RESETABLE TUNED MASS DAMPER AND ITS APPLICATION TO ISOLATED STORIES BUILDING SYSTEM

M.H. Chey[1], A.J. Carr[2], J.G. Chase[3] and J.B. Mander[4]

[1] *PhD Candidate, Dept. of Civil & Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand*
[2] *Professor, Dept. of Civil & Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand*
[3] *Professor, Dept. of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand*
[4] *Zachry Professor, Zachry Dept. of Civil Engineering, Texas A&M University, Texas, USA*
[1] *Email: hnhdad@gmail.com*

ABSTRACT :

The seismic performances of multi-story passive and semi-active tuned mass damper (TMD) building systems are investigated for 12-story moment resisting frames modeled as '10+2' story and '8+4' story. Segmented upper stories of the structure are isolated as a tuned mass, and a passive viscous damper or semi-active resetable device is adopted for energy dissipation. Optimum TMD control parameters and appropriate matching resetable TMD (RTMD) configurations are adopted from a previous study on a simplified two degree of freedom (2-DOF) system. Log-normal statistical performance results are presented for 30 probabilistically scaled earthquake records. The time history analysis and normalized reduction factor results show the response reductions for all seismic hazards. Thus, large semi-active isolated stories building systems can effectively manage seismic response for multi degree of freedom (MDOF) systems across a broad range of ground motions in comparison to passive solutions. This research demonstrates the validity of the isolated stories building systems using RTMD control strategy for consideration in future design and construction.

KEYWORDS: tuned mass damper, semi-active control, resetable device, statistical assessment

1. INTRODUCTION

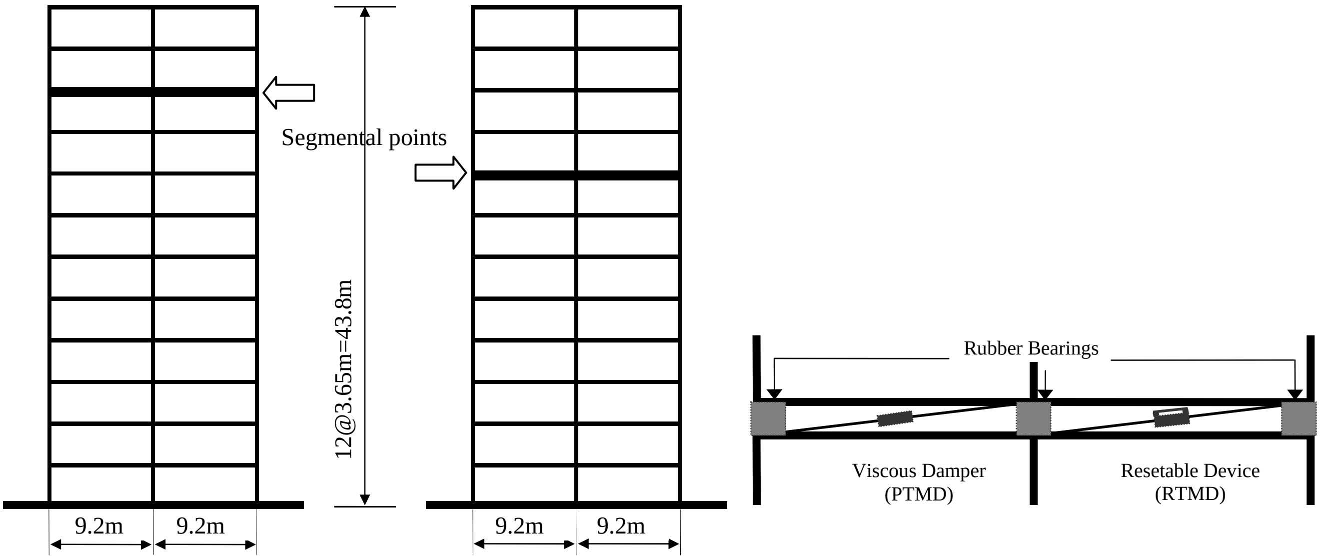
Tuned mass damper (TMD) systems are often considered as a practical seismic response control solution for flexible structures, such as tall buildings. However, the main disadvantage of a TMD system is the sensitivity related to the narrow band control and the fluctuation in tuning the TMD frequency to the controlled frequency of a potentially degrading structure. Another limitation of a TMD is the size of the tuned absorber mass. To overcome this limitation, seismic isolation concepts using TMD principles have been extended to convert a structural system into a TMD system by specially designing the structural system (Charng 1998; Kawamura 2000; Murakami et al. 2000; Pan and Cui 1998; Pan et al. 1995).

In prior research (Chey et al. 2007), 2-DOF passive TMD (PTMD) and semi-active TMD (SATMD) building models were presented and implemented in a system design simulation. The efficiency of these modified systems and the validity of the optimal designs were demonstrated as the reference for multi-degree-of freedom (MDOF) verification. The current study adopts multi-story resetable TMD (RTMD) that uses segregated upper stories as a relatively very large tuned mass and semi-active resetable device to provide robust adaptability to broader ranges of structural response and tuning. For this study, the performance of 12-story RTMD building system models are compared with those from the corresponding uncontrolled (No TMD) and PTMD building systems, subjected to probabilistically scaled ground motions (Sommerville et al. 1997). Results are presented using appropriate log-normal statistics (Limpert et al. 2001) so that results could be put into a standard hazard and design framework. The goal is to validate MDOF analysis of the overall robustness and efficiency of this RTMD design concept in comparison to an equivalent, well recognized PTMD system.

2. 12-STORY CASE STUDY

2.1. Structural Modeling

To demonstrate the effects of the RTMD building system, realistic 12-story two-bay reinforced concrete framed structure models have been developed in Ruaumoko (Carr 2004). For large mass RTMD and PTMD systems, the upper two and four stories are isolated respectively. The resulting retrofitted structures are modeled as '10+2' story and '8+4' story structures, as shown in Figures 1(a) and 1(b). Figure 1(c) shows the schematic of the isolation layer including rubber bearings and viscous damper or resetable device.



(a) '10+2' model (b) '8+4' model (c) Schematic description of isolation layer

Figure 1. '10+2' and '8+4' models of 12-story two-bay reinforced concrete frames

The natural period of the lower part of the each frame model is 1.52sec for the 10-story structure and 1.19sec for the 8-story structure respectively. The structural damping ratio of each structure is assumed to be 5% of critical damping. The total weight of the TMD building structures (10+2 and 8+4 structures) is 19,190kN. The dynamic properties of the frames, including modal characteristics are listed in Table 1.

Table 1. Dynamic properties of 8-story, 10-story and 12-story buildings

Item	8-story	10-story	12-story	Unit
Weight	12,940	16,080	19,190	kN
1st Modal Mass	1,072	1,301	1,514	$kN\text{-}s^2/m$
Natural period	1.187	1.518	1.880	sec
Frequency	5.30	4.14	3.34	rad/sec
Damping Ratio	0.05	0.05	0.05	-
1st Modal Amplitude	1.309	1.343	1.366	-

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. The columns above the first level were specified to remain elastic in accordance with the strong column – weak beam concept. A width of the floor slab equal to 12 times its thickness was considered to contribute to the elastic stiffness of the beams. The slab thicknesses were 120mm for the framed structure. It was noted that under the considered structural properties and the ground excitations, the linear displacement response due to the first mode constitutes approximately 80%~90% of the total displacement response. Thus, the first mode is selected for the designs of the PTMD and RTMD systems.

2.2. Parametric TMD optimization

The optimum TMD parameters for MDOF structures have been shown to be nearly equal to the tuning ratio for a 2-DOF system with the same mass ratio of $\mu\Phi$. In this case Φ is the amplitude of the first mode of vibration for a unit modal participation factor computed at the location of the TMD (Sadek et al. 1997). The equation for the tuning ratio is thus obtained from the equation for the 2-DOF system by replacing μ by $\mu\Phi$.

$$f_{M2opt} = \frac{1}{1+\mu\Phi}\left(1-\xi_1\sqrt{\frac{\mu\Phi}{1+\mu\Phi}}\right) \tag{2.1}$$

The TMD damping ratio is also found to correspond approximately to the damping ratio computed for a SDOF system multiplied by Φ. The equation for the damping ratio is obtained by multiplying the equation for the 2-DOF system by Φ.

$$\xi_{M2opt} = \Phi\left(\frac{\xi_1}{1+\mu} + \sqrt{\frac{\mu}{1+\mu}}\right) \tag{2.2}$$

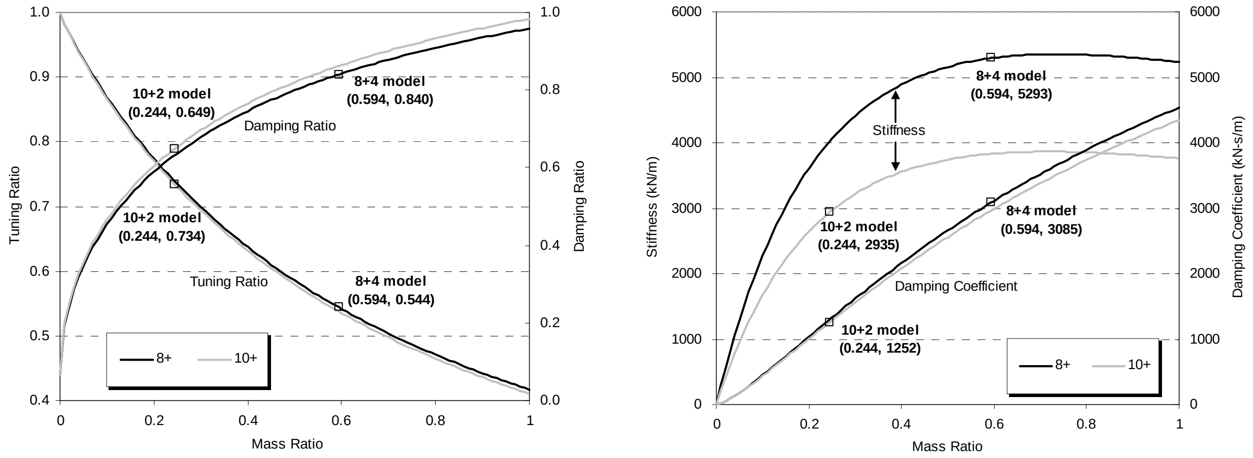
For the MDOF structures, the practical parameters of the optimal TMD stiffness and the optimal damping coefficient can therefore be derived respectively as

$$k_{M2opt} = m_2\omega_1^2 f_{M2opt}^2 = \frac{m_2\omega_1^2}{(1+\mu\Phi)^2}\left(1-\xi_1\sqrt{\frac{\mu\Phi}{1+\mu\Phi}}\right)^2 \tag{2.3}$$

$$c_{M2opt} = 2m_2\omega_1 f_{M2opt}\xi_{M2opt} = \frac{2m_2\omega_1}{1+\mu\Phi}\left(1-\xi_1\sqrt{\frac{\mu\Phi}{1+\mu\Phi}}\right)\left(\frac{\xi_1}{1+\mu} + \sqrt{\frac{\mu}{1+\mu}}\right) \tag{2.4}$$

Figure 2(a) shows the optimum passive TMD tuning and damping ratios against mass ratios of 0 to 1 with 5% of critical damping for 10+2 and 8+4 story models. The optimum values examined here have been marked by small squares on the lines at the mass ratios of 0.244 and 0.594 respectively. For the 10+2 and 8+4 models, the weights of the primary structures are 16,080kN (10-story) and 12,940kN (8-story), and the amplitude of the first modal vibration, Φ, of 1.343 and 1.309 are adopted, respectively. Figures 2(b) shows the optimum TMD stiffness and damping coefficient for the models.

The total value of k_{M2opt} is allocated to rubber bearing stiffness and the stiffness of the SA resetable device. According the results of 2-DOF analysis (Chey et al. 2007), the RTMD having same stiffness values of the resetable device and rubber bearings has been chosen and adopted for each structure and earthquake suite. This equivalent combined stiffness was chosen for simplicity and may not represent an optimal RTMD design (Mulligan 2006), where much lower stiffness values may be used.



(a) TMD tuning and damping ratios (b) TMD stiffness and damping coefficient

Figure 2. Optimum TMD parameters for different mass ratios (10+ and 8+ models with 5% of internal damping)

2.3. Semi-Active Resetable Device

The semi-active resetable device used in this research is the newly designed resetable device (Chase et al. 2006; Rodgers et al. 2007) with independent chambers which eliminates the need to rapidly dissipate energy from one side of the device to the other by using a two-chambered design that utilizes each piston side independently as shown in Figure 3. This approach treats each side of the piston as an independent chamber with its own valve and control, rather than coupling them with a connecting valve. This approach allows a wider variety of control laws to be imposed, as each valve can be operated independently. Thus, independent control of the pressure on each side of the piston is enabled, allowing a greater diversity of device behaviors.

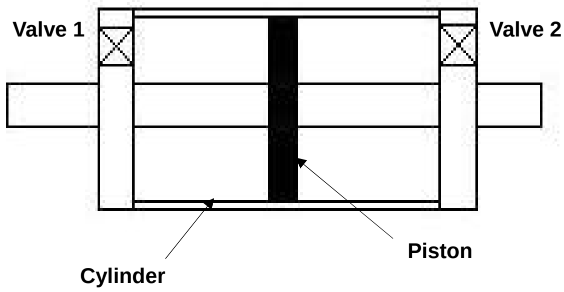
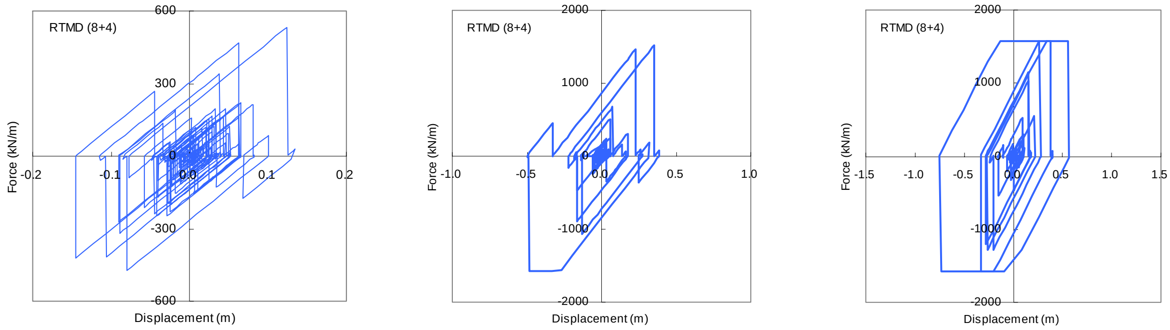


Figure 3. Schematic of independent chamber design.

To represent the effects of the resetable device properly, a 'Semi-Active Resetable Actuator Member' has been developed for the inelastic dynamic analysis program, Ruaumoko (Carr 2004). Figure 4 shows the example of the force-displacement loops for a modeled, ideal '8+4 RTMD' under three different levels of earthquake intensity. The maximum device forces are set at 644kN and 1,573kN, which represent the value of 13.8% (Hunt 2002) of the structural weight multiplied by mass ratios of 0.244 (10+2) and 0.594 (8+4), respectively. The force-displacement loops show that the force grows linearly with displacement until the maximum displacement is reached. At this point, the force drops indicating that the device has reset. The force then decreases linearly with decreasing displacement until the minimum is reached at which the force jumps to zero again showing that the device has once again reset. These loops represent basic, idealized resetable device operations (Barroso et al. 2003; Bobrow et al. 2000; Carr 2004; Hunt 2002; Jabbari and Bobrow 2002).



(a) Kern County (Low Suite) (b) Imperial Valley (Medium Suite) (c) Kobe (High Suite)

Figure 4. Hysteresis behavior of resetable device (8+4 models)

3. PERFORMANCE RESULTS

Figures 5 show the 50th percentile (median) and 84th percentile levels of several seismic response criteria of the No TMD, PTMD (10+2 and 8+4) and RTMD (10+2 and 8+4) as subjected to the medium suite of earthquakes. For comparison, the RTMD*(8+4) which used 33% of optimum TMD stiffness is also presented (Chey et al. 2007). The maximum relative displacements, interstory drift ratios, normalized story shear forces (shear forces divided by structural weight) and total accelerations for all floors are calculated as control effectiveness indices. Overall, the TMD building systems showed good response reduction quantities, and the ability of the SA device and the larger mass ratio to reduce overall structural response measures. In particular, the reduction of seismic demands for these cases is most pronounced in the 84th percentile responses.

The maximum displacements of each level increase steadily over the height of the level and the control effects of the displacement are proportional as the height of the building. Large displacements can be found at the isolation layer, especially in the RTMD system and this tendency has been expected from the previous modal properties of the almost separated modal responses and the increased participation factor of the 2nd mode. The better control effects of the RTMD and the higher mass ratio (8+4) building structures compared to the PTMD building system can be seen in the response of interstory drift and shear force at mid and higher floor levels. For the uncontrolled (No TMD) structure, the location of peak interstory drift occurs in the 9th floor. For the TMD building structures, however, the interstory drifts are distributed constantly or proportionally over the floor level under the suites.

The acceleration responses of the isolated stories of the upper segment have a significant reduction in all cases. The reason for these reductions is that the upper segment is isolated from the main structure, so the base excitation is not transferred to the separated upper portion directly. However, the acceleration response at the isolation interface of the RTMD system is clearly increased due to the operation of resetable device and this point needs to be considered in this type of TMD design.

To compare the relative ability of the different TMD building systems at reducing the seismic demands, the 50th percentile (median) and 84th percentile profiles of the structural reduction factors are generated for the TMD building systems in Figure 6. These multiplicative reduction factors are normalized to the corresponding uncontrolled floor response values.

For the response performance indices presented, the reduction factor profiles indicate the advantage of the structural operation of the PTMD and RTMD building systems clearly. Again, these factors reflect the relative control abilities among the TMD systems compared. The three percentile reduction factors and the bandwidth (84th–16th) of for interstory drift ratios and normalized story shear forces are compared in Tables 2 and 3. It can be seen that, however, the band width between 16th and 84th percentiles of RTMD(8+4)* is broader than RTMD(8+4) and this unexpected result needs to be considered in the future work.

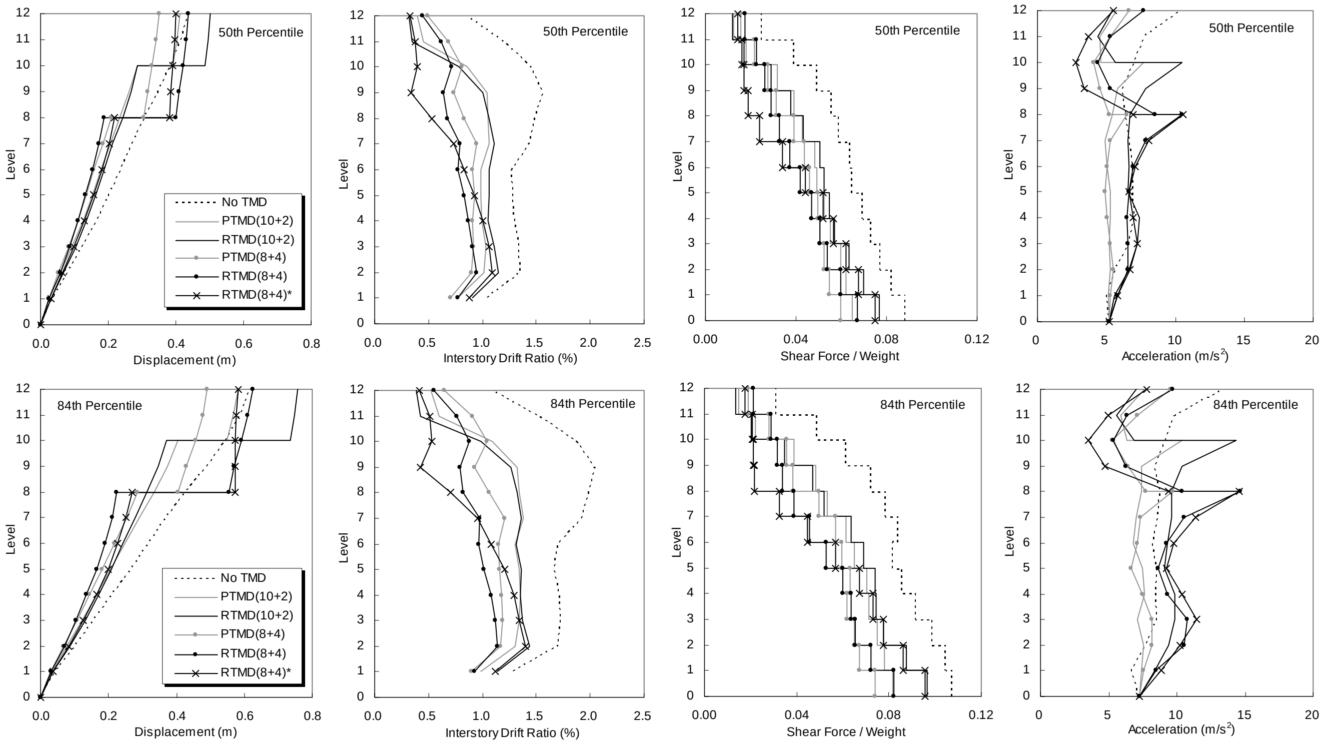


Figure 5. Control performance of ‘10+2’ and ‘8+4’ models (50th and 84th percentiles - Medium Suite)

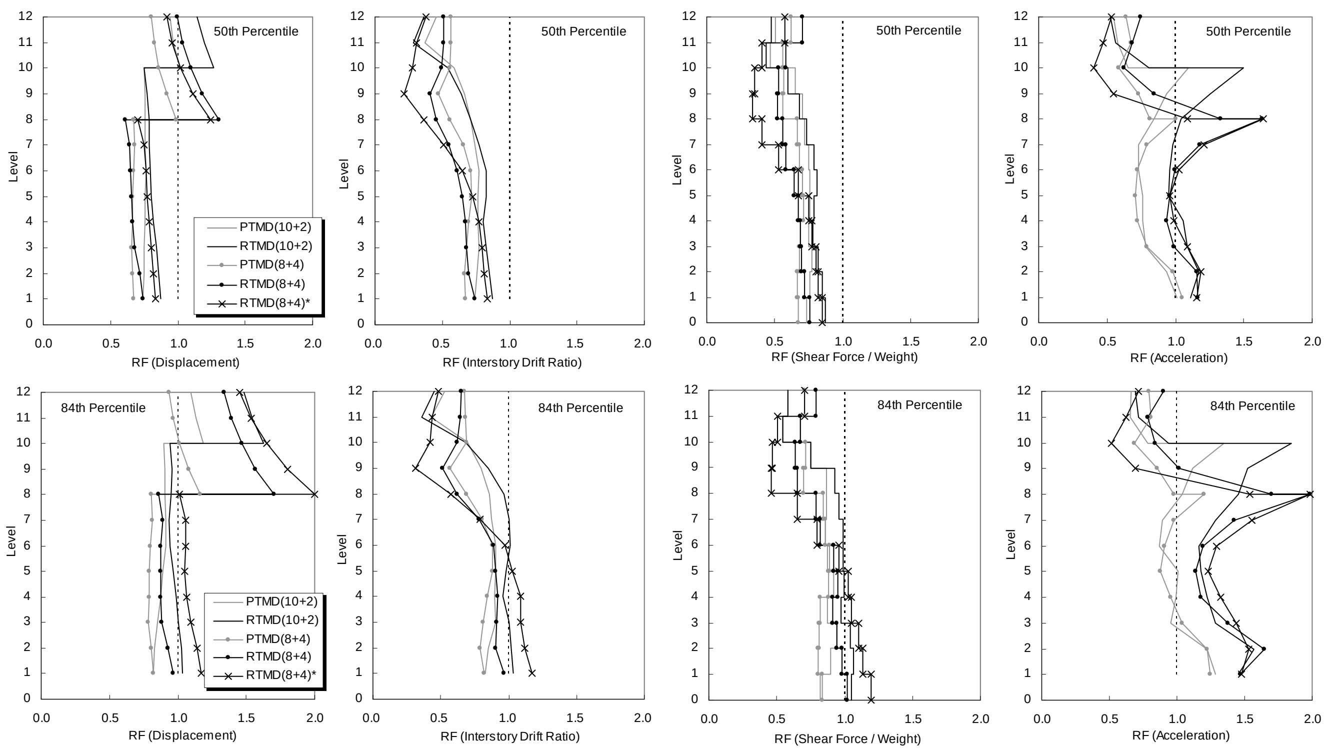


Figure 6. Response reduction factors of ‘10+2’ and ‘8+4’ models (50th and 84th percentiles - Medium Suite)

Table 2. Response reduction factors and band width of TMD (8+4) models (Interstory drift ratio)

TMD		PTMD(8+4)				RTMD(8+4)				RTMD(8+4)*			
Percentile		50th	16th	84th	B/W	50th	16th	84th	B/W	50th	16th	84th	B/W
Level	12	0.56	[0.47	0.67]	0.20	0.51	[0.40	0.65]	0.25	0.38	[0.29	0.48]	0.19
	11	0.56	[0.46	0.69]	0.23	0.51	[0.41	0.64]	0.23	0.31	[0.21	0.44]	0.23
	10	0.56	[0.45	0.69]	0.24	0.49	[0.39	0.62]	0.23	0.27	[0.18	0.42]	0.24
	9	0.47	[0.39	0.57]	0.18	0.41	[0.32	0.51]	0.19	0.22	[0.15	0.32]	0.17
	8	0.56	[0.45	0.69]	0.24	0.45	[0.33	0.62]	0.29	0.36	[0.22	0.57]	0.35
	7	0.66	[0.54	0.80]	0.26	0.55	[0.39	0.78]	0.39	0.51	[0.33	0.79]	0.46
	6	0.71	[0.58	0.88]	0.30	0.61	[0.42	0.89]	0.47	0.65	[0.43	0.97]	0.54
	5	0.72	[0.59	0.88]	0.29	0.65	[0.46	0.90]	0.44	0.72	[0.51	1.03]	0.52
	4	0.70	[0.58	0.84]	0.26	0.67	[0.49	0.92]	0.43	0.77	[0.55	1.08]	0.53
	3	0.68	[0.57	0.82]	0.25	0.68	[0.50	0.91]	0.41	0.79	[0.58	1.09]	0.51
	2	0.66	[0.56	0.79]	0.23	0.70	[0.54	0.91]	0.37	0.81	[0.59	1.12]	0.53
	1	0.67	[0.55	0.82]	0.27	0.74	[0.57	0.97]	0.40	0.84	[0.60	1.17]	0.57

Table 3. Response reduction factors and band width of TMD (8+4) models (Shear force / weight)

TMD		PTMD(8+4)				RTMD(8+4)				RTMD(8+4)*			
Percentile		50th	16th	84th	B/W	50th	16th	84th	B/W	50th	16th	84th	B/W
Level	12	0.62	[0.55	0.71]	0.16	0.70	[0.62	0.79]	0.17	0.58	[0.47	0.71]	0.24
	11	0.56	[0.46	0.67]	0.21	0.58	[0.50	0.68]	0.18	0.41	[0.33	0.51]	0.18
	10	0.56	[0.45	0.71]	0.26	0.53	[0.44	0.64]	0.20	0.35	[0.26	0.47]	0.21
	9	0.56	[0.45	0.69]	0.24	0.52	[0.42	0.66]	0.24	0.34	[0.24	0.46]	0.22
	8	0.66	[0.52	0.85]	0.33	0.56	[0.40	0.79]	0.39	0.40	[0.25	0.65]	0.40
	7	0.68	[0.54	0.86]	0.32	0.58	[0.41	0.82]	0.41	0.53	[0.35	0.80]	0.45
	6	0.71	[0.56	0.89]	0.33	0.64	[0.45	0.92]	0.47	0.68	[0.48	0.96]	0.48
	5	0.72	[0.58	0.88]	0.30	0.68	[0.48	0.95]	0.47	0.75	[0.54	1.03]	0.49
	4	0.69	[0.58	0.82]	0.24	0.69	[0.52	0.91]	0.39	0.77	[0.57	1.05]	0.48
	3	0.68	[0.57	0.81]	0.24	0.69	[0.51	0.94]	0.43	0.81	[0.59	1.10]	0.51
	2	0.67	[0.55	0.81]	0.26	0.72	[0.54	0.98]	0.44	0.82	[0.59	1.13]	0.54
	1	0.68	[0.55	0.84]	0.29	0.76	[0.56	1.02]	0.46	0.85	[0.61	1.19]	0.58

Finally, it should be noted that the PTMD results are optimal, but not necessarily practical. Specifically, the 60-80% damping ratio might not be really achieved as discussed in Chey et al. (Chey et al. 2007). Thus, similar RTMD results indicate that optimal level solutions can be obtained without resulting to infeasibly large non-linear viscous dampers.

4. CONCLUSIONS

This paper presents a case study on the seismic response of a multi-story passive and semi-active tuned mass damper building systems using probabilistically scaled suites of earthquake records. To demonstrate the effects of the PTMD and RTMD building systems model of a 12-story, two-bay reinforced concrete framed structure has been developed in Ruaumoko. From modal analysis, it has been found that the TMD building systems have the unique modal features to isolate the superstructure to be controlled effectively and the SA resetable devices provide a more advanced control function by anticipating to the isolation layer. The time history analyses and the normalized reduction factor results showed that TMD building systems present significant reductions on the control indices to all seismic hazards at the cost of increasing the acceleration at the isolation interface. This research has demonstrated the validity of the PTMD and RTMD building systems for consideration in future design and construction. Further studies are underway to investigate the inelastic seismic response of the structures based on the energy and damage indices.

REFERENCES:

Barroso, L. R., Chase, J. G., and Hunt, S. (2003). Resettable smart dampers for multi-level seismic hazard mitigation of steel moment frames. *Journal of Structural Control*, **10(1)**, 41-58.

Bobrow, J. E., Jabbari, F., and Thai, K. (2000). A new approach to shock isolation and vibration suppression using a resetable actuator. *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*, **122(3)**, 570-573.

Carr, A. J. (2004). RUAUMOKO. Computer Program Library, Department of Civil Engineering, University of Canterbury.

Charng, P. H. (1998). Base isolation for multistorey building structures, PhD, University of Canterbury, Christchurch.

Chase, J. G., Mulligan, K. J., Gue, A., Alnot, T., Rodgers, G., Mander, J. B., Elliott, R., Deam, B., Cleeve, L., and Heaton, D. (2006). Re-shaping hysteretic behaviour using semi-active resettable device dampers. *Engineering Structures*, **28(10)**, 1418-1429.

Chey, M. H., Carr, A. J., Chase, J. G., and Mander, J. B. (2006) Design of Semi-Active Tuned Mass Damper Building Systems using Resetable Devices. *8th Pacific Conference on Earthquake Engineering*, Singapore.

Hunt, S. J. (2002). Semi-active smart-dampers and resetable actuators for multi-level seismic hazard mitigation of steel moment resisting frames, ME, University of Canterbury, Christchurch, New Zealand.

Jabbari, F., and Bobrow, J. E. (2002). Vibration suppression with resettable device. *Journal of Engineering Mechanics*, **128(9)**, 916-924.

Kawamura, S., Sugisako, R., Ogura, K., Maezawa, S., Tanaka, S., and Yajima, A. (2000) Seismic isolation retrofit in Japan. *12th World Conference of Earthquake Engineering, Paper No. 2523*, Auckland, New Zealand.

Limpert, E., Stahel, W. A., and Abbt, M. (2001). Log-normal distributions across the sciences: Keys and clues. *Bioscience*, **51(5)**, 341-352.

Mulligan, K. J., Miguelgorry, M., Novello, V., Chase, J.G., Mander, J.B., Rodgers, G.W., Carr, A.J., Deam, B.L. and Horn, B. (2006) Semi-active Tuned Mass Damper Systems. *19th Australasian Conference on Mechanics of Structures and Materials (ACMSM)*, Christchurch, New Zealand.

Murakami, K., Kitamura, H., Ozaki, H., and Teramoto, T. (2000) Design and analysis of a building with the middle-story isolation structural stystem. *12th World Conference of Earthquake Engineering, Paper No. 0857*, Auckland, New Zealand.

Pan, T. C., and Cui, W. (1998). Response of segmental buildings to random seismic motions. *ISET Journal of Engineering Technology*, **35(4)**, 105-112.

Pan, T. C., Ling, S. F., and Cui, W. (1995). Seismic response of segmental buildings. *Earthquake Engineering & Structural Dynamics*, **24(7)**, 1039-1048.

Rodgers, G. W., Mander, J. B., Chase, J. G., Mulligan, K. J., Deam, B. L., and Carr, A. (2007). Re-shaping hysteretic behaviour - Spectral analysis and design equations for semi-active structures. *Earthquake Engineering & Structural Dynamics*, **36(1)**, 77-100.

Sadek, F., Mohraz, B., Taylor, A. W., and Chung, R. M. (1997). A method of estimating the parameters of tuned mass dampers for seismic applications. *Earthquake Engineering & Structural Dynamics*, 26(6), 617-635.

Sommerville, P., Smith, N., Punyamurthula, S., and Sun, J. (1997). Development of ground motion time histories for Phase Ⅱ of the FEMA/SAC steel project. *Report No. SAC/BD-97/04*.