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Analytical modelling and MDOF response considerations for semi-active tuned mass damper building systems subjected to earthquake excitation

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Abstract

Passive and Semi-Active Tuned Mass Damper (PTMD and SATMD) building systems can reduce structural response due to earthquake excitation. The structure's upper portion can be used either as a passive TMD, or as a semi-active resetable device in a SATMD system. The seismic performance of multi-story passive and semi-active tuned mass damper (PTMD and SATMD) building systems are investigated for 12-story moment resisting frames modeled as '10+2' stories and '8+4' stories. Segmented upper stories are isolated to act as the tuned mass. Passive viscous damper or semi-active resetable devices are evaluated using an energy dissipation strategy based on an optimal TMD design stiffness and damping value. The semi-active approach uses feedback control to alter or manipulate the reaction forces, effectively re-tuning the system depending on the structural response. Statistical performance metrics are presented for 30 earthquake records from the 3 suites of the SAC project. Time history analyses are used to compute response reduction factors across a wide range of seismic hazard intensities. Results show that SATMD systems can effectively manage seismic response for multi-degree-of freedom (MDOF) systems across a broader range of ground motions in comparison to passive solutions. Specific results include the identification of differences in the mechanisms by which SATMD and PTMD systems remove energy, based on the differences in the devices used. Less variability is also seen for the SATMD systems, indicating an increased robustness.

Key words: Semi-Active, TMD, Segmented Structures, Seismic Response.

1. Introduction

TMD systems are practical, well accepted, systems for the structural control particularly of tall buildings. Their added mass, together with properly tuned spring and damping elements, provide a frequency-dependent hysteresis that increases damping in the primary structure. The mechanism of suppressing structural vibrations by attaching a TMD to the structure is to transfer the vibration energy of the structure to the TMD and to dissipate the energy in the damper of the TMD. A number of TMDs have been installed in tall buildings, bridges, towers, and smoke stacks for response control.

The passive TMD (PTMD) is undoubtedly a simple, inexpensive and somewhat reliable means to suppress the undesired vibrations. However, one of the limitations of the TMD design is the narrow bandwidth of the frequency tuned control. The difficult of tuning the TMD frequency to the controlled frequency of a structure means that the PTMD is not entirely reliable or robust despite its passive nature. Furthermore, the method used to support the large added mass and provide precise frequency control is an important issue in the design of a TMD. Thus, the ultimate performance of the TMD system is limited by the size of the additional mass, which is typically 0.25~1.0% of the building's weight in the fundamental mode.

In an attempt to increase the performance of the TMD, active TMD (ATMD) systems have been proposed [1-6]. However, ATMDs are more complex and are considered less reliable than passive systems, limiting implementation to special certain cases. To overcome these limitations, it has been suggested that using a portion of the building itself as a tuned mass may be more effective, either passively or via emerging semi-active devices, which might provide greater robustness and control quality as seen in recent analytical spectral analysis studies [7, 8].

2. Resetable Devices and Multi-Story SATMD System Models

This research uses novel resetable devices that can independently control the hysteretic response of the structure. In particular, details can be found in [9] with spectral analyses also presented in recent works to show their effectiveness. Not covered in this work, detailed design, analysis and dynamics of these devices are covered in several references [8-10].

A 12-story, two-bay reinforced concrete framed structure is used to demonstrate the potential and beneficial effects of TMD building systems [11]. This model was designed originally according to the New Zealand Loadings Code [12] based on the concept of capacity design. For SATMD and PTMD systems, the upper two and four stories are isolated. The resulting retrofitted structures are thus modeled as '10+2' story and '8+4' story structures, as shown in Figure 1.Figure 2 shows the schematic description of isolation layer including rubber bearings and viscous damper or resetable device. The member sizes adopted in this study are shown in Table 1. The dynamic properties of the uncontrolled 8-story and 10-story frames under the isolation layer are listed in Table 2.

Table 1: Frame member sizes

Members	Level	Dims. (mm)
Beams	1 – 6	900 × 400
	7 – 8	850 × 400
	9 – 12	800 × 400
Exterior Columns	1 – 6	775 × 500
	7 – 8	750 × 500
	9 – 12	650 × 500
Interior Column	1 – 6	800 × 800
	7 – 8	725 × 725
	9 – 12	675 × 675

Table 2: Frame dynamic properties

	8-story	10-story	Unit
Weight	12,940	16,080	kN
1st Mode Mass	1,072	1,301	ton
Natural period	1.187	1.518	sec
Frequency	5.30	4.14	rad/sec
Damping Ratio	0.05	0.05	-
1st Mode Amplitude	1.309	1.343	-

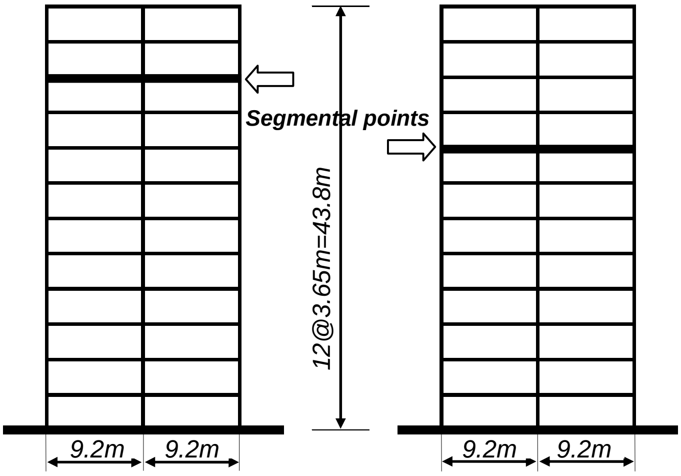

Figure 1: ‘10+2’ and ‘8+4’ models of 12-story two-bay reinforced concrete frames

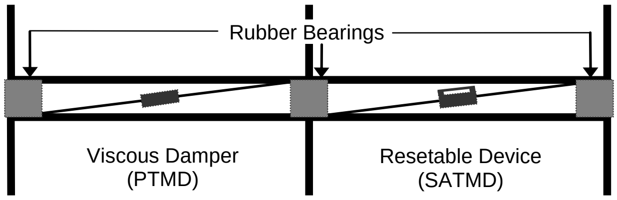

Figure 2: Schematic description of isolation layer

For the optimum TMD parameters, the tuning ratio for a MDOF system was found to be nearly equal to the tuning ratio for a 2-DOF system for a mass ratio of μΦ, where Φ is the amplitude of the first mode of vibration for a unit modal participation factor computed at the location of the TMD [13]. Thus, the tuning and damping ratios are obtained from the equations for the 2-DOF system by replacing μ by μΦ. Thus:

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

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

The practical parameters TMD stiffness and the damping coefficient are thus:

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

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

The resulting optimum parameters are listed in Table 3. The value of k_{M2opt} is allocated to rubber bearing stiffness and the stiffness of the SA resetable device. This equivalent combined stiffness was chosen for simplicity and may not represent an optimal SATMD design [14], where much lower stiffness values may be used.

To demonstrate performance, inelastic nonlinear time history analyses, including the nonlinear effects of (i) P-delta effects and a (ii) modified Takeda hysteresis model, are used. Interstory drift ratio and structurally dissipated hysteretic energy are presented to evaluate performance, and specifically to show response performance (reduction) and improvements in potential damage by reductions in the structurally dissipated energy. The results are generated via nonlinear simulation using Ruaumoko™ software

Table 3: Parameters for the TMD building systems studied

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

For robustness, multiple time history records over a range of seismic levels are used from the SAC Phase II project [15]. Each suite has 20 pairs of records with probabilities of occurrence of 2% in 50 years (High Suite), 10% in 50 years (Medium Suite) and 50% in 50 years (Low Suite). Ten records from the odd half (1, 3, …) are used. For analysis, log-normal statistics are used [16, 17] and the 50th percentile, and 84th percentile results presented for simplicity.

3. Results

3.1 Interstory Drift Ratio Results

Figures 3 and 4 show the 50th and 84th percentile interstory drift results over all 3 suites analysed for each system. The left and right top plots show the Low and Medium suite results. The bottom and third plot shows the High suite.

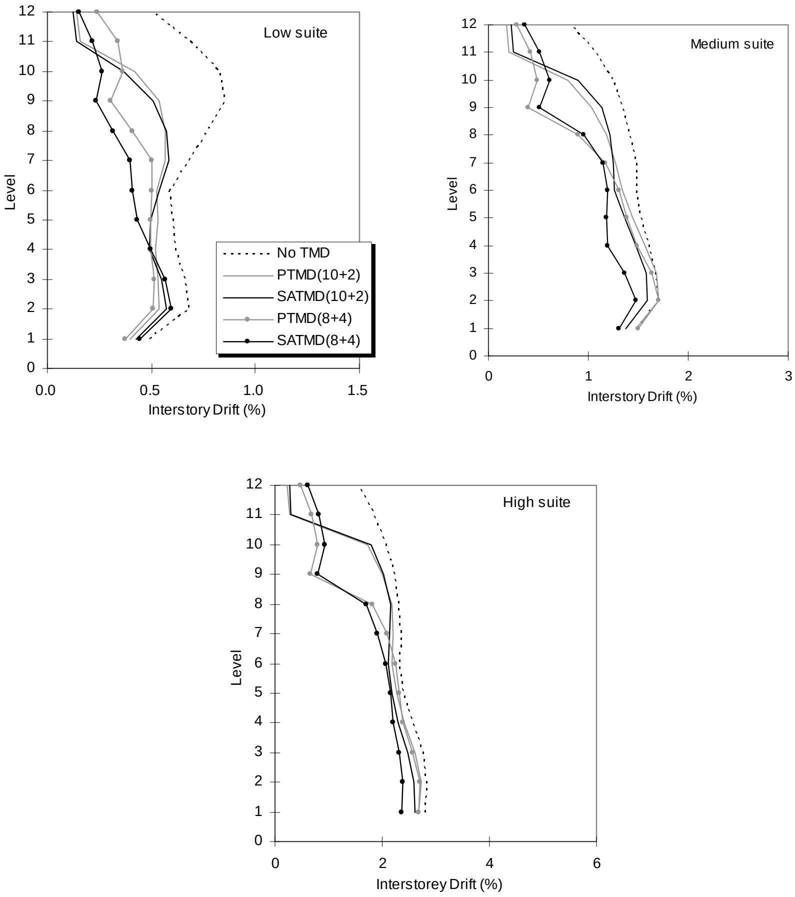

Figure 3: Interstory drift ratio (50th Percentile / Low, Medium and High suites)

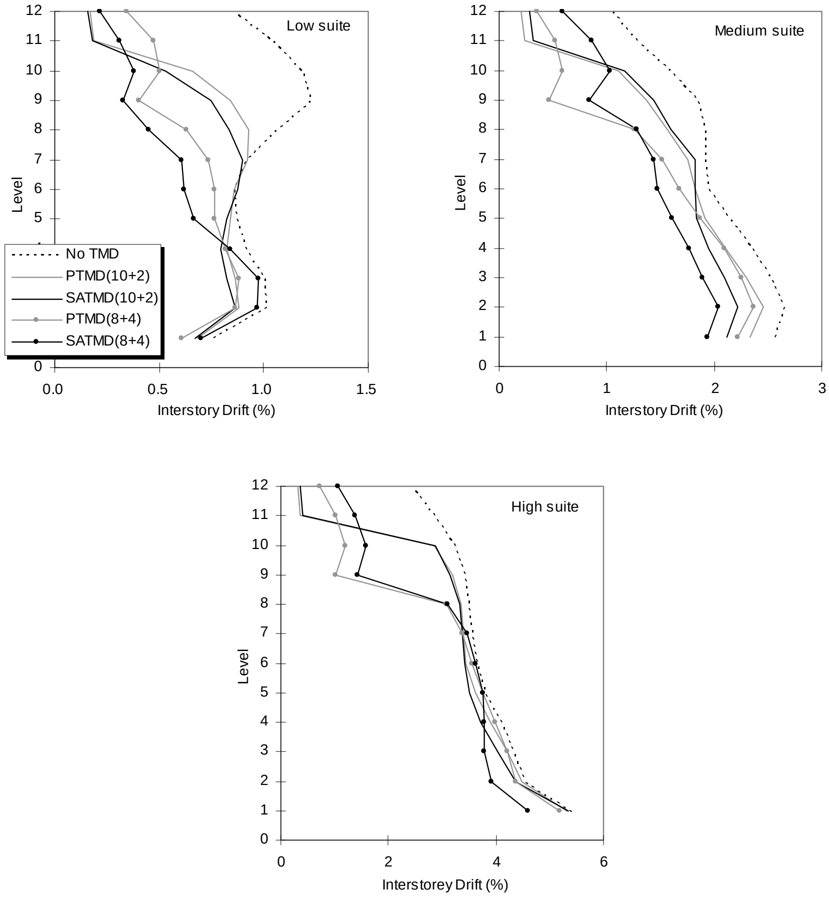

Figure 4: Interstory drift ratio (84th Percentile / Low, Medium and High suites)

Figures 3-4 show that the TMD systems reduced the response of the isolated upper stories, as well as the lower stories. The profiles clearly reflect the systematic advantage of the SATMD systems. Increasing the levels of seismic hazard increases the interstory drift however, the increased drift ratios in the isolated upper stories are still small and the peak drift locations are shifted to the lower stories. For the Medium and Low suites, all the drift demands of the TMD systems are less than the life safety limit of 2.5% for the numerical time history analysis specified in NZS4203 [18].

3.2 Structurally Dissipated Hysteretic Energy Results

Figures 5-8 show the 50th and 84th percentile structurally dissipated hysteretic energy results, a marker for damage and necessary repairs. Compared to the No TMD case these results can thus measure reductions in damage or repair, particularly in combination with the results of Figures 3-4. The use of suites with known probability of occurrence ensures that these damage estimates are related to likelihood of occurrence making the results suitable for standard hazard analyses.

As expected, as the severity of ground motions increases, the hysteretic energy dissipated by the structure increases. There are clearly lower energy demands at stories above the isolation layer. Energy demands at lower stories are also reduced. Hence, the energy transferred from the base is decreased by splitting the overall structural mass and, therefore, the dissipated energy along the height is reduced. In the Low suite, the energy curves of the isolated upper structures lie along the y-axis, successfully isolating the upper structure within elastic limits. In the Medium and High suites, the TMD systems keep the response essentially linear, as indicated by very low values of hysteretic energy indices.

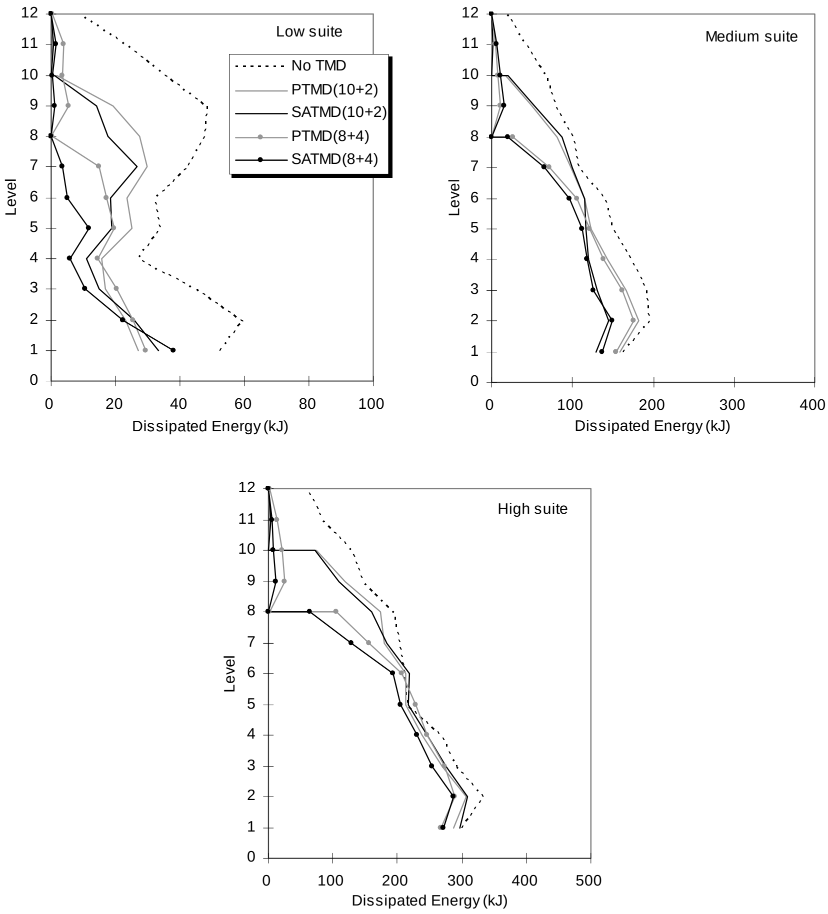

Figure 5: Story dissipated energy (50th Percentile / Low, Medium and High suites)

Finally, as a representative energy value, all of the dissipated energy values along the height are summed to establish a total structural hysteretic dissipated energy index, as seen in specifically in Figures 6 and 8. Again, the control effects are more significant for the larger mass ratio (8+4) and the SATMD system. In addition, the difference in control effectiveness is pronounced from the PTMD(10+2) to the SATMD(8+4) systems. Overall, all TMD systems reduced the seismic hysteretic energy demands at all hazard levels.

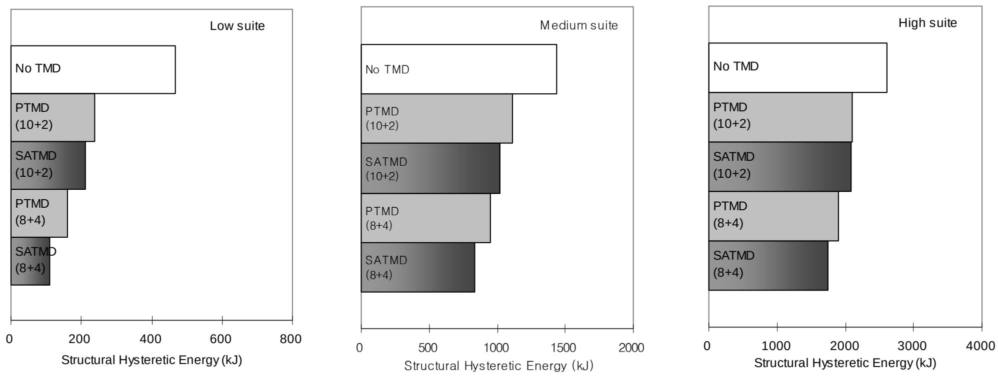

Figure 6: Structural dissipated energy (50th Percentile / Low, Medium and High suites)

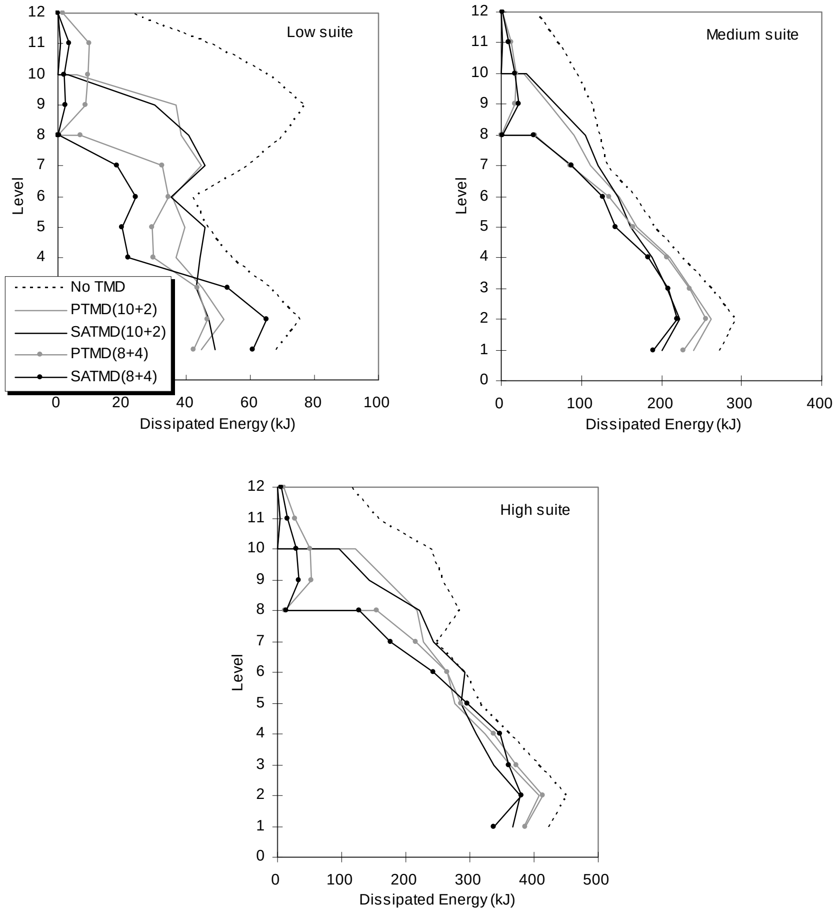

Figure 7: Story dissipated energy (84th Percentile / Low, Medium and High suites)

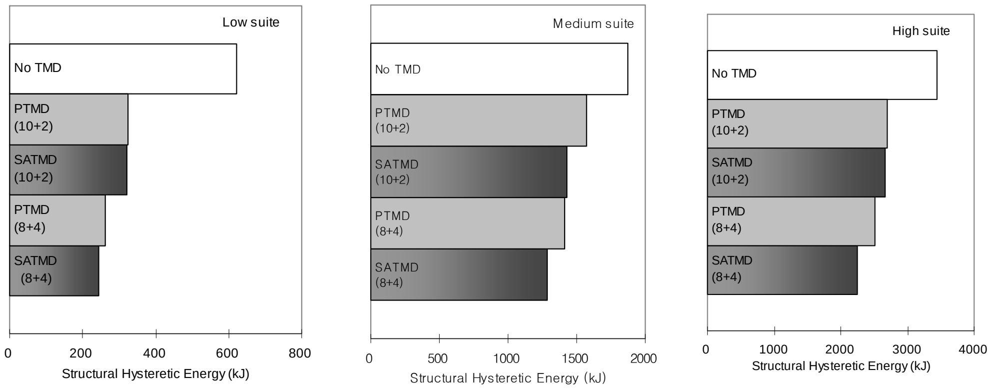

Figure 8: Structural dissipated energy (84th Percentile / Low, Medium and High suites)

4. Discussion and Conclusions:

This paper has investigated the seismic performance of five different nonlinear TMD building systems (No TMD, PTMD (10+2 and 8+4) and SATMD (10+2 and 8+4)) over three probabilistically scaled suites of earthquake records. The seismic demands were based on several assumptions concerning structural parameters and modeling, including P-delta effects, modified Takeda hysteresis, and several others. Performance comparisons were based on statistically calculated interstory drift ratio, hysteretic dissipated energy and practical damage assessments to provide information regarding the cumulative damage to the structure, which may be more important in evaluating potential damage and degradation. The TMD building systems were successful in reducing the seismic demands in statistical point of view for the new designs (10+2 and 8+4).

Overall, the SATMD system provided more robust response mitigation over a range of ground motions within each suite. It should be noted that the PTMD results are optimal, but not necessarily practical. Specifically, the 60-80% damping ratio required for the PTMD solutions might not be realistically achieved. Thus, similar SATMD results indicate that optimal level solutions can be obtained without resulting to infeasible and oversized non-linear viscous dampers. Thus, it might be concluded that the SATMD is the better choice for the seismic case where future input motions are unknown.

This analysis has demonstrated the validity of realistic SATMD building systems for consideration in future design and construction in an analytical setting. Further analysis and experimental examinations would be the next steps in seeing this concept move toward reality. This work would also include the development of full scale device prototypes where, to date, only ~0.1MN capacity resetable devices have been created that also have the unique behaviors used in this analysis.

Overall, the details and results of a set of comparative studies are used to assess the feasibility and effectiveness of such isolation systems. In view of these findings, and the fact that they might be relatively easy to construct using these emerging SA devices, it is concluded that the proposed SATMD building system has the potential to become a practical and effective way to reduce earthquake damage. Thus, these systems merit further studies to examine their advantages and to further develop experimental validation and design solutions, leading eventually to practical initial designs.

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