Design of Semi-Active Tuned Mass Damper Building Systems using Resetable Devices

M. H. Chey & A. J. Carr

Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

J. G. Chase

Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand.

J. B. Mander

Department of Civil Engineering, Texas A&M University, College Station, TX, USA.

ABSTRACT: Passive and Semi-Active Tuned Mass Damper (SATMD) building systems are proposed to mitigate structural response due to seismic loads. A structure's upper portion itself plays a role as a tuned mass and a viscous damper or a semi-active (SA) resetable device is adopted as a control feature for the Passive TMD (PTMD), creating a SATMD system. Two-degree-of-freedom (2-DOF) analytical studies are employed to design the prototype structural system, specify its element characteristics and determine its effectiveness for seismic response mitigation, including defining the resetable device dynamics. For the PTMD system realistic 15% and much higher optimal TMD damping ratios are compared. For the SATMD system the stiffness of the resetable device design is combined with and without rubber bearing stiffness. From the parametric results, the most effective SATMD system can be derived and then adopted as a practical control scheme. Response spectrum results using suites of earthquake are used to compare the SATMD scheme to an uncontrolled (No TMD) and an ideal passive tuned mass damper (PTMD) building system. The results from this design focused research will be utilised to assess the non-linear seismic response of realistic multi-degree-of-freedom (MDOF) structures.

1 INTRODUCTION

Semi-active (SA) control is emerging as an effective method of mitigating structural damage from large environmental loads, with three main benefits over active control and passive solutions. First, a large power or energy supply is not required to have a significant impact on the response. However, it can provide a broad adaptive feedback range of control. Semi-active systems are also strictly dissipative and do not add energy to the system, guaranteeing stability. Thus, they are better able to respond to changes in the structural behaviour, particularly due to non-linearity, damage or degradation over time, when compared to passive solutions.

Resetable devices were first introduced by Bobrow et al. (2000) and Jabbari and Bobrow (2002) who investigated the basic analytical techniques needed to characterise structural systems that use resetable devices for vibration suppression. Barroso et al. (2003) and Hunt (2002) presented a deeper investigation of resetable devices to mitigate structural response in the presence of hysteretic, geometric and yielding nonlinearities under various intensity level seismic hazard suites to define control efficiency and seismic hazard statistics. Furthermore, Chase et al. (2006) and Rodgers et al. (2007) proposed a series novel and improved device control laws, and presented results as cumulative hazard distribution based on responses to probabilistically scaled suites of ground motions from the SAC project (Sommerville et al., 1997).

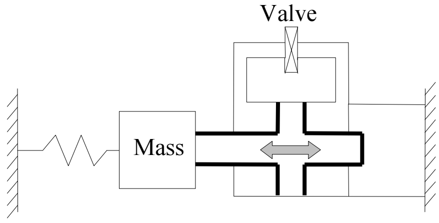
Meanwhile, to overcome the limitations of low TMD mass ratios, it has been suggested that using a portion of the building itself as a mass damper may be very effective. In particular, one idea is to use the building's top storey as a tuned mass. The concept of an 'expendable top storey' introduced by

Jagadish et al. (1979), or the ‘energy absorbing storey’ presented by Miyama (1992) is an effective alternative where the top storey acts as a vibration absorber for lower stories. Pan et al. (1995) and Charng (1998) sought to evaluate the effect of using segmental structures where isolation devices are placed at various heights in the structure, as well as at the base, to reduce the displacements imposed on each of the devices. Thus, a variety of research has examined using segments of the structure itself as a tuned mass for passive vibration mitigation.

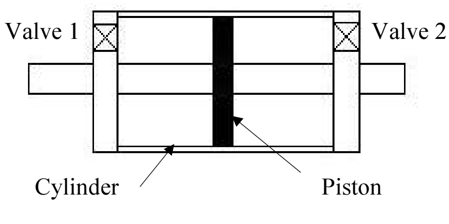
This paper defines a 2-DOF SATMD building system, in which resetable devices are incorporated for a structure divided into two segments. In this case, the interface represents or contains the isolation layer. For this study, the dynamic characteristics and seismic linear elastic responses are investigated and the results are compared with those from the corresponding uncontrolled (No TMD) and ideal passive (PTMD) building systems. The control effects of the TMD (PTMD and SATMD) systems are represented in the combined graphical plots of the time history analysis (2-DOF) and response spectrum (SDOF) analysis. To encompass a broad variety of earthquake ground motions, thirty earthquake events of three different probabilistic hazard intensity levels representing ground motions having low, medium and high probability of exceedance in 50 years for the Los Angeles area are used. Performance is thus evaluated statistically using log-normal distributions. The overall goal is thus to utilise response spectrum analysis to statistically quantify the potential of the SATMD concept relative to more traditional approaches.

2 RESETABLE DEVICE & TMD BUILDING SYSTEM

SA resetable devices are relatively reliable and simple devices which can act autonomously. Described fundamentally as a non-linear pneumatic spring element, the equilibrium position or rest length can be reset to obtain maximum energy dissipation from the structural system (Bobrow et al., 2000). Figure 1(a) shows the conventional resetable device configuration, with a single valve connecting the two sides. Unlike previous resetable devices, a recently developed design (Chase, 2005; Mulligan et al., 2005) eliminates the need to unrealistically dissipate energy between chambers. The two chamber design utilises each piston side independently, as shown in Figure 1(b). This new approach allows a wider variety of control laws to be imposed, as each valve can be operated independently allowing independent control of the pressure on each side. In this paper, a resetable device denoted a ‘1-4 device’ that provides damping in all four quadrants, is used for the SA control scheme as it provides dissipation over the entire SATMD motion as shown in Figure 2.



(a) Conventional resetable device (Bobrow et al., 2000)



(b) Two chamber resetable device (Chase, 2005; Mulligan et al., 2005)

Figure 1. Two types of resetable device

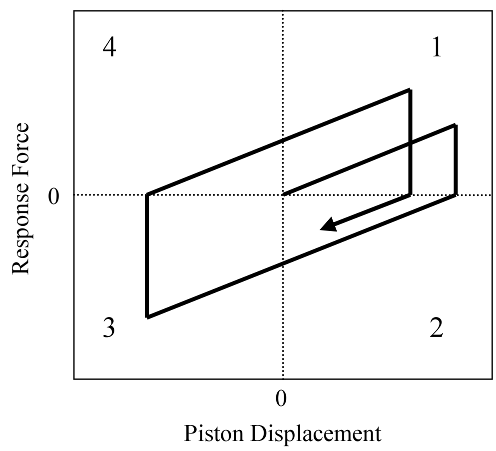


Figure 2. Hysteretic response of resetable device (Carr, 2004; Mulligan, 2006)

The suggested TMD building system concept can be defined as an extension of the conventional TMD system, but using a large mass ratio. The upper portion is supported by rubber bearings that are attached on the top of the main frame's columns, as shown schematically in Figure 3. The overall mechanism of suppressing structural vibration induced by an earthquake is to transfer the vibration energy of the structure to the isolated upper storey. The transferred energy is dissipated at the isolation interface. Thus, overall effectiveness depends on the amount of energy transferred or the size of the tuned mass, and the ability of the isolating elements (viscous damper or resetable device) to dissipate that energy via the relative motions at the interface.

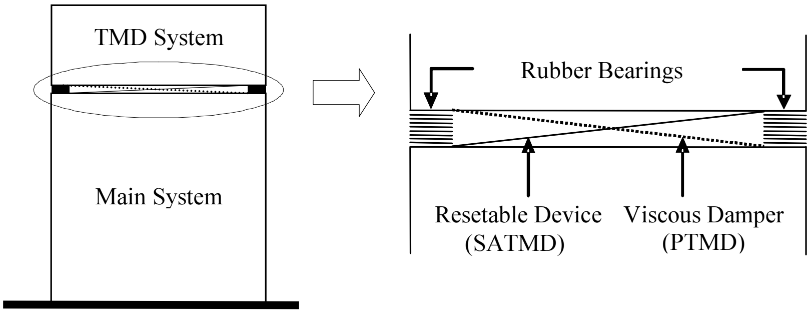
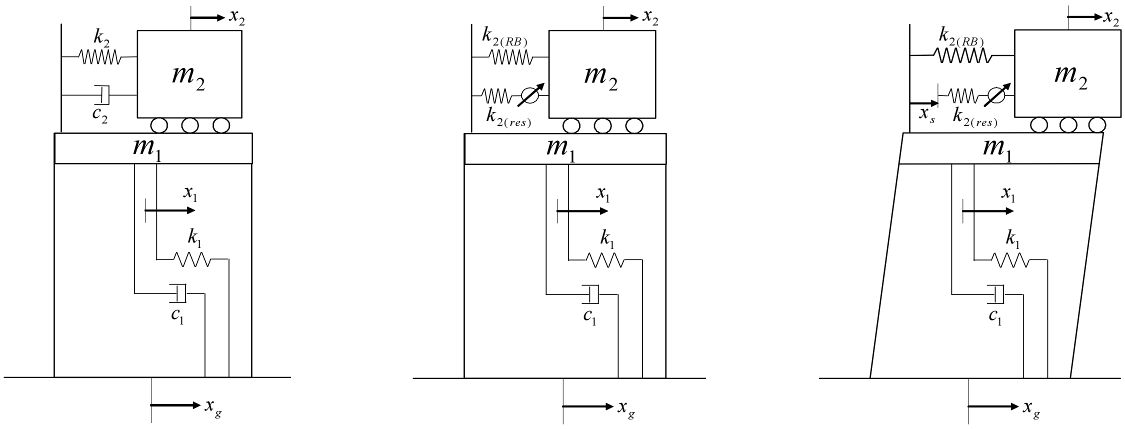


Figure 3. Schematic of model concept with resetable device and viscous damper used

3 STRUCTURAL MODELLING

3.1 Motion characteristics and equations

Being characterized by its mass, tuning and damping ratios, the PTMD system consists of a TMD connected by a spring and a viscous damper, as shown in Figure 4a. Figures 4b and 4c represent SATMD building systems including passive and resetable springs at the instants of rest and reset respectively. As the relative displacement between the main system and the SATMD increases, both springs (passive and resetable spring) stretch and work together against the relative motion of the SATMD. When the relative displacement reaches its maximum position, the velocity is zero and the resetable semi-active device resets, releasing the energy stored. Thus, the equilibrium position or unstretched length of the resetable spring is time variant. In contrast, the viscous damper-based PTMD acts for all motion.



(a) PTMD at rest (b) SATMD at rest (c) SATMD at reset

Figure 4. TMD building systems

For the 2-DOF PTMD and SATMD systems, the seismic equations are defined:

$$
\begin{aligned}
m_1\ddot{x}_1 &= -k_1(x_1 - x_g) - c_1(\dot{x}_1 - \dot{x}_g) + k_{2(RB)}(x_2 - x_1) + c_2(\dot{x}_2 - \dot{x}_1) \\
m_2\ddot{x}_2 &= -k_{2(RB)}(x_2 - x_1) - c_2(\dot{x}_2 - \dot{x}_1)
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
m_1\ddot{x}_1 &= -k_1(x_1 - x_g) - c_1(\dot{x}_1 - \dot{x}_g) + k_{2(RB)}(x_2 - x_1) + k_{2(res)}(x_2 - x_s) \\
m_2\ddot{x}_2 &= -k_{2(RB)}(x_2 - x_1) - k_{2(res)}(x_2 - x_s)
\end{aligned} \tag{2}
$$

where m_1 = mass of main system; m_2 = mass of TMD; k_1 = stiffness of main system; $k_{2(RB)}$ = stiffness of rubber bearings; $k_{2(res)}$ = stiffness of resetable device; c_1 = damping coefficient of main system; c_2 = damping coefficient of TMD; x_1 = displacement of main system; x_2 = displacement of TMD; x_g = displacement of ground and x_s = equilibrium position (unstretched length) of the resetable spring.

3.2 **Parametric optimisation and modelling of TMD systems**

Performance of TMD systems is usually assessed by parametric studies. Thus, optimal parameters, such as the frequency tuning ratio and damping ratio of the TMD, need to be determined to achieve the best performance. Sadek et al. (1997) derived the optimal parameters of frequency tuning and damping ratios for a large mass TMD. For high values of mass ratio, μ, it is likely that the TMD will not be an appendage added to the structure, but a portion of the structure itself, such as one or more upper storeys. According to Sadek et al., the equation of the optimal frequency tuning ratio, f_{2opt}, and the optimal damping ratio, ξ_{2opt}, of the TMD systems are defined:

$$
f_{2opt} = \frac{1}{1+\mu}\left(1 - \xi_1\sqrt{\frac{\mu}{1+\mu}}\right) \tag{3}
$$

$$
\xi_{2opt} = \frac{\xi_1}{1+\mu} + \sqrt{\frac{\mu}{1+\mu}} \tag{4}
$$

For practical application, it is necessary to obtain the resulting optimal TMD stiffness, k_{2opt} and optimal damping coefficient, c_{2opt}. These parameters can be derived using f_{2opt} and ξ_{2opt}.

$$
k_{2opt} = m_2\omega_1^{\,2} f_{2opt}^{\;\;2} = \left(\frac{\xi_1}{1+\mu}\sqrt{\frac{\mu}{1+\mu}} - 1\right)^2 \tag{5}
$$

$$
c_{2opt} = 2m_2\omega_1 f_{2opt}\xi_{2opt} = \frac{2m_2\omega_1}{1+\mu}\left(1 - \xi_1\sqrt{\frac{\mu}{1+\mu}}\right)\left(\frac{\xi_1}{1+\mu} - \sqrt{\frac{\mu}{1+\mu}}\right) \tag{6}
$$

where ω_1 is the frequency of the main system.

Figures 5 shows the optimum TMD stiffness and damping coefficient from the Equations (3) to (6) for three different periods of main system (T=1.19, 1.52 and 1.88sec) with the same structural damping, ξ_1. As expected, a TMD with both larger stiffness and larger damping is needed for larger mass rations, μ. From these trends, it can be predicted that there is no more increase in the TMD stiffness when the mass ratio is over 1.0, which is likely an unrealistic value. The effects of the damping ratio of the main system are amplified with increase in mass ratio. This tendency is increased for stiffer main structures having relatively short natural periods. A nearly linear increase in TMD damping coefficient is observed with increasing mass ratio, and it is also observed that there is nearly no effect of the damping ratio of the main structure (ξ_1) on the TMD damping coefficient for the fundamental natural periods examined.

An optimal TMD stiffness, k_{2opt}, is applied to the sum of the stiffness of the SA device and rubber bearings (SATMD) or to the whole stiffness of the rubber bearings (PTMD) in the transverse direction. Thus, the optimal stiffness of the semi-active system is assumed to be the same as for the passive TMD case, which may neglect or underuse certain qualities of the SA devices (Mulligan et al., 2005; Mulligan, 2005; Mulligan, 2006). This research uses basic hysteresis loops representing the idealised behaviours of the SA resetable device member used in Ruaumoko (Carr, 2004). This is an idealized element and several methods of further customizing these hysteresis loops have been presented (Chase, 2006; Rodgers, 2007).

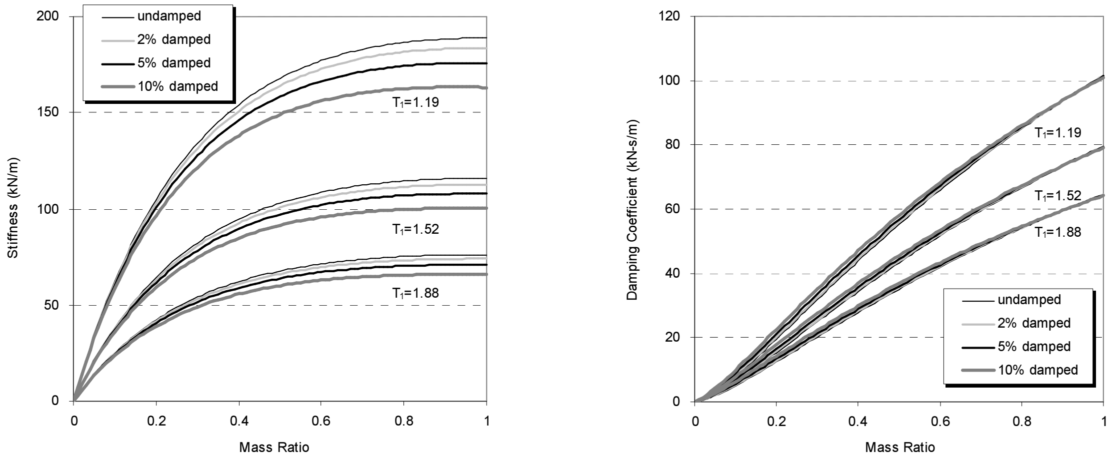


Figure 5. Optimum TMD parameters for different mass ratios and dampings of main system (m_1 =27.3kN)

4 EARTHQUAKE SUITES AND STATISTICAL ASSESSMENT

Statistical assessment of structural response is an important step in performance-based seismic design. Most prior research into active or semi-actively controlled structures employed either sinusoidal, random, single, or selected earthquake excitations to illustrate the benefits of control. As the characteristics of seismic excitation are entirely random and vary significantly, the use of a number of multiple time history records over a range of seismic levels is essential for effective controller evaluation. The three ground motion acceleration suites used here were developed by Sommerville el al. (Sommerville et al., 1997) for the SAC Phase II project. Each suite has, 10 pairs of recorded or generated ground motion accelerograms selected to fit the magnitude and distance characteristics of the seismic hazard at the LA site. The first suite represents ground motions for which the structural demand has a 50% chance of being exceeded in 50 years (Low suite). The second suite represents a 10% chance in 50 years (Medium suite) and the final (High) suite a 2% chance in 50 years. To reduce the computational requirements, the first of each of the 10 pairs of records (odd half) were used in this paper. To combine these results across the earthquakes in a suite, log-normal statistics are used (Hunt, 2002; Limpert et al., 2001).

5 2-DOF MODEL IMPLEMENTATION

5.1 Method of analysis

To demonstrate the proposed control methodology, 268kN weighted single degree of freedom (SDOF) linear models including 5% internal structural damping with natural periods of 1.19, 1.52 and 1.88 seconds are investigated. For these main systems, a mass ratio of 0.5 of the 1st modal mass of the TMD to the total mass of the main system is used. To assess the effect of the resetable device, the percentage of resetable device stiffness to the total optimal TMD stiffness is selected as 25% (SA25TMD), 50% (SA50TMD), 75% (SA75TMD), 100% (SA100TMD) and 33% (SA33TMD* without rubber bearing) of k_{2opt}. The 33% case examines a resetable device only system with relatively low stiffness.

Performance with No TMD, optimum PTMD, and off-optimum PTMD are compared with the SATMD cases. For the off-optimum PTMD, the TMD damping ratio (ξ_2) of 0.15 was used and this value is the realistic figure compared to the optimum one of 0.611, so that the reliability of the optimum parameters can be estimated. Also, this value represents relatively maximum amount of damping that can be obtained practically, and is thus reasonable for broad comparison of various SATMD cases. The TMD parameters used for each case obtained from Equations (3) to (6) are listed in Table 1.

Table 1. Parameters for TMD system (μ =0.5)

Period (sec)	TMD	f_{2opt}	ξ_{2opt}	k_{2opt} (kN/m)	c_{2op} (kN-s/m)
1.19	PTMD(off)	0.647	0.150	158.7	14.0
	PTMD(on)	0.647	0.611	158.7	56.9
	SATMDs	0.647	-	158.7	-
	SA33TMD*	0.647	-	52.8	-
1.52	PTMD(off)	0.647	0.150	97.4	10.9
	PTMD(on)	0.647	0.611	97.4	44.6
	SATMDs	0.647	-	97.4	-
	SA33TMD*	0.647	-	32.4	-
1.88	PTMD(off)	0.647	0.150	63.7	8.8
	PTMD(on)	0.647	0.611	63.7	36.0
	SATMDs	0.647	-	63.7	-
	SA33TMD*	0.647	-	21.2	-

To demonstrate the relative control effects of the TMD systems, performance is evaluated statistically from the individual structural responses for the 10 seismic records within each suite (low, medium and high). All controlled displacement and acceleration values are examined and reduction factors (RF) normalised to the uncontrolled (No TMD) result are evaluated. Reduction factors more clearly indicate effect and are more readily incorporated into performance-based design methods when using suites of probabilistically scaled events (Rodgers, 2007). Thus, the response reduction factors for PTMD (off and on), SA33TMD* (without rubber bearing) and SATMDs for low, medium and high suites are presented.

To indicate the range of spread of results over a suite at a given natural period, the 16th, 50th and 84th percentiles are used. The values of median (50th percentile) and the width, which is the spread between the 16th and 84th percentiles, are taken for each period. Thus, a specific system would be considered more robust to different events if the width between the 16th and 84th percentile curves is small. Thus, a 'Standard Error of Control (SEC)' can be defined:

$$SEC = \frac{RF(84^{th}) - RF(16^{th})}{RF(50^{th})} \tag{7}$$

where $RF(16^{th})$, $RF(50^{th})$ and $RF(84^{th})$ are the reduction factors (RF) normalised to the No TMD for each percentile respectively. Thus, the best trade off between band width reduction and response reduction can be determined.

5.2 Performance results

Response spectra are generated for the structural displacement and acceleration at natural periods of T = 1.19, 1.52 and 1.88sec under the three suites of ground motions. Figure 6 and 7 present the displacement and acceleration response reduction factors. The solid lines represent the reduction factors, while the grey lines represent the resulting SEC value, as the upper, central and lower curves represent the 84th, 50th and 16th percentiles.

Even though control efficiency is not too different, the SATMD systems around SA50TMD showed relatively better displacement reductions than other SATMD cases. Especially, the SA33TMD* system shows a much smaller bandwidth and SEC value than any of the TMD systems, indicating an improvement in performance and robustness. From Figure 7, it can be found that all the SATMD cases reduced acceleration response. However, this reduction is less than that of the PTMD systems (especially, optimum PTMD), due to TMD damping provided.

Table 2 show the lists of statistical final outcomes of the response reduction factors from the uncontrolled (No TMD) systems for each TMD case and natural period. For the SATMD, in these tables, the case showing best response reduction factor based on 50^{th} percentile is listed for each main system and the percentile values of 16^{th} and 84^{th} are also listed as bracketed form.

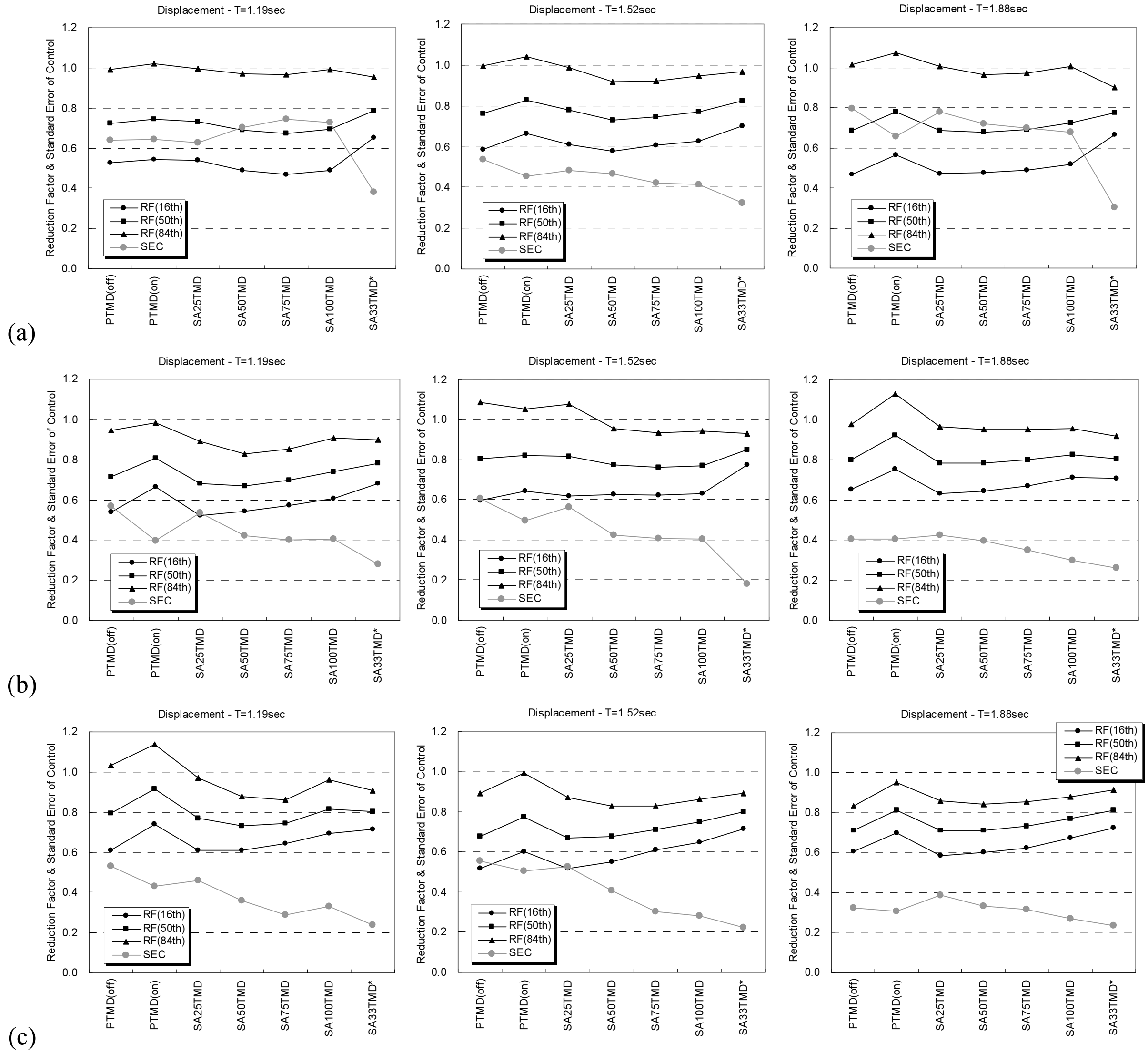


Figure 6. Displacement reduction factors and standard error of control – (a) Low (b) Medium and (c) High suites

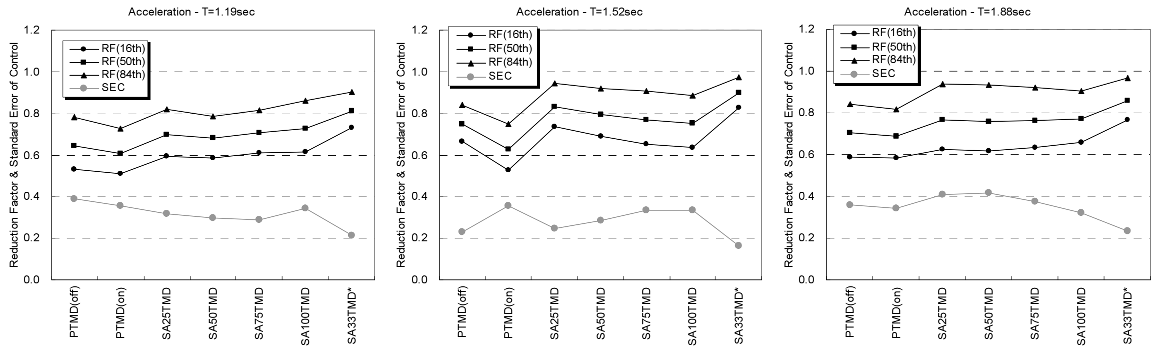


Figure 7. Acceleration reduction factors and standard error of control – Medium suite

For all the TMD systems, again, the values of SEC for the SA33TMD* systems shows remarkable small values when compared to any other system. More importantly, the 84^{th} percentile for the PTMD systems is greater than 1.0 indicating that some events lead to increased response. In contrast, and reflecting low SEC values, the SATMD systems are all lower than 1.0 indicating the robustness to all types of events.

Table 5. Displacement reduction factors of TMD systems

Suite	Period (sec)	RF (Displacement)					RF (Acceleration)				
		TMD	Reduction Factor			SEC	TMD	Reduction Factor			SEC
			50^{th}	[16^{th}	84^{th}]			50^{th}	[16^{th}	84^{th}]	
Low	1.19	PTMD(off)	0.723	[0.527	0.990]	0.640	PTMD(off)	0.668	[0.507	0.881]	0.559
		PTMD(on)	0.744	[0.542	1.022]	0.645	PTMD(on)	0.569	[0.417	0.777]	0.632
		SA75TMD	0.672	[0.467	0.967]	0.744	SA100TMD	0.678	[0.475	0.968]	0.728
		SA33TMD*	0.788	[0.651	0.953]	0.382	SA33TMD*	0.833	[0.691	1.003]	0.375
	1.52	PTMD(off)	0.762	[0.584	0.993]	0.537	PTMD(off)	0.703	[0.560	0.881]	0.457
		PTMD(on)	0.829	[0.662	1.038]	0.454	PTMD(on)	0.645	[0.520	0.800]	0.433
		SA50TMD	0.729	[0.578	0.918]	0.466	SA75TMD	0.739	[0.581	0.941]	0.487
		SA33TMD*	0.823	[0.701	0.966]	0.322	SA33TMD*	0.869	[0.769	0.984]	0.249
	1.88	PTMD(off)	0.687	[0.466	1.013]	0.796	PTMD(off)	0.669	[0.511	0.875]	0.543
		PTMD(on)	0.777	[0.563	1.073]	0.656	PTMD(on)	0.620	[0.453	0.848]	0.638
		SA50TMD	0.677	[0.476	0.963]	0.721	SA75TMD	0.719	[0.538	0.962]	0.589
		SA33TMD*	0.773	[0.664	0.900]	0.305	SA33TMD*	0.821	[0.720	0.937]	0.265
Medium	1.19	PTMD(off)	0.713	[0.539	0.945]	0.569	PTMD(off)	0.645	[0.531	0.782]	0.389
		PTMD(on)	0.809	[0.665	0.985]	0.396	PTMD(on)	0.608	[0.510	0.725]	0.354
		SA50TMD	0.670	[0.543	0.826]	0.422	SA50TMD	0.680	[0.586	0.787]	0.296
		SA33TMD*	0.783	[0.681	0.899]	0.279	SA33TMD*	0.811	[0.730	0.902]	0.211
	1.52	PTMD(off)	0.804	[0.596	1.084]	0.608	PTMD(off)	0.747	[0.666	0.839]	0.231
		PTMD(on)	0.823	[0.673	1.052]	0.498	PTMD(on)	0.629	[0.527	0.750]	0.356
		SA75TMD	0.764	[0.624	0.935]	0.407	SA100TMD	0.751	[0.624	0.935]	0.335
		SA33TMD*	0.849	[0.775	0.929]	0.231	SA33TMD*	0.900	[0.829	0.967]	0.162
	1.88	PTMD(off)	0.799	[0.654	0.975]	0.402	PTMD(off)	0.703	[0.588	0.840]	0.359
		PTMD(on)	0.921	[0.753	1.126]	0.405	PTMD(on)	0.689	[0.581	0.817]	0.342
		SA50TMD	0.782	[0.643	0.951]	0.395	SA50TMD	0.760	[0.618	0.934]	0.416
		SA33TMD*	0.805	[0.707	0.916]	0.260	SA33TMD*	0.860	[0.765	0.966]	0.233
High	1.19	PTMD(off)	0.795	[0.612	1.033]	0.530	PTMD(off)	0.695	[0.603	0.801]	0.285
		PTMD(on)	0.918	[0.741	1.136]	0.430	PTMD(on)	0.663	[0.536	0.821]	0.431
		SA50TMD	0.733	[0.612	0.877]	0.362	SA25TMD	0.738	[0.653	0.833]	0.244
		SA33TMD*	0.805	[0.715	0.906]	0.237	SA33TMD*	0.847	[0.772	0.928]	0.184
	1.52	PTMD(off)	0.679	[0.517	0.893]	0.554	PTMD(off)	0.634	[0.519	0.773]	0.400
		PTMD(on)	0.774	[0.602	0.995]	0.507	PTMD(on)	0.580	[0.463	0.725]	0.452
		SA25TMD	0.671	[0.518	0.871]	0.525	SA50TMD	0.698	[0.596	0.818]	0.319
		SA33TMD*	0.800	[0.716	0.894]	0.222	SA33TMD*	0.846	[0.767	0.933]	0.196
	1.88	PTMD(off)	0.711	[0.604	0.836]	0.325	PTMD(off)	0.694	[0.593	0.812]	0.316
		PTMD(on)	0.814	[0.698	0.950]	0.309	PTMD(on)	0.631	[0.554	0.719]	0.262
		SA25TMD	0.710	[0.586	0.861]	0.386	SA75TMD	0.768	[0.678	0.869]	0.250
		SA33TMD*	0.814	[0.724	0.916]	0.235	SA33TMD*	0.887	[0.800	0.983]	0.207

6 CONCLUSION

SATMD system with reasonable combination of TMD parameters provides a better control strategy than PTMD systems, especially if the optimum stiffness of TMD is not ideal or perfect due to degradation or mismodelling of the building. Thus, more effective parameter combinations may be available beyond the scope of this initial spectral parametric analysis. Semi-active solutions are also not constrained to the optimum stiffness of TMD and its control ability is improved when the value of less stiffness is used, providing robust and effective seismic energy management. Thus, the SATMD system is easier to design as the tuning of the system to the structure, by altering the stiffness value, is not as critical as for the PTMD system where slight "out-of-tunig" can have a detrimental effect. Thus, there is also good potential for SATMD building concept, especially in retrofit where lack of space constrains development to expand upward.

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