke ratio	RMS (m)	Stroke ratio
Artificial	0.360	2.9	0.229	2.2
El Centro (NS)	0.255	3.3	0.125	2.5
Pacoima (N16E)	0.414	2.9	0.221	2.0
Sylmar (NS)	0.263	3.1	0.128	2.3

used. The time-history behaviour of the TMD (the stroke the relative displacement of the TMD to the top floor) is in Table 6 and 7, summarising the results of the TMD stroke in terms of Root-Mean-Square (RMS) values. In shown Table 6 and 7, the stroke ratio is defined as the RMS stroke length divided by the RMS displacement of the top floor. As it can be seen in the Table 6 and 7 increasing the mass ratio decreases the TMD stroke and for the models with small damping ratio (2%), the stroke length is larger. The stroke ratios for the 5% TMD is less than those of the 2% TMD.

For the case of 5% Rayleigh damping model, the values are decreased with stroke ratios of 2.1 and 2.9. This means that the TMD relative motion is about 3 times and 2 times the motion of the structure model with the 2% TMD and the 5% TMD, respectively. It is noted that there is not a significant difference in the TMD stroke between the two different structural damping ratios.

In conclusion with a larger mass ratio, the TMD inertia increases, causing the stroke to reduce. Also with the TMD absorbing most of the energy of the excitation, its displacement is much larger than that of the top floor. Hence, it is noted that the stroke is dominated by the mass ratio. From the result data illustrating the response of the TMD stroke behaviour, a designer therefore, can use the TMD response property as the important design factor for optimum TMD design.

CONCLUSION

Based on the parametric analysis described before, the structural analysis was conducted using the program Ruaumoko and a 12 storey, two-bay reinforced concrete framed structure was adopted to demonstrate the effects of the TMD. As input excitations, four different earthquake records including an artificially generated earthquake record according the spectra specified in the New Zealand Standard NZS4203 (1992) were used. For comparison, the response behaviours were simulated with 2 and 5% internal structural damping values were adopted for the inter-storey drift response case. From the viewpoint of the TMD, the mass ratios of 2 and 5% TMD were applied on the top floor to compare the effectiveness of the TMD. With the specified conditions, some important practical information were derived as follows.

The optimum parameters with respect to displacement were derived and the optimal frequency tuning ratio increases and the optimal TMD damping ratio decreases with increasing mass ratio. From the structural analysis for the 12 storey frame, the results with respect to the parameters such as mass ratio, frequency tuning ratio and TMD damping ratio, correspond to the results from the parametric analysis studies.

LIMITATIONS

Although, there is some uncertainty as to the effectiveness of the TMD for the individual earthquakes, a proposed optimum TMD reduces the displacement responses, especially for the earthquake records having large spectral displacements.

As the response of the structure is increased, the corresponding TMD response is increased with regard to the both TMD stroke. This disadvantage is related to space limitations and construction facilities and should be solved in the future.

RECOMMENDATIONS

For a given level of critical damping in the structure increasing the mass ratio makes the TMD more effective in reducing structural response. This implies that a system with higher intrinsic damping requires a TMD with a larger mass ratio to provide similar reduction to that needed for a system with lower damping.

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