USING UPPER STOREYS AS SEMI-ACTIVE TUNED MASS DAMPER BUILDING SYSTEMS – A CASE STUDY ANALYSIS

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ABSTRACT

This paper presents an exploratory case study based analysis of the seismic performance of multi-storey passive and semi-active tuned mass damper (PTMD and SATMD) building systems are investigated for 12-storey moment resisting frames modelled as '10+2' storey and '8+4' storey. 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 SATMD configurations are adopted from a companion 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 normalised reduction factor results show the response reductions for all seismic hazards. Thus, large SATMD 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 TMD building systems for consideration in future design and construction. It also provides a template for the design and analysis of passive or semi-active TMD buildings utilising large masses, or more efficiently, added storys, for improving seismic response performance.

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 PTMD and 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 MDOF verification.

The current study adopts multi-storey semi-active TMDs (SATMDs) that use segregated upper storeys as a relatively very large tuned mass and semi-active devices to provide robust adaptability to broader ranges of structural response and tuning.

For this case study analysis, the performance of 12-storey SATMD 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 can be incorporated into a standard seismic hazard and structural design framework. The overall goal is to validate MDOF analysis of the overall robustness and efficiency of this SATMD design concept in comparison to an equivalent, well recognised passive TMD (PTMD) system. In addition, the results are readily generalised and relevant to passive designs and similar approaches.

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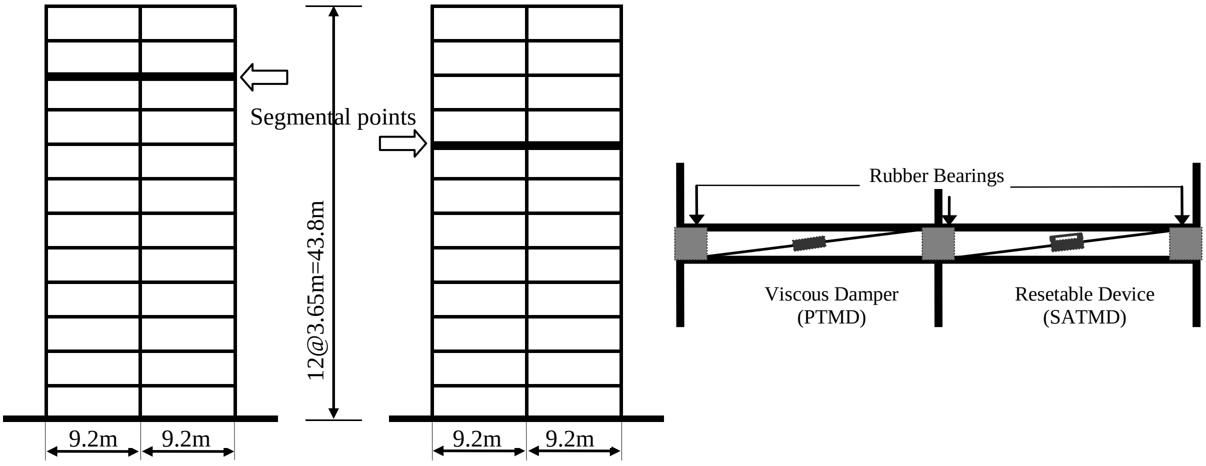
2 12-STOREY CASE STUDY

2.1 Structural Modelling

To demonstrate the effects of the SATMD building system, realistic 12-story two-bay reinforced concrete framed structure models have been developed in the non-linear time-history finite element analysis software package, Ruaumoko (Carr, 2004). For large mass SATMD and PTMD systems, the upper two and four storeys are isolated respectively. The resulting retrofitted structures are modelled as '10+2' storey and '8+4' storey structures, as shown in Figures 1a and 1b. Figure 1c 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-storey two-bay reinforced concrete frames.

The natural period of the lower part of the each frame model is 1.52sec for the 10 storey structure and 1.19sec for the 8 storey 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 19,190 kN. The dynamic properties of the frames, including modal characteristics are listed in Table 1.

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

Item	**8-storey**	**10-storey**	**12-storey**	**Unit**
Weight	12,940	16,080	19,190	kN
1st Modal Mass	1,072	1,301	1,514	kN-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 SATMD systems.

2.2 Parametric TMD optimisation

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 $\mu\Phi$.

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

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.

$$\xi_{M2opt} = \Phi\left(\frac{\xi_1}{1+\mu}+\sqrt{\frac{\mu}{1+\mu}}\right) \tag{2}$$

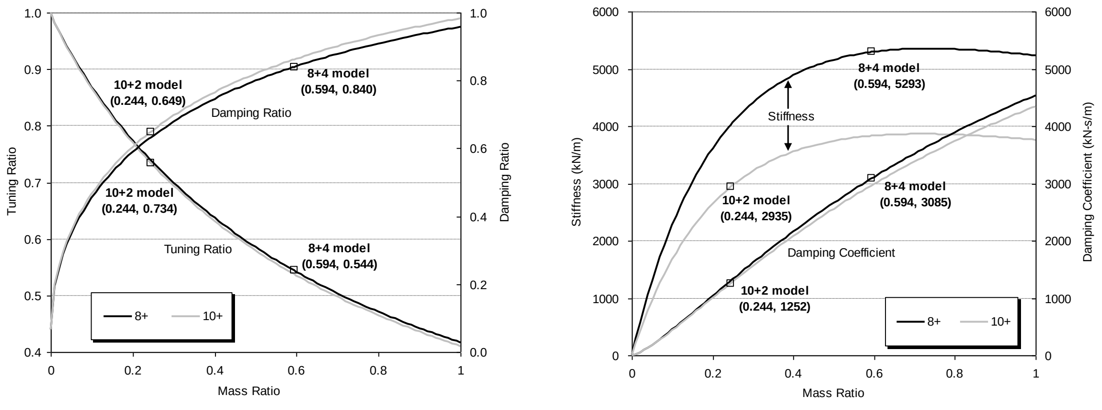
For the MDOF structures, the practical parameters of the optimal TMD stiffness and the optimal damping coefficient can therefore be derived respectively as:

$$k_{M2opt} = m_2\omega_1^{\ 2} f_{M2opt}^{\ \ 2} = \frac{m_2\omega_1^{\ 2}}{(1+\mu\Phi)^2}\left(1-\xi_1\sqrt{\frac{\mu\Phi}{1+\mu\Phi}}\right)^2 \tag{3}$$

$$\begin{aligned} c_{M2opt} &= 2m_2\omega_1 f_{M2opt}\xi_{M2opt} \\ &= \frac{2m_2\omega_1}{1+\mu\Phi}\left(1-\xi_1\sqrt{\frac{\mu\Phi}{1+\mu\Phi}}\right)\left(\frac{\xi_1}{1+\mu}-\sqrt{\frac{\mu}{1+\mu}}\right) \end{aligned} \tag{4}$$

Figure 2a 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 storey 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 16,080 kN (10 storey) and 12,940 kN (8 storey), and the amplitude of the first modal vibration, Φ, of 1.343 and 1.309 are adopted, respectively. Figures 2b shows the optimum TMD stiffness and damping coefficient for the models. It can be seen that the gaps between the optimum TMD stiffness lines for the two models are increased with the increase of mass ratio. However, just small gaps can be found between the optimum TMD damping coefficients for the two models. The resulting optimum parameters are listed in Table 2.

The total value of k_{M2opt} is allocated to rubber bearing stiffness and the stiffness of the SA resetable device. According the results from (Chey *et al.*, 2007) for 2-DOF analysis (system design), the SATMD 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 SATMD design (Mulligan, 2006).



(a) TMD tuning and damping ratios

(b) TMD stiffness and damping coefficient

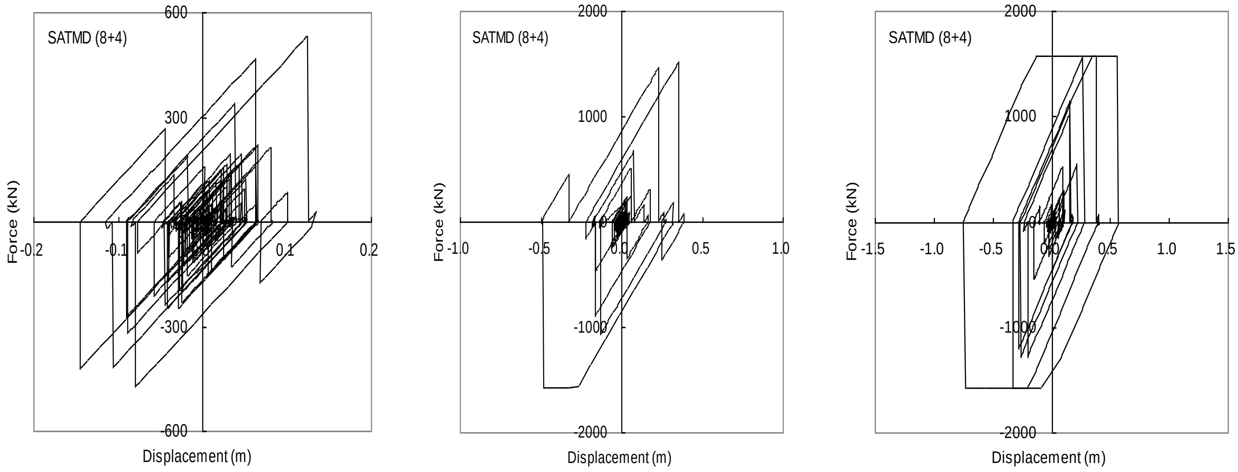
Figure 2: Optimum TMD parameters for different mass ratios (10+ and 8+ models with 5% of internal damping).

Table 2. Parameters for TMD building systems

Model	μ	f_{M2opt}	ξ_{M2opt}	k_{M2opt} (kN/m)	c_{M2opt} (kN-s/m)	Device force (kN)
PTMD(10+2)	0.244	0.734	0.649	2,935	1,252	-
SATMD(10+2)	0.244	0.734	-	2,935	-	644
PTMD(8+4)	0.594	0.544	0.840	5,293	3,085	-
SATMD(8+4)	0.594	0.544	-	5,293	-	1,573

2.3 Dynamics of Resetable Devices

Figure 3 shows the example of the force-displacement loops for a modelled, ideal ‘8+4 SATMD’ under three different levels of earthquake intensity. The maximum device forces are set at 644 kN and 1,573 kN, 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, idealised resetable device operations (Barroso *et al.*, 2003; Bobrow *et al.*, 2000; Carr, 2004; Hunt, 2002; Jabbari and Bobrow, 2002). Newer resetable devices can provide highly customised hysteresis loops (Chase, 2006; Rodgers, 2007). Finally, devices with up to 1.7 MN are already in use in limited numbers of commercial structures (Kurino *et al.*, 2006; Shmizu *et al.*, 2006).

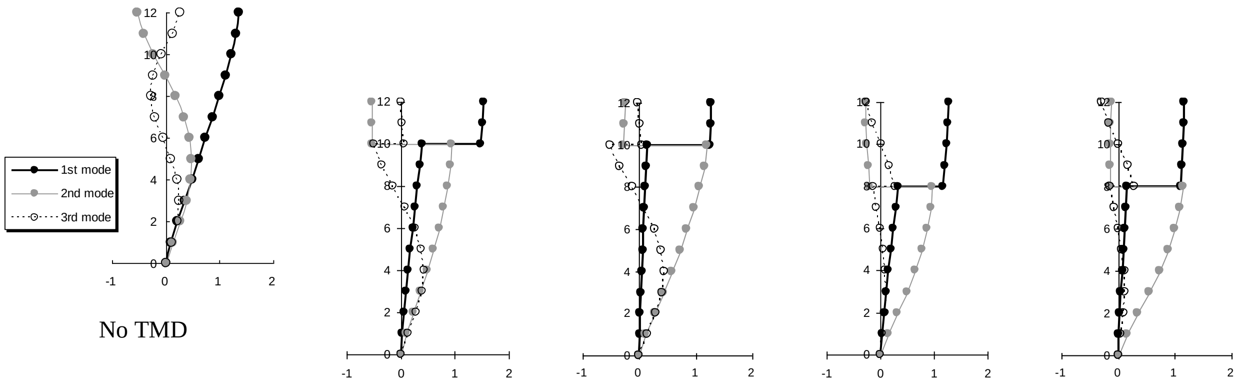


(a) Kern County (Low Suite)   (b) Imperial Valley (Medium Suite)   (c) Kobe (High Suite)

Figure 3: Hysteresis behaviour of resetable device (8+4 models).

3 MODAL ANALYSIS

Modal analysis results using Ruaumoko are shown in Figure 4. The TMD building systems now offer two major modes of vibration instead of one in the 12-storey uncontrolled (No TMD) case. Despite having two major modes and thus a system susceptible to receiving larger amounts of input energy from the earthquake, a relatively large portion of the entrapped energy is concentrated on the isolation layer. For the SATMD building systems, the 1st mode dominates the upper storeys and a much smaller magnitude 2nd mode dominates lower storeys. Thus, the both 1st and 2nd modes are decoupled by the isolation layer.



No TMD

PTMD(10+2) SATMD(10+2) PTMD(8+4) SATMD(8+4)

Figure 4: Modal analysis for TMD building systems.

These results indicate two different potential methods of dissipating energy. The PTMD dissipates energy via tuned absorption. The SATMD dissipates energy via enhanced relative motion obtained by decoupling the segments.

The parameter of modal participation factor for i^th mode is defined as:

$$\Gamma_i = \frac{L_i}{M_i} \tag{5}$$

where L_i is the earthquake excitation factor for i^th mode, and M_i is the generated modal mass of that mode. Another useful parameter for the modal analysis is the mass participation factor.

$$\beta_i = \frac{M_{eff,i}}{M} = \frac{1}{M}\frac{L_i^2}{M_i} \tag{6}$$

in which M_{eff} is the effective mass for the i^th mode and M is the total mass of the building. Because the effective mass indicates the importance of the contribution of the i^th mode to the total base shear acting on the structure, the mass participation factor can be an index showing how much of the total mass of the building will contribute in generating base shear in that mode. So, if the mass participation factor of the 1^st mode is much higher than that of the 2^nd mode, the 1^st mode can be readily excited by base excitation.

Table 3 shows the numerical results of the modal analysis. Second modal participation factors of the SATMD (10+2 and 8+4) building systems are closer to those of first mode and relatively larger than those of the second mode of PTMD. Furthermore, the second mass participation factors of the SATMD building systems are larger than those of the first modes. Therefore, in the SATMD building system, the interaction between the first and second modes is more pronounced and the relatively larger mode and mass participations of the second mode for the SATMD building system may contribute to the further reduction of the overall responses of displacement and base shear with these devices relying on relative motion, rather than relative velocity.

Table 3. Numerical results of modal analysis

TMD	**Mode**	**Mass ($kN\text{-}s^2/m$)**	**Frequency (rad/sec)**	**Participation Factor**	
				mode	**mass**
No TMD	1st	1514	0.53	1.37	0.805
	2nd	252	1.52	-0.53	0.134
	3rd	74	2.73	-0.27	0.039
PTMD (10+2)	1st	816	0.38	1.53	0.436
	2nd	812	0.74	0.94	0.434
	3rd	181	1.92	-0.50	0.097
SATMD (10+2)	1st	513	0.27	1.27	0.274
	2nd	1109	0.68	1.20	0.593
	3rd	187	1.90	-0.50	0.100
PTMD (8+4)	1st	1020	0.36	1.29	0.541
	2nd	697	0.96	0.97	0.370
	3rd	39	2.39	0.28	0.021
SATMD (8+4)	1st	834	0.27	1.17	0.442
	2nd	878	0.89	1.15	0.465
	3rd	47	2.33	-0.30	0.025

4 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 SATMD (10+2 and 8+4) as subjected to the medium suite of earthquakes. For comparison, the SATMD*(8+4) which used 33% of optimum TMD stiffness is also presented (Chey *et al.*, 2007). The maximum relative displacements, interstorey drift ratios, normalised storey 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 provide very good response reductions, and the ability of the SA device and the larger mass ratio to reduce overall structural response measures are very clear. 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 SATMD 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 SATMD and the higher mass ratio (8+4) building structures compared to the PTMD building system can be seen in the response of inter-storey drift and shear force at mid and higher floor levels. For the uncontrolled (No TMD) structure, the location of peak inter-storey drift occurs in the 9th floor. For the TMD building structures, however, the inter-storey drifts are distributed constantly or proportionally over the floor level under the suites.

The acceleration responses of the isolated storeys 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 SATMD 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 normalised 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 SATMD 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 inter-storey drift ratios and normalised storey shear forces are compared in Tables 4 and 5. It can be seen that, however, the band width between 16th and 84th percentiles of SATMD(8+4)* is broader than SATMD(8+4) and this unexpected result needs to be considered in the future work.

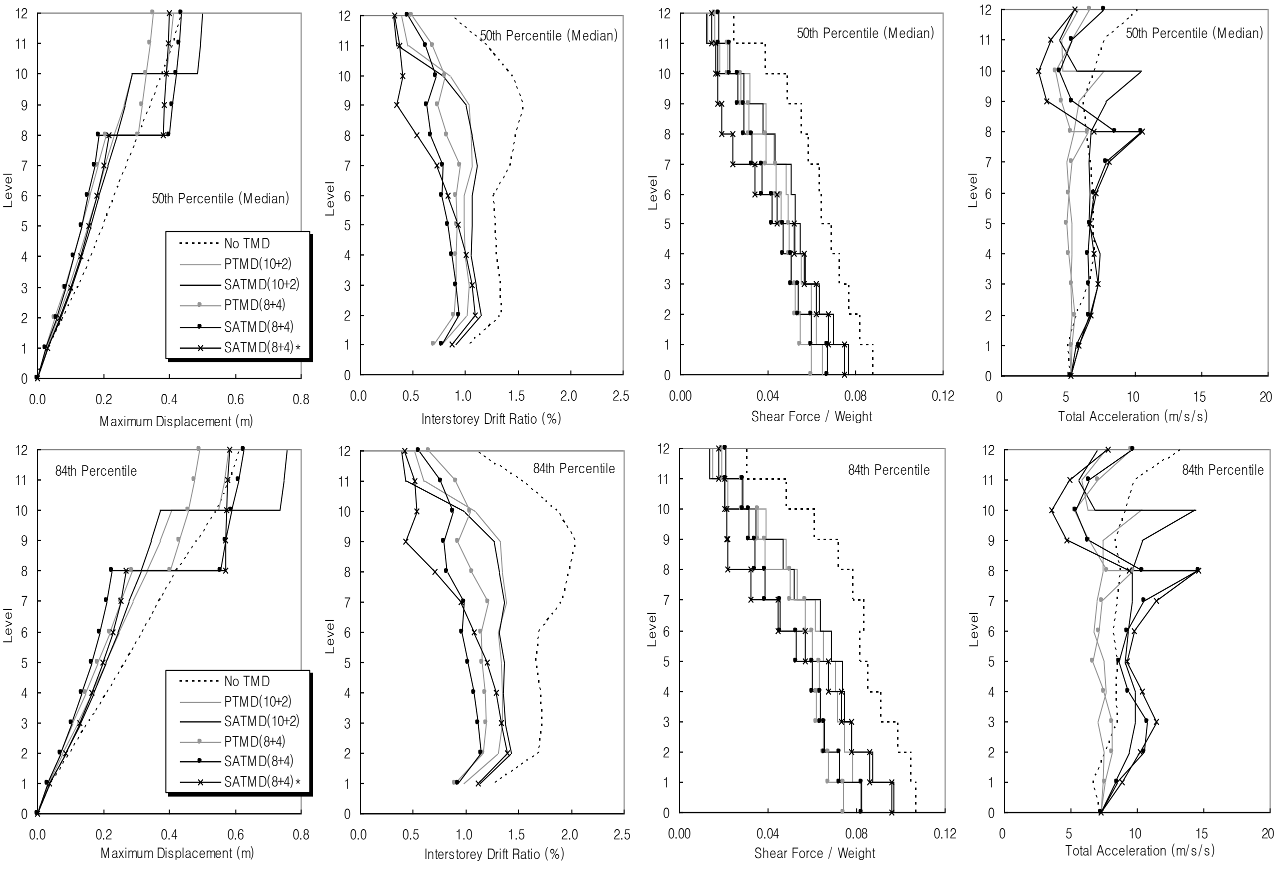


Figure 5: Control performance of '10+2' and '8+4' models (50th and 84th percentiles - Medium Suite).

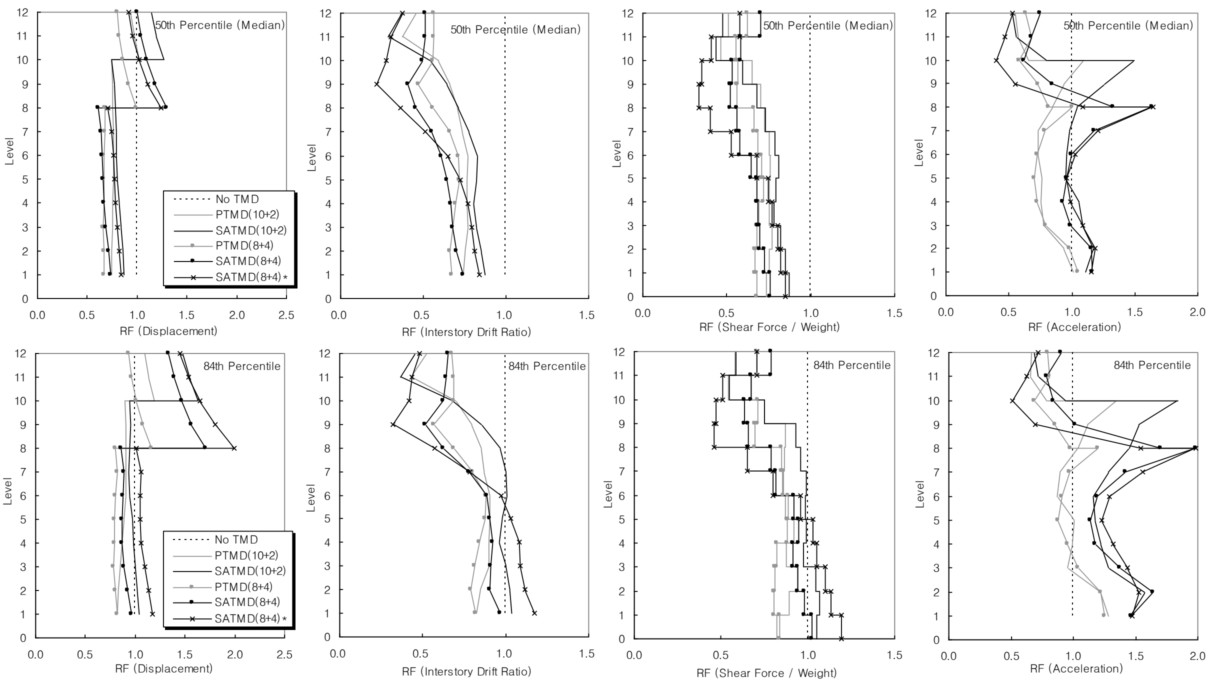


Figure 6: Response reduction factors of '10+2' and '8+4' models (50th and 84th percentiles - Medium Suite).

Table 4. Response reduction factors and bandwidth of TMD (8+4) models for inter-storey drift ratio (50th percentile with 16th and 84th range, and bandwidth (BW = 84th – 16th percentile reduction factors)).

TMD		PTMD(8+4)				SATMD(8+4)				SATMD(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 5. Response reduction factors and band width of TMD (8+4) models for normalised shear force (Shear force / weight), the data shows (50th percentile with 16th and 84th range, and bandwidth (BW = 84th – 16th percentile reduction factors)).

TMD		PTMD(8+4)				SATMD(8+4)				SATMD(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 SATMD results indicate that optimal level solutions can be obtained without resulting to unfeasibly large non-linear viscous dampers.

5 CONCLUSIONS

This paper presents an exploratory case study on the seismic response of a multi-storey passive and semi-active tuned mass damper building systems using probabilistically scaled suites of earthquake records. The primary goal is to demonstrate the effects of the PTMD and SATMD building systems model of a 12-storey, 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 normalised 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 SATMD 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 indices of the energy and damage.

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 Thesis*, University of Canterbury, Christchurch, 298 pp.

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., 2007. 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 Thesis*, 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.

Kurino, H., Yamada, T., Matsunaga, Y. and Tagami, J., 2006. Switching Oil Damper with Automatic Valve Operation System for Structural Control, *4th World Conference on Structural Control and Monitoring*, University of California, San Diego.

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, John B., Chase, J. Geoffrey , Mulligan, Kerry J., Deam, Bruce L. and Carr, Athol J., 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.

Shmizu, K., Orui, S. and Kurino, H., 2006. Observed Response of the High-Rise Building with Semi-Active Switching Oil Dampers to Earthquake and Typhoon, *4th World Conference on Structural Control and Monitoring*, University of California, San Diego.

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.